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Characterization of Tsunami and Palaeo-tsunami deposits in the Neil Island, South Andaman, India

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The nature of tsunamigenic and palaeo-tsunamigenic sediments in Neil Island, deposited by the great Indian Ocean in 2004 is documented herein. Pit, trench and core samples were collected from the four beaches, namely, Bharatpur, Ramnagar, Sitapur and Lakshmanpur; which exhibit distinguished anomalies in the sedimentological parameters, *viz*. skewness, kurtosis and standard deviation at various depths. The palaeontological study shows the simultaneous occurrence of characteristic benthic taxa of near-shore environment and upper part of continental slope along with the open ocean dweller planktic foraminifera- an intermixed foraminiferal assemblage is mainly due to the tsunami wave actions. The multiproxy approach reveals the occurrence of the tsunami and palaeo-tsunami deposits in Neil Island from 9 to 40 cm and below 60 cm depth, respectively.

[**Keywords**: Foraminifera, Neil Island, Palaeo-tsunami deposit, Tsunami deposit]

Introduction

The devastating Indian Ocean earthquake of M 9.3 triggered the most severe tsunami during the twentieth and twenty-first centuries on 26 December 2004, killing 230,000 people[1–3]. The continuous group of waves devastated Andaman and its surrounding islands. The approximate time between the waves was about 30 – 35 minutes. The huge tsunami occurs with the arrival of wave trains, one after another. Each wave generates high-energy flows on and along the coast. The repeated arrival of tsunami waves generates a series of run-up and backwash flows in the coastal area. The deposits formed by these waves also include the succession of arriving waves. The second or third one of the Indian Ocean Tsunami waves was the highest among three consecutive waves and affected vast tracts of the coast, estuaries and embayment and inland depression[4]. Apart from the Andaman coast, Neil Island was also affected by the earthquake and the resulting tsunami. Neil Island lies about 32 km east of Port Blair and in the southern part of the Archipelago, to the south of Havelock Island. The low-lying areas near estuaries and inlets went barren; mangroves and coconut plantations died due to waterlogging caused by the devastating tsunami[5].

According to eyewitnesses, the low-lying areas were flooded by tsunami water with a foul-smelling sticky brown to black mud, which caused an itchy sensation on the skin[5]. Generally, the tsunami deposits are less than 25 cm thick and tend to drape the pre-existing landscape[6]. It commonly consists of a single, homogeneous bed that ranges from coarser-grained at the bottom to finer-grained at the top or a bed with only a few thin layers[5]. The wavelength and period of tsunamis are controlled by the water depth and the size of the areas from where they originate, whereas, in storm surges, the traces of individual waves are scarcely preserved due to frequent erosion[6]. The provenance assessment of anomalous sand layers formed by the tsunami waves and preserved within coastal sediments is complicated by the presence of a mixture of marine, brackish and terrestrial sediments[7-10]. Generally, the tsunamigenic sediment is comprised of two erosive sedimentation units that were probably deposited by successive waves in the tsunami wave train based on the sedimentologic and stratigraphic features[11]. The tsunamigenic sediments are subjected to minor alteration and erosion. Thus, the multi-proxy approach is necessary to assess the tsunami and palaeo-tsunami deposits. Detailed grain size analysis and its statistical approach are helpful in this regard[12-14].

The microfossils have also been recognized as a valuable tool to find out tsunami and palaeo-tsunami deposits[10,15–18]. An inverted sequence with fine-grained sediments and small foraminifers sandwiched between normal detrital sediments at water depths of 10 – 20 m was reported along the Coast of Kachchh, NW India. The erosion and transportation of fine-grained sediments from deeper water, and their deposition in shallower water against the rule of gravity, were considered storm/tsunami deposits[19]. Foraminifera study is very useful due to the presence of certain species, which indicate the transportation from the shallow depth or deep-water offshore. The effect of the strong seasonality on benthic foraminifera living within the Oxygen-Deficient Zone (ODZ) due to the exchange of seawaters of different seas creates a distinct depth zonation in living benthic foraminiferal species[20]. That is attributed to the lack of denitrification and associated processes[21]. This observation supported the concept of a clear identification of earlier tsunamigenic events. Moreover, foraminifera are a highly reliable proxy to reconstruct various environmental parameters in the past[22-25]. Vaziri *et al.*[26] used the allochthonous tests of foraminifera to infer palaeo-tsunami deposits in low-energy environments such as coastal lagoons, ponds and marshes. Although, the sizeable parts of the Andaman Islands are still unexplored. The 2004 tsunami deposits were found as black humic mud-fine sand often mixed with shell fragments and/or coral boulders[5]. Similar anomalous deposits could be observed further down in the sediment column of the south Andaman coast, which had been interpreted as palaeo-tsunami deposits at Therur, Corbyn's Cove, Sippighat, Collinpur and Wandoor areas[5]. Tsunami deposits have also been studied based on the presence of foraminifera and Ostracoda shells at Andaman[27]. However, there is no information available about the tsunami deposits from Neil Island. The hydrological investigation suggests that Neil Island was severely affected by the 2004 tsunami[28].

This paper aims to find out the tsunami and palaeo-tsunami deposits on Neil Island. The areas considered for this study include beaches, near-shore and shallow-water regions, which were affected severely during the Tsunami inundation.

Study sites

Neil Island is a tiny island located east of the South Andaman Islands. This area is famous for its coral reef, white sandy beaches, and a natural coral bridge in the Lakshmanpur area. The parent rocks are not visible due to the thick light-coloured sand cover, which is composed of mainly coral fragments, shell fragments, or of biogenic origin. The dense, tropical forest and vegetation in a few regions with magnificent biodiversity were reported on the island. The eastern part of the island is mostly covered by vegetation. The terrain of this island is relatively flat (range of elevation varies from 0 to 95 m, with the highest elevation being 101 m) as compared to the other Andaman Islands. The sediment samples were mainly collected from tsunami-affected areas in Neil Island, such as Bharatpur, Lakshmanpur, Sitapur and Ramnagar (Fig. 1). It has been reported by eyewitnesses that low-lying areas, even roads of the towns and settlements like Janglighat, Corbyns' Cove and Mithakari were flooded with a foul-smelling sticky brown to black mud, with an itchy sensation on the skin[5] (Fig. 2).

The area suffered subsidence by approximately 1 m[(ref. 29)] after the 2004 tsunami. The southern and western coastal segments were downfaulted by a maximum of 1 m, while the northern and eastern segments were upthrown relatively[30]. It allowed the water logging to continue in patches in some areas of South Andaman after the tsunami. Tsunami water carried massive chunks of sediment from the offshore and beaches and deposited them in the low-lying areas of the coasts. The enormous velocity of the large tsunami waves carried huge amounts of water, sediments and microfossils along with dark-coloured suspensions of fine-grained materials from ocean environments into the coastal areas[31].

Material and Methods

The tsunami inundation map was prepared to identify tsunami-affected low-lying areas with the help of ASTER GDEM data. The pre- and post-tsunami remote sensing data were used to delineate waterlogged areas. Visual interpretation of post-tsunami data was used as an input while delineating the affected areas[32]. The post-tsunami ASTER GDEM data helps to find out low-lying subsided areas. The map was used as an input with the Survey of India toposheet to carry out ground truth verification to get the final affected areas (Fig. 1). The samples were collected from these identified low lands. The possibility to find the tsunami and palaeo-tsunami deposit appears to be maximum in low-lying areas. Palaeo-tsunami deposits occur as anomalous layers

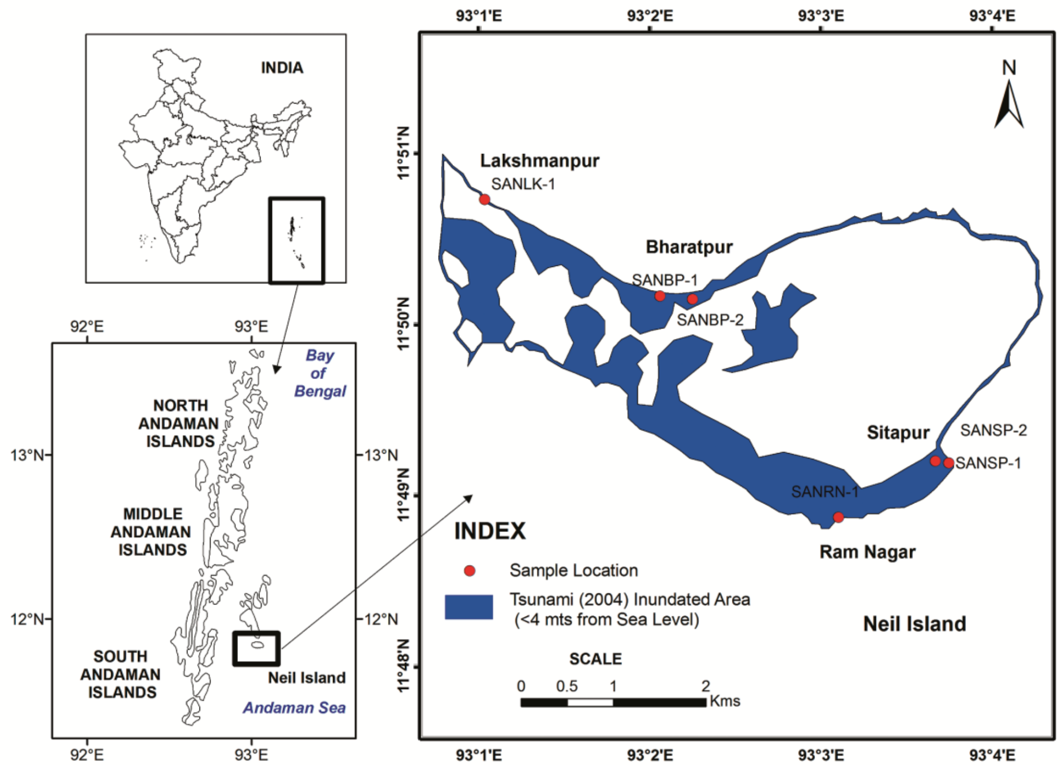

Fig. 1 — Samples collected from probable tsunami inundated area in Neil Island (< 4 m from sea level) (Data Source: ASTER GDEM)

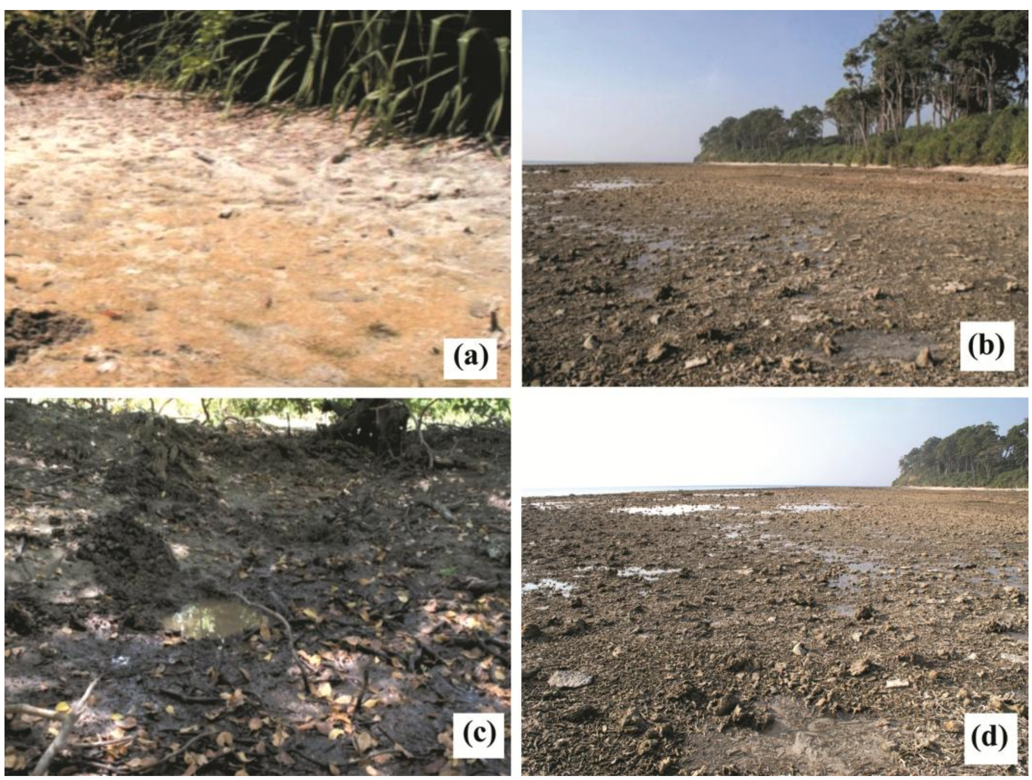

Fig. 2 — Black tsunami mud deposited at low inland areas of a) Bharatpur beach, b) Lakshmanpur beach, c) Sitapur beach, and d) Ramnagar beach

within sedimentary sequences of coastal depositional environments[33]. They are generally recognized by investigating similar types of physical, geochemical and microbiological content of sediments[33]. The sediments were collected by pitting, trenching and coring from coastal sites and various tsunami-affected beaches, estuaries, creeks and swamps in Neil Islands. The trenches were dug up to a depth of 2 m and a length of about 5 to 7 m. The sediments which lay at a deeper depth were taken by plastic core pipes from the surface to 1.5 m below the surface, from specific localities of low-lying areas identified from the tsunami inundated map (Fig. 1), to observe different anomalous zones caused by the tsunami. The different layers/zones of core and trench samples were analyzed based on grain size, colour variation and microfossil assemblages. The most common method applied is grain-size-distribution analysis (Table 1), which provides valuable information about the hydrodynamic conditions during deposition[34]. The deposits were divided into several sedimentary units based on sedimentary structures, colour and vertical changes in grain size. The grain size analysis was carried out by using 1.41 mm, 1 mm, 0.5 mm, 0.35 mm, 0.25 mm, 0.177 mm, 0.125 mm, 0.088 mm, 0.0625 mm size sieves[31,35]. Before analysis, the organic matter and carbonates were removed by using 30 % H_2O_2 and 10 % HCl and dried at 50 °C for 72 hours[14]. The anomalous zones of the tsunami and palaeo-tsunami horizons from pre- and post-tsunami deposits were identified by determining statistical parameters, including mean grain size (average grain size- Mz), skewness (degree of symmetry of the grain-size distribution-SkI), kurtosis (peakedness of a grain-size distribution-KG) and standard deviation (degree of sorting-σ1). The tsunamigenic sediments could also be distinguished by their content of broken shell fragments[36], coral boulders[37], granules[38], beach rubbish and plastic, embedded in the fine sediments.

Foraminiferal tests were separated from sediment samples of each size fraction by a conventional micropalaeontological technique. Generally, the foraminifera were collected from the size fraction of 45 μm to 120 μm sieve size. About 200 – 300 foraminifera specimens were collected by brush and kept on micropalaeontological slides. All specimens were identified under a stereo zoom binocular microscope (Leica S8-APO). Systematic classification concepts and morphological criteria of foraminifera are based on Barker[39], Loeblich & Tappan[40] and Sen Gupta[41]. Selected specimens were photographed with a Scanning Electron Microscope (SEM). Most specimens were benthic with a few planktonic foraminifera found at limited horizons.

The tsunamigenic sediment in South Andaman is rich in organic matter. Increased organic concentrations tend to be associated with the finer sediments usually deposited at great depth for inland basins or marginal areas[42] where the continental shelf is relatively narrow. The organic matter enriched black mud helps to identify the anomalous zones formed by tsunami and palaeo-tsunami. The organic carbon content in those black muds was determined by Walkley and Black method[43]. In this process, the organic carbon is oxidized with potassium dichromate ($K_2Cr_2O_7$) in the presence of concentrated H_2SO_4, which produces nascent oxygen and combines with the carbon of organic matter to produce CO_2. The remaining volume of excess $K_2Cr_2O_7$ is titrated against the standard solution of ferrous ammonium sulphate in the presence of phosphoric acid (H_3PO_4) and diphenylamine indicator, thus the volume of $K_2Cr_2O_7$ can be found which is required to oxidize organic carbon. The determination of organic carbon by the Walkley-Black method showed better accuracy than other methods[44].

Results

The entire island is covered by white sandy beaches and dense forests. The dark-coloured tsunami deposits were identified from white coralline sand in the coastal area[45,46]. According to eyewitnesses, the four villages, namely Sitapur, Bharatpur, Lakshmanpur, and Ramnagar, were devastated by the tsunami (Fig. 2). Similar grey-coloured discontinuous tsunamigenic sediments with brown, rooted soil were found in Papua New Guinea[47]. The 2004 tsunamigenic sediments dominantly consist of broken, abraded and reworked foraminifera species with a few fresh specimens. The broken specimens with angular edges were classified as fragmented, whereas the broken specimens with rounded edges were classified as reworked[48]. The taphonomic (or surface) condition of individual foraminifera is an indicator of the origin and transport history of the sediment[9,49,50]. The proxies of foraminifera are also used to recognize both the pollution and past climatic changes[51].The reworked/older specimens can also be an indicator of the Holocene high sea stand at the lower reaches of the estuary[19].

Table 1 — Grain size analysis data from different boreholes collected from different locations

BH No. SANBP-1 (Bharatpur)

Latitude: 11.8261 N; Longitude: 93.0343 E

From (cm)	To (cm)	Thickness (cm)	Mean size	Standard Deviation	Graphic Skewness	Graphic Kurtosis
0.00	20.00	20.00	2.3859 (fine sand)	3.1328 (very poorly sorted)	-0.1941 coarse skewed)	4.5875 (extremely leptokurtic)
20.00	39.00	19.00	2.3861 (fine sand)	0.5248 (mod. well sorted)	0.0668 (near symmetrical)	0.8432 (platykurtic)
39.00	75.00	36.00	1.4169 (medium sand)	0.547 (mod. well sorted)	-0.015 (near symmetrical)	1.8798 (very leptokurtic)

BH No. SANLK-1 (Lakshmanpur)

Latitude: 11.8454 N; Longitude: 93.0169 E

From (cm)	To (cm)	Thickness (cm)	Mean size	Standard Deviation	Graphic Skewness	Graphic Kurtosis
0.00	12.00	12.00	0.0249 (coarse sand)	1.9515 (poorly sorted)	-0.4818 (coarse skewed)	1.1906 (leptokurtic)
12.00	30.00	18.00	0.477 (coarse sand)	1.6702 (poorly sorted)	-0.5792 (strongly coarse skewed)	1.728 (very leptokurtic)

BH No. SANSP-1 (Sitapur)

Latitude: 11.8198 N; Longitude: 93.0624 E

From (cm)	To (cm)	Thickness (cm)	Mean size	Standard Deviation	Graphic Skewness	Graphic Kurtosis
0.00	20.00	20.00	-0.5554 (very coarse sand)	2.3476 (very poorly sorted)	-0.1524 (coarse skewed)	1.2422 (leptokurtic)
20.00	60.00	40.00	1.4552 (medium sand)	1.3853 (poorly sorted)	0.1376 (fine skewed)	1.3069 (leptokurtic)
60.00	140.00	80.00	-0.6614 (very coarse sand)	2.6344 (very poorly sorted)	-0.4147 (strongly coarse skewed)	1.2491 (leptokurtic)

BH No. SANSP-2 (Sitapur)

Latitude:11.82 N; Longitude: 93.061E

From (cm)	To (cm)	Thickness (cm)	Mean size	Standard Deviation	Graphic Skewness	Graphic Kurtosis
0.00	18.00	18.00	2.1616 (fine sand)	0.7227 (moderately sorted)	-0.3103 (strongly coarse skewed)	0.6638 (very platykurtic)
18.00	30.00	12.00	2.6877 (fine sand)	0.3517 (well sorted)	-0.3722 (strongly coarse skewed)	1.2648 (leptokurtic)
30.00	55.00	25.00	2.0801 (fine sand)	0.6143 (mod. well sorted)	0.139 (fine skewed)	1.7084 (very leptokurtic)
55.00	60.00	5.00	7.0465 (coarse silt)	0.611839 (poorly sorted)	-0.7771 (strongly coarse skewed)	4.472 (leptokurtic)

BH No. SANRN-1 (Ramnagar)

Latitude: 11.8140 N; Longitude: 93.0519 E

From (cm)	To (cm)	Thickness (cm)	Mean size	Standard Deviation	Graphic Skewness	Graphic Kurtosis
0.00	9.40	9.40	2.8796 (fine sand)	2.5011 (very poorly sorted)	0.3587 (fine skewed)	0.745 (platykurtic)
9.40	29.80	20.40	3.0174 (very fine sand)	2.82 (very poorly sorted)	0.0435 (near symmetrical)	1.5265 (very leptokurtic)
29.80	56.00	26.20	1.4284 (medium sand)	2.2285 (very poorly sorted)	-0.4929 (strongly coarse skewed)	1.2916 (leptokurtic)

The black mud was preserved in low inland areas of Bharatpur, Lakshmanpur, Sitapur and Ramnagar Beach of Neil Island (Fig. 2). After gravel and sand were deposited, the suspended black mud was re-settled through the water column and deposited on the sand layer[52].

Bharatpur

Bharatpur beach is composed mainly of biogenic medium-grained calcareous sand comprising fragments of coral and foraminifera (Fig. 2a). The tsunami deposits found here were about 39 cm in thickness admixes with top sand, which was observed from the grain size analysis data (Fig. 3). This horizon is composed mainly of biogenic grey-coloured sands with abundant foraminifera species distinguished from the calcareous beach soil. Based on compositional variation, grain size data, foraminiferal variation, presence of shell fragments and rootlets, these horizons could be subdivided into different zones that indicated different phases of tsunami waves together formed the thick tsunami horizon. The top 20 cm deposits consisted of an abundance of deeper water benthic foraminiferal species of *Bolivina spathulata* (Fig. 4). Some distorted specimens of *Pararotalia* sp. were also found. Different forms of shallow water inner shelf benthic foraminifera, such as *Pararotalia nipponica*, *Elphidium* sp., *Gyroidina* sp., *Cribroelphidium* sp., *Elphidium* sp., *Amphistegina lessonii*, *Elphidium botaniensis* were predominant on the top horizon of the deposit. The sharp anomaly observed from the depth of 20 to 39 cm of tsunamigenic black mud was composed of moderately well to very poorly sorted fine sand (2.3 Φ) with abundant planktonic and benthic foraminifera, such as *Elphidium hispidulum*, *Amphistegina lessonii*, *Notorotalia* sp., *Pararotalia nipponica*, *Globigerina ruber*, *Quinqueloculina* sp. (Figs. 3, 4 & 5). The organic carbon content of this horizon is quite high at 1.25 % compared to the other horizons. The tsunamigenic horizon was well preserved over the normal horizon (39 – 75 cm) of medium-grained light-coloured mixed sand comprising *Notorotalia* sp., *Amphistegina lessonii*, *Amphistegina radiata*,

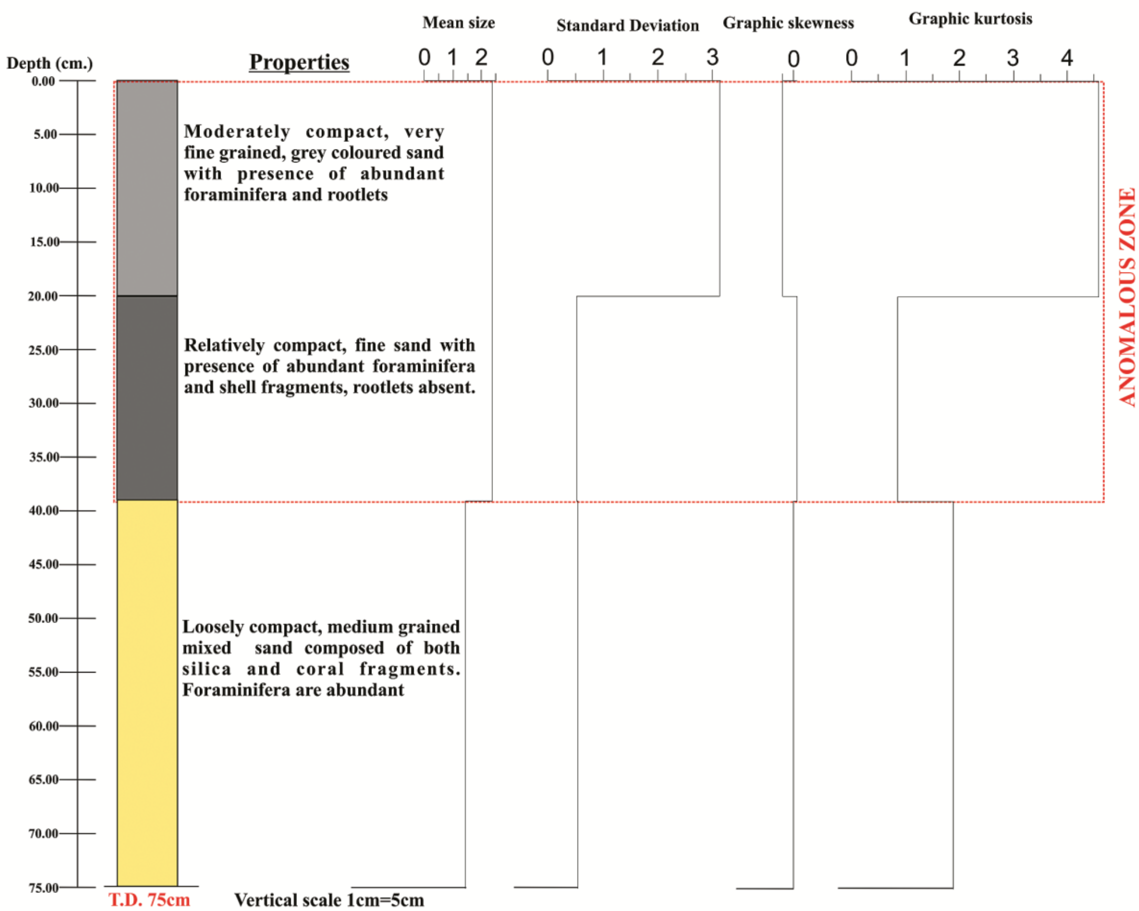

Fig. 3 — Statistical properties of grainsize at different depths of sediments at Bharatpur beach of Neil Island

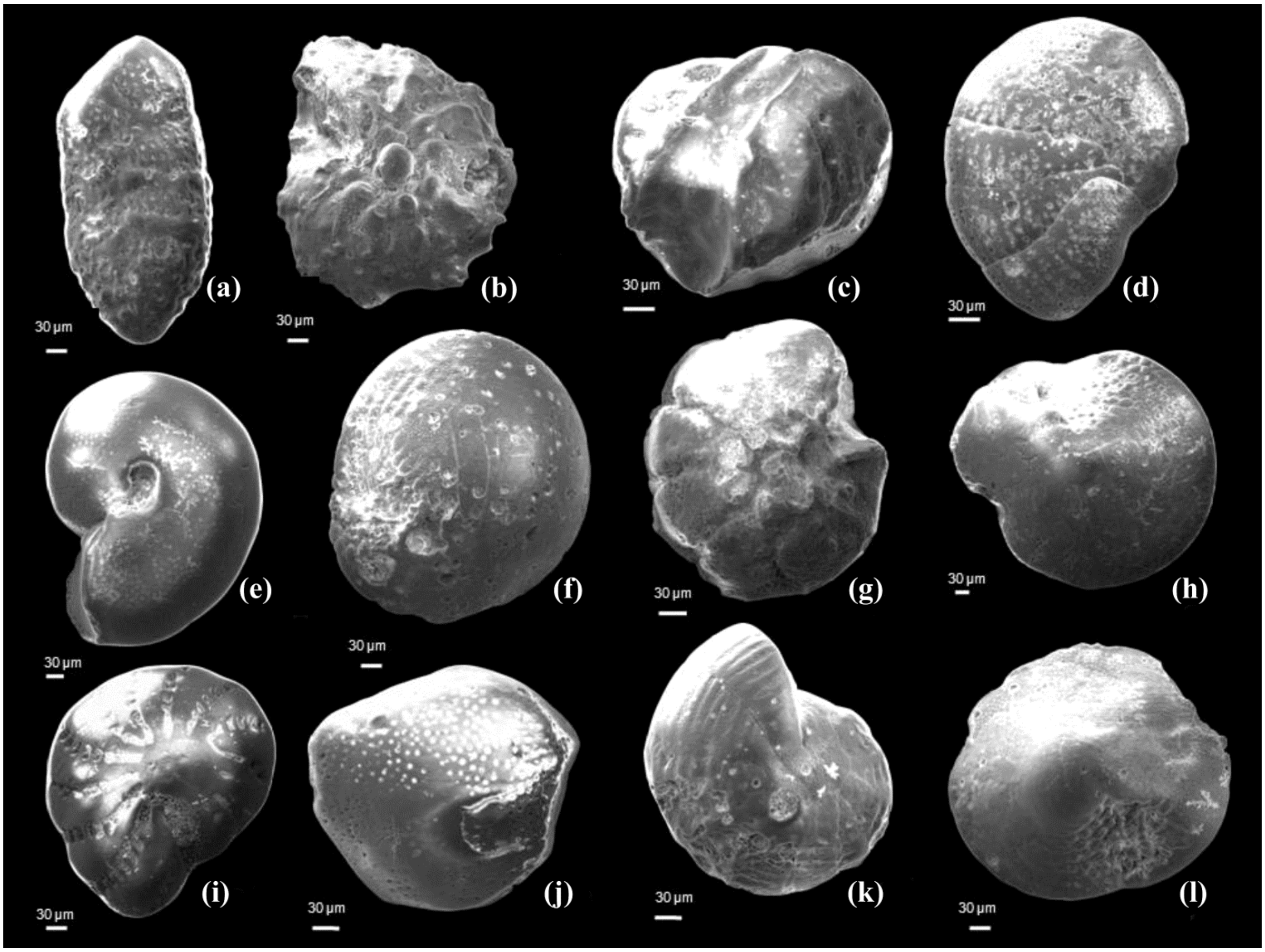

Fig. 4 — Some of the selected species of foraminifera in different types of sediment at Bharatpur beach, Neil Island. 2004 Tsunami Deposit (depth 0 – 20 cm, a – j): (a) *Bolivina spathulata*, (b) *Pararotalia nipponica* - Ventral view, (c) Specimen distorted, (d) *Elphidium* sp., (e) *Gyroidina* sp., (f) *Cribroelphidium* sp., (g) *Pararotalia nipponica* - Ventral view, (h) *Amphistegina lessonii*, (i) *Elphidium botaniensis*, (j) Specimen distorted; 2004 Tsunami deposit (depth 20 – 39 cm, k – l), (k) *Elphidium hispidula*, and (l) *Amphistegina lessonii*

Elphidium crispum, *Elphidium* sp., *Calcarina* sp. (Fig. 5). The statistical analysis of grain size data indicated a moderately well-sorted, very leptokurtic medium-grained (1.4 Φ) nature with a sharp fluctuation at 39 cm depth (Table 1). Here the tsunami deposit indicated a typical anomalous nature from the normal beach sediment by their extremely leptokurtic to platykurtic, coarse skewed to near-symmetrical, very poorly sorted, fine-grained nature. Another sample collected by coring at other places of Bharatpur beach also represents similar characteristics of graphic lithology (SANBP-2).

Lakshmanpur beach

The 12 m thick tsunamigenic sediments at the top horizon were distinguished from normal beach sediments by typical organic matter enriched coarse-grained (0.0249 Φ) poorly sorted calcareous sand with pinnacles and pelecypod shells (SANLK-1) (Figs. 2b & 6; Table 1). The organic carbon content is 1.7 %. Pelecypod molluscs are also considered an indicator of tsunami deposit[53,54].

Sitapur beach

Sitapur Beach, situated at the tip of Neil Island, is prone to high tides as it is exposed to the open sea. This beach is famous for its limestone formations. Lots of coral boulders were exposed over the beach sediments at the top horizon and carried with water due to tsunami activity (Fig. 2c). The tsunamigenic black sand was identified by leptokurtic, coarse skewed, very poorly sorted, very coarse-grained calcareous sands with coral fragments (-0.055 Φ), reworked foraminifera and shell fragments, which

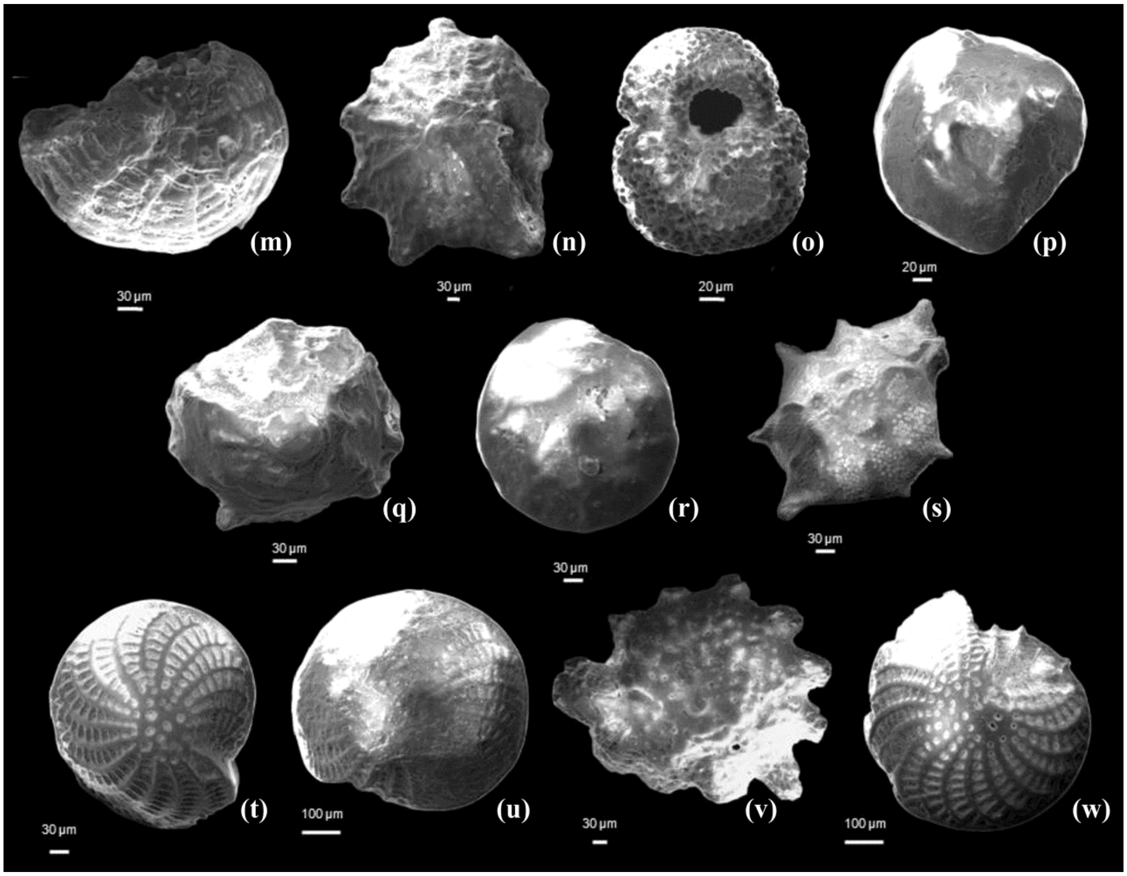

Fig. 5 — Some of the selected species of foraminifera in different types of sediment at Bharatpur beach, Neil Island. 2004 Tsunami deposit (depth 20 – 39 cm, m – p): (m) *Notorotalia* sp., (n) *Pararotalia nipponica* - Dorsal view, (o) *Globigerina ruber*, (p) *Quinqueloculina* sp.; Normal Sediment (depth 39 - 75 cm): (q) *Notorotalia* sp., (r) *Amphistegina lessonii*, (s) *Amphistegina radiata*, (t) *Elphidium crispum*, (u) *Elphidium* sp., (v) *Calcarina* sp., and (w) *Elphidium crispum*

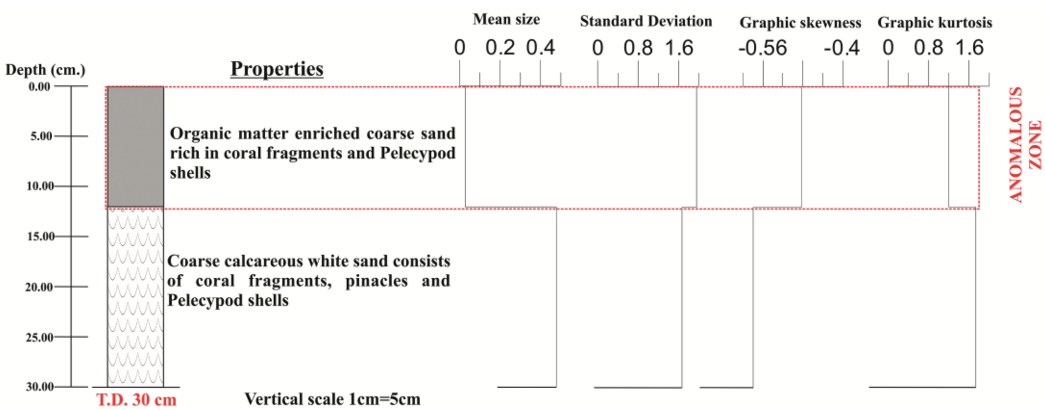

Fig. 6 — Statistical properties of grainsize at different depths of sediments at Lakshmanpur beach of Neil Island

were observed up to 20 cm (SANSP-1) (Fig. 7; Table 1). The organic carbon content is 1.54 % distinguished from the normal horizons with poor organic matter. The tsunami sediment was underlain by medium-grained (1.4 Φ), calcareous sand. A similar type of organic matter enriched dark sand was found below 60 cm consisting of leptokurtic, strongly coarse skewed, very poorly sorted, very coarse-grained sand (-0.66 Φ) with shell fragments, rootlets and reworked foraminifera. This horizon was considered as palaeo-tsunami I with relatively high organic carbon content, *i.e.*, 0.64 % (Fig. 7). The tsunami and palaeo-tsunami deposits contained a variety of benthic and planktonic foraminifera.

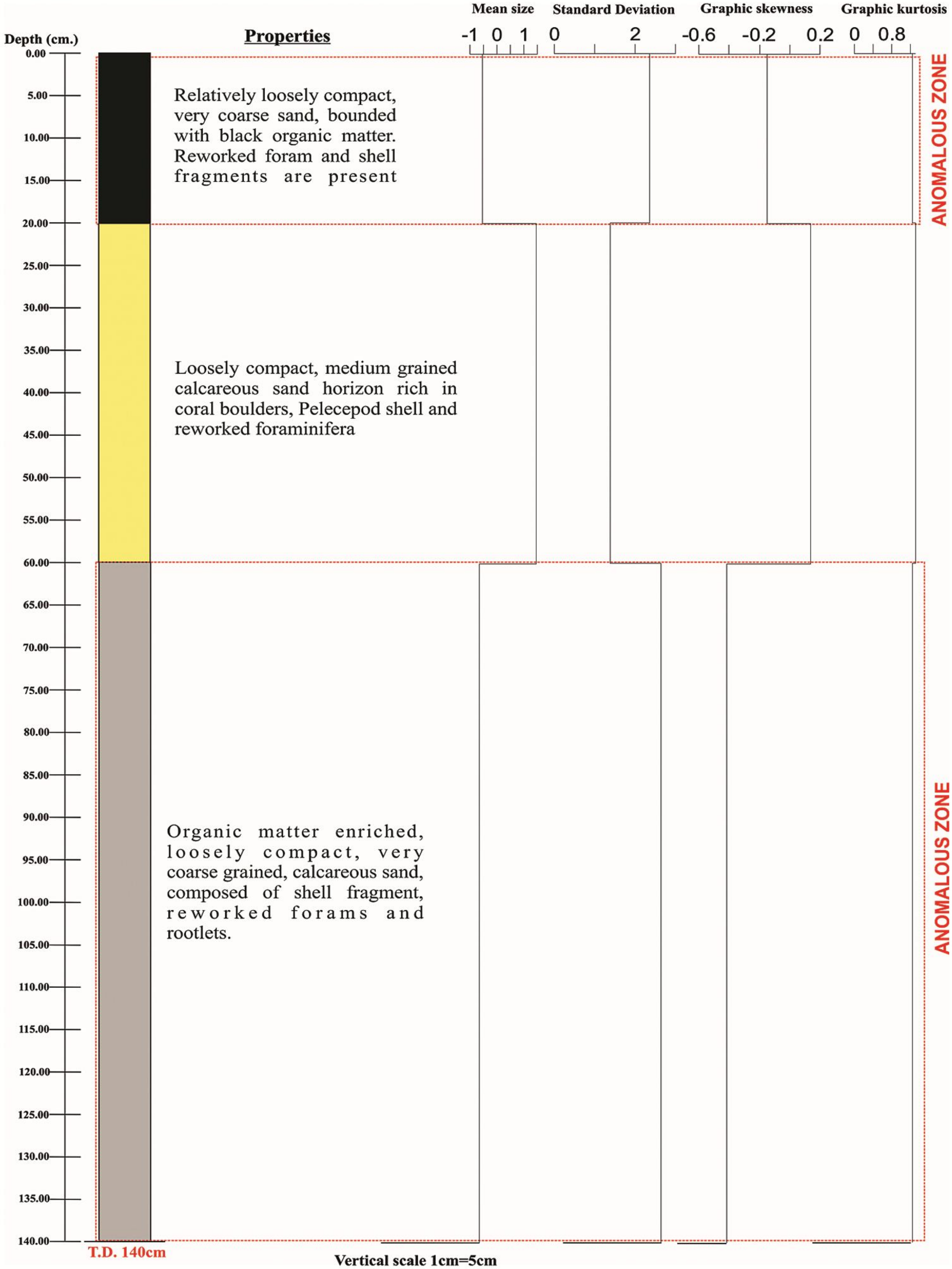

Fig. 7 — Tsunami and palaeo-tsunami deposits preserved at Sitapur beach

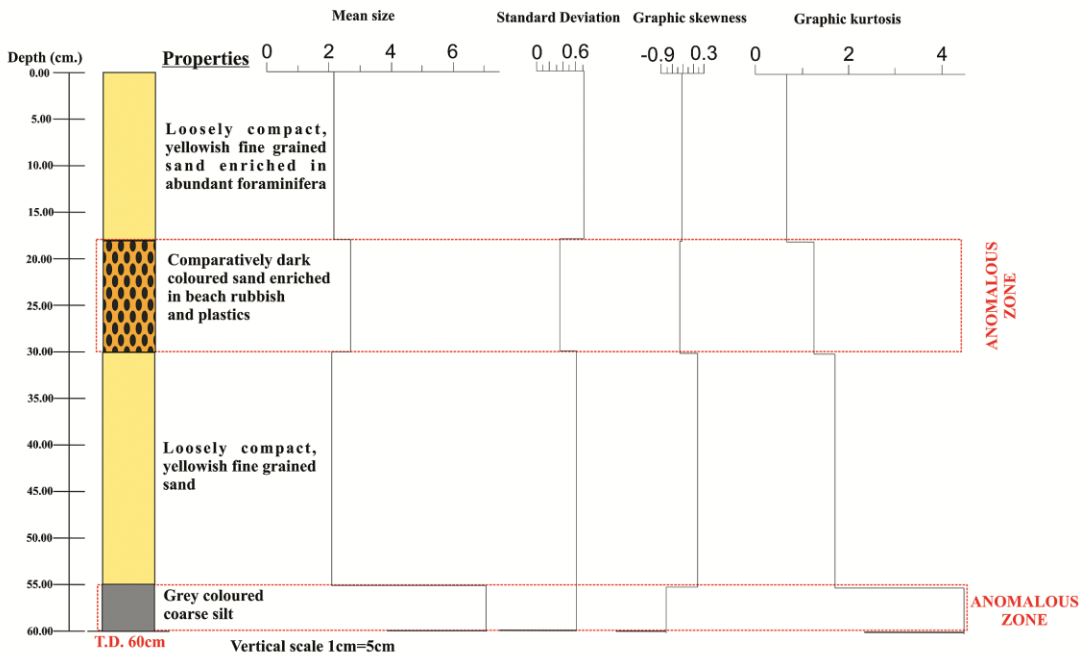

Fig. 8 — Tsunami and palaeo-tsunami deposits preserved at Sitapur beach

The 2004 tsunami deposit was also well-preserved at another trench section between 18 and 30 cm depth (SANSP-2) (Fig. 8). This horizon consisted of dark organic matter enriched with well-sorted, coarse skewed, leptokurtic fine sand (2.6 Φ) with foreign materials like beach rubbish and plastics which may be derived due to high energy conditions during tsunami waves. The benthic foraminifera, *Quinqueloculina* sp., *Calcarina* sp., *Amphistegina papillosa*, *Elphidium norvangi* were reported in the tsunami deposit (Figs. 9 & 10). The top horizon (18 cm in thickness) comprised only *Calcarina calcar*, *Elphidium* sp., *Rosalina globularis* (Fig. 9), but lesser in abundance. The palaeo-tsunami horizon contained mainly planktonic foraminifera, *Trilobatus sacculifer*, *Pullenia quadriloba*, *Orbulina universa*, *Orbulina* sp., *Globorotalia tumida* and benthic foraminifera of *Calcarina* sp. and *Lagena* sp. between 55 and 60 cm depth (Fig. 10). The organic matter-enriched sediments and deeper water foraminifera might be carried out during the 2004 tsunami and preserved in particular low-lying areas of Sitapur beach.

Ramnagar beach

The top horizon of beach sediment consisted of platykurtic fine sand (2.8 Φ) with abundant foraminifera (Fig. 11). The black mud was recorded at a depth of 9.4 to 29.8 cm that exhibited more or less sharp anomaly between the depth of 9.4 to 29.8 cm with very high organic carbon content, *i.e.*, 1.8 % and consisted of very leptokurtic, very poorly sorted, very fine sand (3.017 Φ) (Table 1) with lesser foraminifera. It was deposited above moderately compact, yellowish medium sand (1.4 Φ). The reworked and broken foraminiferal species of tsunami deposit were distinctly distinguished from the fresh foraminifera of *Quinquelocuilna* sp., *Elphidium crispum* at the top horizon. The tsunami deposit was dominantly enriched in reworked foraminifera with few broken forms of *Elphidium crispum*. This deposit was underlain by medium-grained sand which is comprised of *Elphidium crispum*, *Amphistegina papillosa*, *Calcarina* sp. (Fig. 12). This fluctuation also indicates an imprint of the 2004 tsunami deposit between 9.4 and 29.8 cm depth below tidally flooded beach sediment and above the normal sediment.

Discussion

Tsunami and palaeo-tsunami deposits can be the black humic mud mixed with the fine sand horizon, and coral boulders and can be distinguished as the marker horizon in south Andamans (Fig. 2). Srisutam *et al.*[45] and Singarasubramanian *et al.*[46] also found similar dark grey fine sand deposits at the Thai Andaman coast and Rameswaram-Thoothukudi coast after the 2004 Tsunami. It might be the product of the waning current of high-velocity tsunami waves. These waves mobilized the materials at the shore and transported them inland. The mobilized material, composed of grain sizes that can vary from clay to

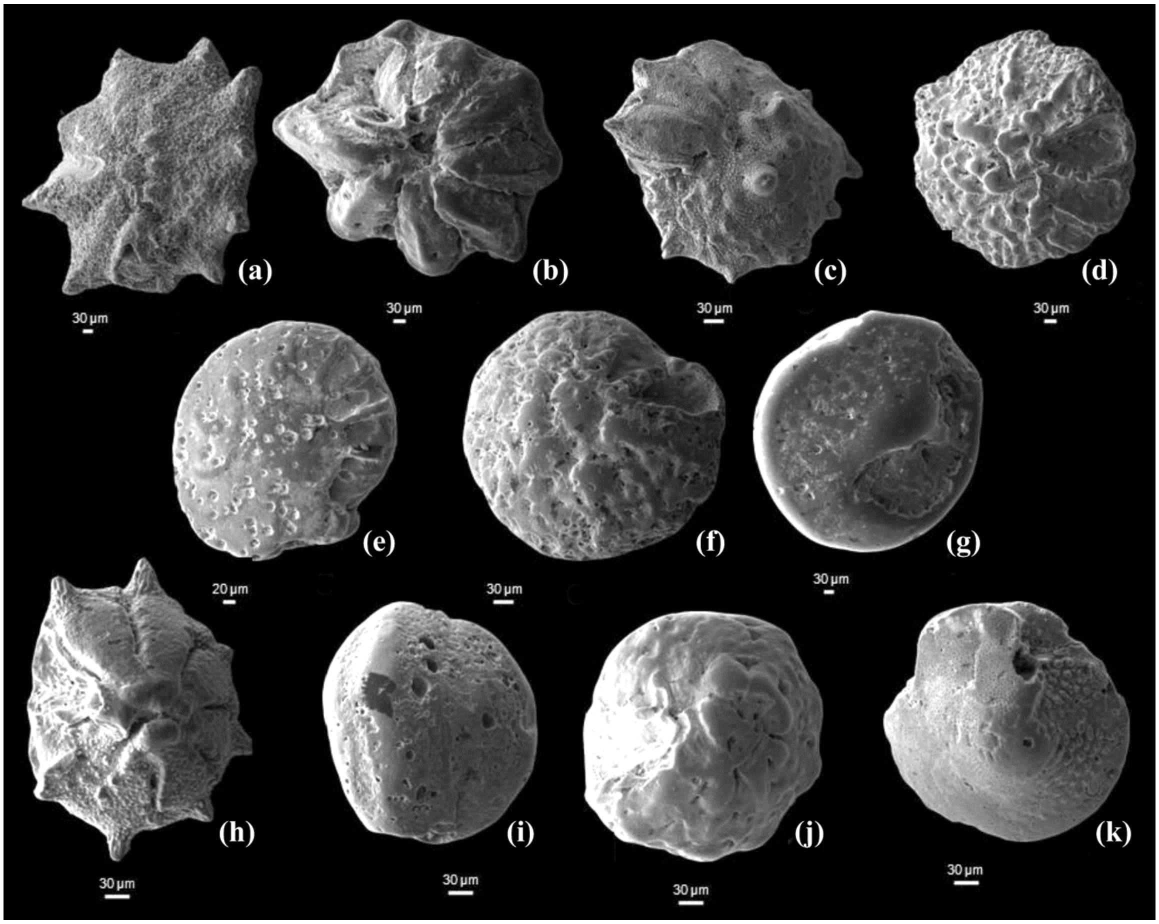

Fig. 9 — Some of the selected species of foraminifera in different types of sediment at Sitapur beach, Neil Island. Normal horizon (depth 0 – 18 cm, a – h): (a) *Calcarina calcar* – dorsal view, (b) *Calcarina calcar* – ventral view, (c) *Calcarina* sp. – ventral view, (d) *Calcarina* sp., (e) *Elphidium* sp., (f) *Elphidium excavatum*, (g) *Rosalina globularis*, (h) *Calcarina calcar*; 2004 Tsunami deposit (depth 18 – 30 cm, i – k), (i) *Quinqueloculina* sp., (j) *Calcarina* sp., and (k) *Amphistegina papillosa*

boulders, is deposited in terrestrial lowlands as inflow deposits, general thinning and fining inland. In some cases, the deposits consist of normally graded units, with coarse sand near the base and fine sand at the top and contain multiple 'fining' upward sequences[55].

Occasionally, these units are bounded by erosional surfaces indicating the changes in wave energy. The coral boulders were derived from adjacent areas of reef and they had been transported by the tsunami and deposited farther inland, in the low-lying areas. The black humic anoxic mud represented a shelf edge environment with sand containing abraded and reworked benthic foraminifera and shell fragments[5,27]. The shell fragments within the deposits are considered one of the possible indicators for finding tsunamigenic sediment due to high energy condition[56].

Based on sedimentological characteristics, micropalaeontological study and organic carbon content, the tsunami deposit was inferred at Bharatpur (20 to 39 cm), Lakshmanpur (12 m), Sitapur beach (20 cm, 18 to 30 cm) and Ramnagar beach (9.4 to 29.8 cm depth). The tsunami deposit mainly consists of moderately well to very poorly sorted, leptokurtic, coarse skewed sand with black mud. Similar characteristics of deposit were found at Sitapur beach (below 60 cm) considered as the palaeo-tsunami horizon.

The foraminiferal in these tsunami deposits were mostly reworked, broken and abraded. These features were investigated at a deeper level in Neil Island to pick up the palaeo-tsunami deposits. Planktonic and benthic foraminifera were found to be associated with the tsunami and palaeo-tsunami deposits. In Bharatpur, *Pararotalia* sp., *Bolivina* sp., *Elphidium* sp., *Amphistegina* sp., *Parrellina* sp., *Globigerina* sp. and *Notoratalia* sp. were found in the tsunami mud. In Sitapur, *Amphistegina* sp., *Quinqueloculina* sp.,

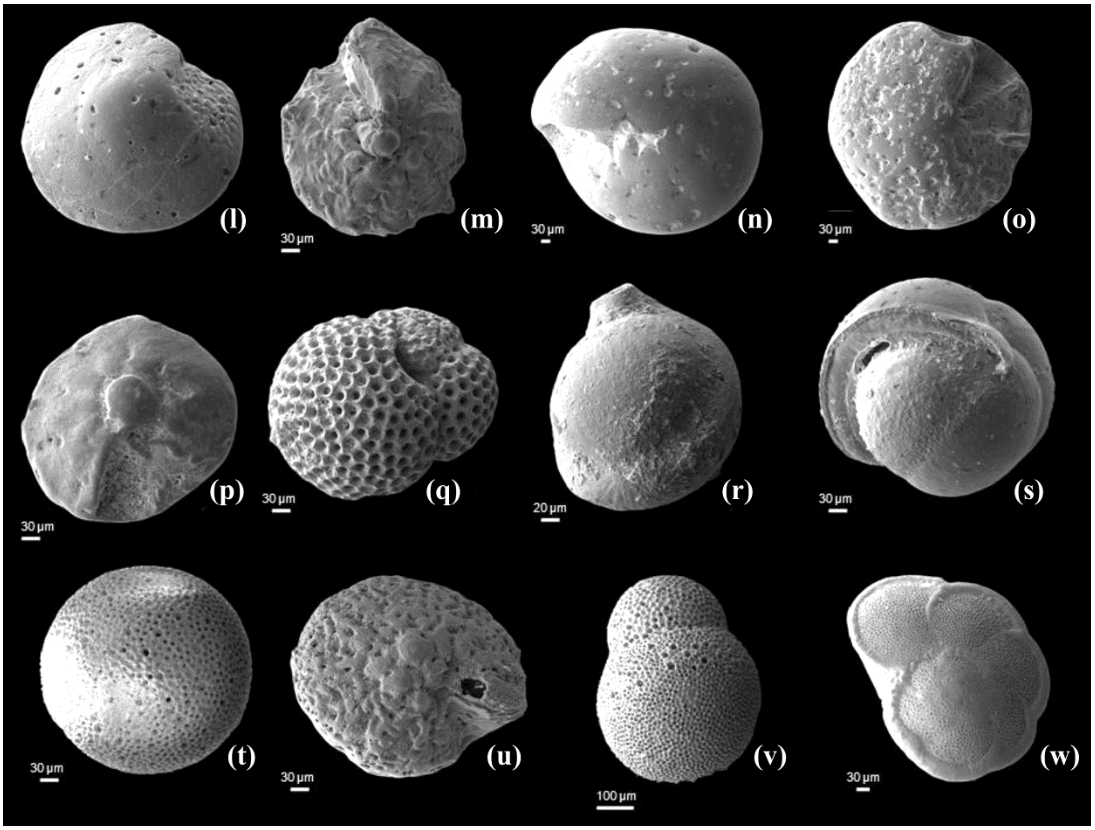

Fig. 10 — Some of the selected species of foraminifera in different types of sediment at Sitapur beach, Neil Island. 2004 Tsunami deposit (depth 18 – 30 cm, l – n): (l) *Amphistegina papillosa*, (m) *Calcarina* sp., (n) *Elphidium norvangi*; Normal sediment (depth 30 – 55 cm, o – p): (o) *Elphidium excavatum*, (p) *Amphistegina* sp.; Palaeo-Tsunami horizon (depth 55 – 60 cm, q – w): (q) *Trilobatus sacculifer*, (r) *Lagena* sp., (s) *Pullenia quadriloba*, (t) *Orbulina universa* - planktonic, (u) *Calcarina* sp., (v) *Orbulina* sp. - planktonic, and (w) *Globorotalia tumida* - Planktonic-Non-spinose

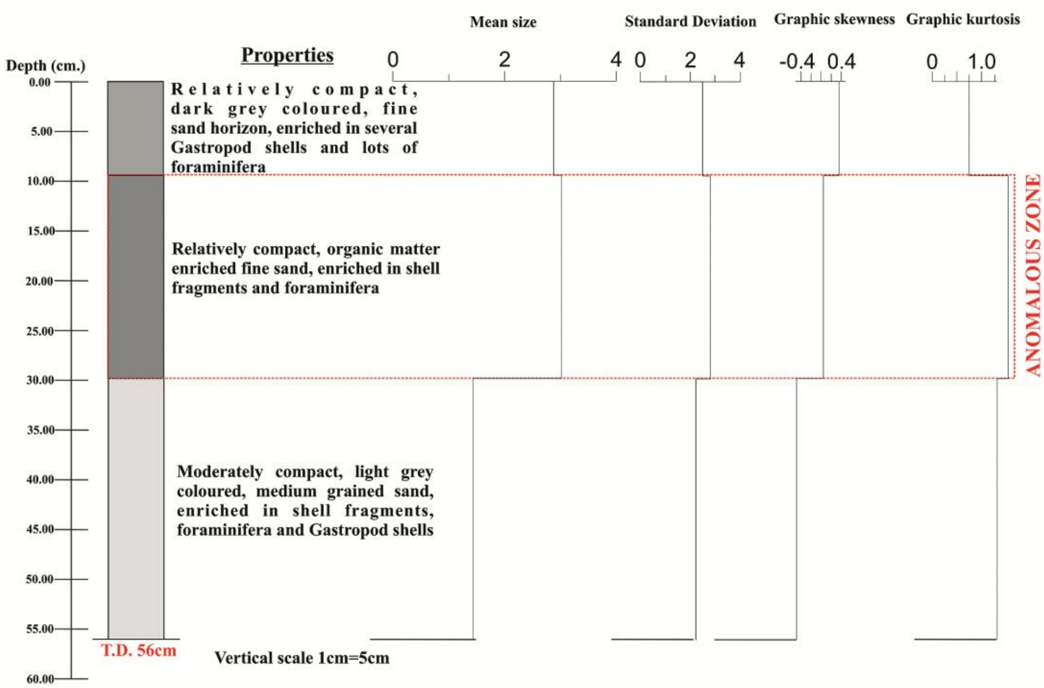

Fig. 11 — Statistical properties of grainsize at different depths of sediments at Ramnagar beach of Neil Island

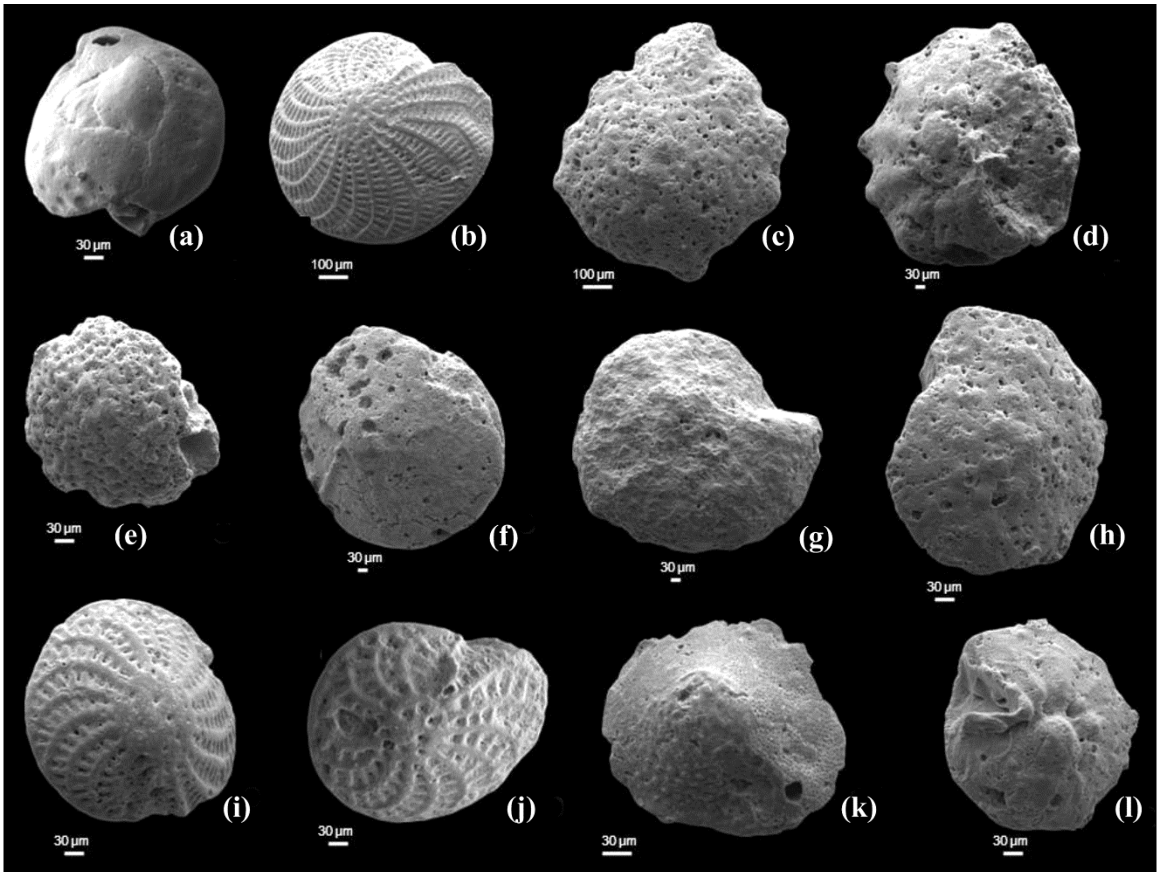

Fig. 12 — Some of the selected species of foraminifera in different types of sediment at Ramnagar beach, Neil Island. Normal horizon (depth 0 – 9.4 cm, a, b): (a) *Quinqueloculina* sp., (b) *Elphidium crispum*; 2004 Tsunami deposit (depth 9.4 – 29.8 cm, c – h): Reworked Foraminifera, (i) *Elphidium crispum*; Normal horizon (depth 29.8 – 56 cm, j – l): (j) *Elphidiumcrispum*, (k) *Amphistegina papillosa*, and (l) *Calcarina* sp.

Calcarina sp., *Trilobatus sacculifer*, *Lagena* sp., *Pullenia quadriloba*, *Orbulina universa*, *Orbulina* sp., *Globorotalia tumida* and *Elphidium* sp. were generally recorded, whereas in Ramnagar reworked foraminifera and *Elphidium* sp. were more predominant. Overall, the recorded foraminiferal assemblage shows that the *Rotaliana* occupies a dominant place followed by *Miliolina* and others. Among the generas, *Elphidium*, *Pararotalia* and *Amphistegina* are dominant followed by *Notorotallia* and *Gyroidina*, etc. These are typically near-shore dwellers hence, indicating that sediments were derived from near-shore regions. A similar assemblage comprised of 50 % of more reworked foraminiferal specimens reported from the tsunamigenic sediments of the east coast of Tamil Nadu indicating sediments source from a water depth of at least 55 m[57]. Highly to moderately abraded milky white coloured *Amphistegina* sp. and *Calcarina* sp. in tsunamigenic sediments of Andaman Islands are probably due to churning action and transportation[25,27]. Few uncommon taxa of near-shore environment *viz*. *B. spathulata* and *P. quadriloba* indicate mixing of foraminifera assemblage due to the tsunami wave actions. *B. spathulata* is characterized by the presence of pores at the initial sutures that are sharp and straight. However, in the present reworked specimens from the Bharatpur beach, these morphological features are not discernible. This taxon is known to prefer a high nutrient environment and shows enormous tolerance to variation in hydrographic conditions[20,58]. The dissolved oxygen and organic carbon control benthic foraminiferal distribution[21]. Waller[59] recorded *B. spathulata* from the upper slope – outer shelf depths (135 – 220 m) in the South China Sea. *Pullenia quadriloba* is distinguished by its slightly compressed test, acute periphery and four chambers in the last whorl gradually increasing in size. It has been reported from the lower bathyal to abyssal depths in the Indian Ocean[60,61]. On the other hand, the planktic foraminifera thrive in the relatively deeper open ocean environment. The combined physicochemical factors of a particular depth also play a major role in the distribution of benthic foraminifera.

This horizon was considered palaeo-tsunami I. This horizon contained mainly planktonic and benthic foraminifera. The black Tsunami deposit preserved at Ramnagar beach at a depth of 9.4 to 29.8 cm, consisted of mainly very leptokurtic, and very poorly sorted, very fine sand (3.017 Φ) with a lower amount of reworked foraminiferal species.

Conclusion

In Neil Island, the anomalous horizons of tsunami deposits were found at variable depths depending upon the magnitude of waves (tsunami wave at each observation site) with relative subsidence/ uplift and erosion/ deposition. In the Bharatpur area, the 39 cm thick tsunamigenic sediments were preserved in low-lying areas. In Sitapur, tsunamigenic black mud was observed upto 20 cm. Another anomalous deposit was found below 60 cm. In Lakshmanpur, 12 m thick tsunamigenic sediments were reported at the top horizon. On Ramnagar beach, the black tsunamigenic sediment was preserved between 9.4 and 29.8 cm. Most of the benthic species indicate that they are inhabitants of near-shore littoral. Albeit, the occurrence of deeper water benthic and planktic foraminifera in the Bharatpur and Sitapur beaches indicates the source of tsunamigenic sediments as deeper as from the upper part of the Continental Slope ~ 1000 m.

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Conflict of Interest

The authors declare no conflict of interest.

Ethical Statement

This is to certify that the reported work in the paper entitled "Characterization of Tsunami and Palaeo-Tsunami Deposits in the Neil Island, South Andaman, India" submitted for publication is an original one and has not been submitted for publication elsewhere. I/we further certify that proper citations to the previously reported work have been given and no data/table/figure has been quoted verbatim from other publications without giving due acknowledgement and without the permission of the author(s). The paper reflects the authors' own research and analysis in a truthful and complete manner. The paper properly credits the meaningful contributions of co-authors and co-researchers. The consent of all the authors of this paper has been obtained for submitting the paper to the 'Indian Journal of Geo-Marine Sciences.

Author Contributions

Conceptualization, validation and investigation: DS, SH; methodology and writing: DS, SKB; formal analysis and writing—review and editing: DS, SKB, SH; supervision and project administration: SH. All authors have read and agreed to the published version of the manuscript.

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