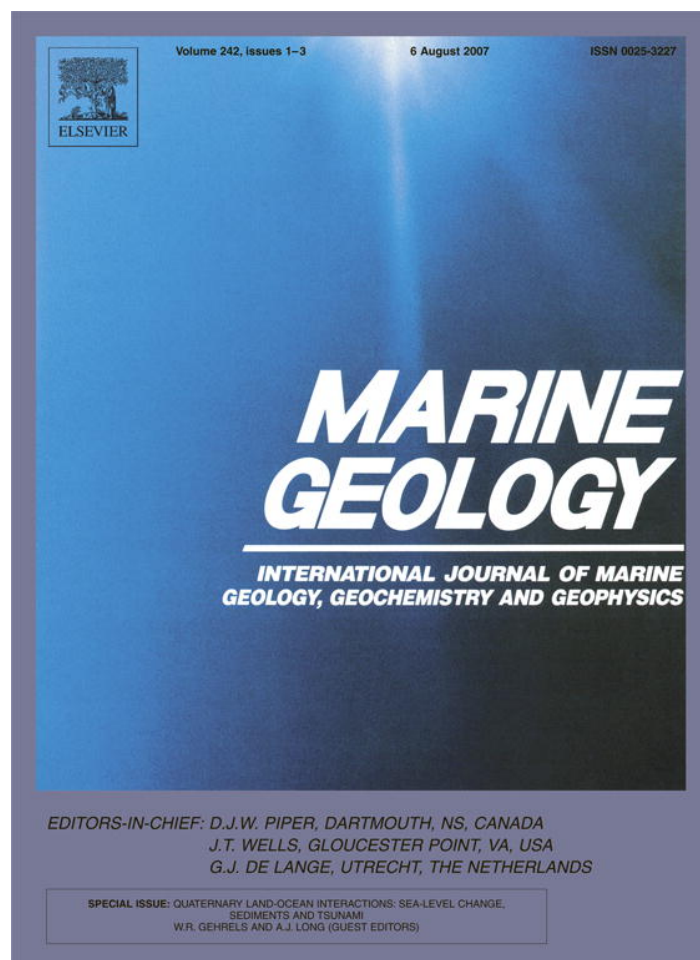




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Tsunami of December 26, 2004 on the southwest coast of India: Post-tsunami geomorphic and sediment characteristics

A.C. Narayana^{a,*}, R. Tatavarti^b, N. Shinu^a, A. Subeer^a

^a Department of Marine Geology and Geophysics, Cochin University of Science and Technology, Lakeside Campus, Cochin-682 016, India

^b Naval Physical and Oceanographic Laboratory, Defence Research and Development Organization, Cochin-682 021, India

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Abstract

This paper discusses the impact of the December 26, 2004 tsunami on the geomorphic features and sediment characteristics along the southwest coast of India. The data used include field observations made after the tsunami, and the inferences drawn from the satellite imagery taken before and after the tsunami. Sediment samples collected from the inner shelf, beach and estuarine environments were analyzed to understand post-tsunami changes in grain-size characteristics. The tsunami eroded and transported landwards significant volumes of distinct black sands, rich in heavy minerals, from the shelf onto the beaches of the Kerala region, and up to 500 m inland of the present coast.

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1. Introduction

Tsunamis and their dynamics have long attracted the interests of many researchers, although their potential for extensive sediment transport and their ability to reshape coastal geomorphology were generally ignored until Coleman (1968) highlighted their importance in shaping the continental shelf profile and the consequent sculpting of coastal geomorphic features. Evidence for these impacts are well preserved in the geomorphology and sedimentology of coastal environments (see for example, Smith et al., 2004; Shi and Smith, 2003; Bryant et al., 1991; Dawson et al., 1988, 1995).

The landward fining of grain-size is a characteristic signature of tsunamigenic flooding, especially in

intermediate and reflective coastal environments (Dawson, 1994; Dawson et al., 1988, 1995; Minoura and Nakaya, 1991; Moore et al., 1994; Andrade et al., 2001). However, there is little information on changes in the geomorphic and sediment characteristics on dissipative beaches, such as those present along the Kerala coast of southwest India, following a tsunamigenic event. High-magnitude tsunamigenic flooding can generate erosional and depositional signatures along a coastline, and the tremendous energy of the tsunami can transport sediments from deep offshore regions along its propagation path and deposit them far inland.

The sediment records of tsunami may help in inferring the time and magnitude of earthquakes, as the conspicuous contrasts in textural and lithological characteristics of sediment sequences may be used as proxies to identify and interpret such catastrophic disturbances (e.g. Nelson et al., 1996). Along coastal

* Corresponding author.

E-mail address: a_c_narayana@yahoo.com (A.C. Narayana).

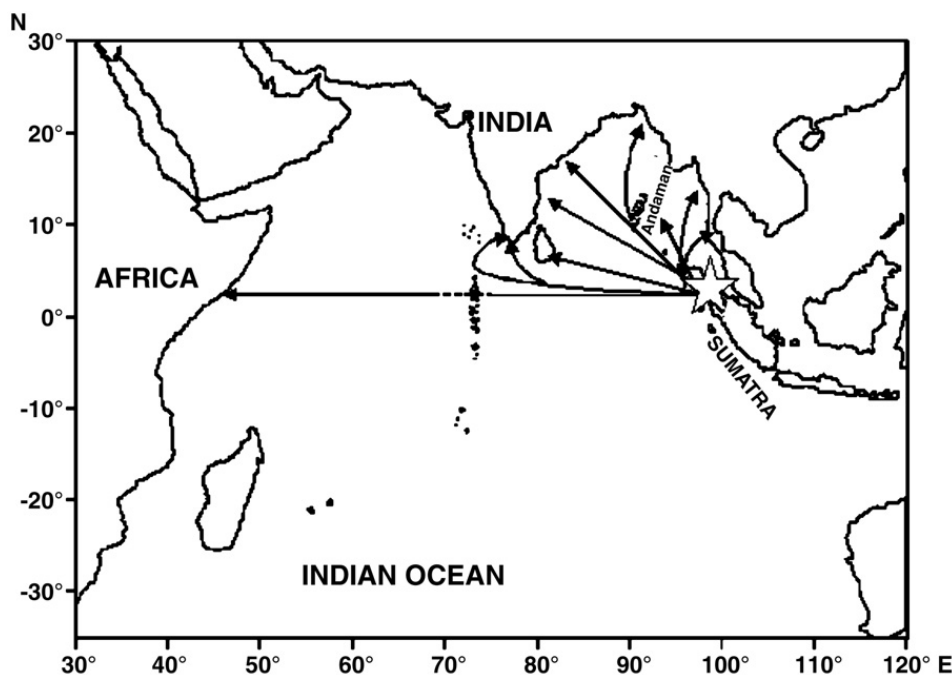


Fig. 1. Location of tsunami generation and travel direction in the India Ocean.

rivers, the normal trend is for downstream fining of sediment, whereas during strong wave activity associated with tsunami, the deposits become coarser towards the shore (Bryant et al., 1991; Smith et al., 2004).

2. The Great Sumatra–Andaman earthquake

The Great Sumatra–Andaman earthquake (Mw: 9.3) occurred off the west coast of northern Sumatra, Indonesia at 00:58:50 UTC on 26th December 2004 and triggered widespread tsunami (Fig. 1). The epicentre of the earthquake was 3.3°N–96.1°E with a focal depth of 16.6 km. The earthquake lasted 9 min, ruptured over more than 1500 km length and nearly 250,000 km² of oceanic rock, a large fraction of it slipping 10–15 m across the fault surface and released as much strain energy as all other earthquakes combined over the last 15 yrs (Lay et al., 2005). The total energy released by the December 26, 2004 earthquake has been estimated to be 2.0×10^{18} J, and was sufficiently large to result in a shift of the earth's mass. Some of the smaller islands, southwest of Sumatra, shifted southwest by 7–20 m (Bilham, 2005; Lay et al., 2005). Thousands of after shocks along the stretch running from Sumatra in the south to the Andaman Island in the north have occurred since, including 150 in January 2005 alone. Moreover, it is believed that the December 2004 earthquake triggered the 28 March 2005 earthquake (Mw: 8.7) off Sumatra – the second largest in 40 yrs. As a consequence of

the earthquake, the Nicobar and Andaman regions may have shifted horizontally by about 5 m in the SW to WSW direction, and by about 1 m in the west direction, respectively (Gupta, 2005).

3. Tsunami of December 26, 2004

The December 26, 2004 Great Sumatra–Andaman earthquake generated a tsunami of unprecedented proportions that devastated the shores of many continents (Narayana et al., 2005; Titov et al., 2005). The tsunami waves with their substantially long wavelengths and high speeds were influenced by bathymetry and were topographically steered to different locations in many countries of the Asian and African continents. Because of the characteristically long wave nature of tsunami, the earth's rotation and ensuing Coriolis force played a significant role in steering them towards the right side of the travel directions (Narayana et al., 2005) (Fig. 1). In the Indian region, the tsunami not only devastated the Andaman and Nicobar Islands, and the east coast of the mainland, but also affected the southwest coast (Kerala), which was located in the shadow zone with respect to the direction of tsunami propagation (Fig. 1).

Historical records of tsunami on the east coast of India triggered by earthquakes in the Sumatra–Andaman region date back to December 31, 1881 and June 26, 1941 (Oldham, 1884; Murty and Rafiq, 1991). On

the west coast of India (especially the Gujarat region), historic records indicate tsunamis on June 16, 1819 (MacMurdo, 1823) and November 28, 1945 (Berninghusen, 1966). However, there was no record of any tsunami affecting the Kerala coast (southwest coast of India) prior to December 26, 2004.

The present study focuses on the impact of the tsunami waves on geomorphic features and sediment characteristics of the Kerala coast; particularly the area adjoining the Kayamkulam estuary (Fig. 3) which was the worst hit region on the southwest coast of India. Along the Kerala coast, during November to January, the coastal currents generally have a counter-clockwise direction due to the orientation of the coast and the prevailing wind conditions. The significant wave heights are approximately 0.5 m, with periods ranging from 10 to 12 s. Two groynes were constructed recently on either side of the Kayamkulam estuary as part of an on-going development of a fishing harbor inside the estuary. As part of coastal erosion mitigation efforts, a seawall made of granite boulders was constructed. Fig. 2 shows the tidal elevation recorded by the coastal tide gauge off Kochi in Kerala from 25th to 29th December 2004. The time of occurrence of the tsunami on the southwest coast of India can be seen as an abrupt rise in sea level (from 85 cm to 155 cm i.e., a rise of 70 cm) in the tidal elevation plot.

It is now generally agreed that shallow focus seismic activity with significantly high magnitude can trigger tsunamis (Titov et al., 2005). As the tsunami approaches the shore, it slows down and grows in height. The tsunami, like other water waves, begins to lose energy as it moves onshore – part of the wave

energy is reflected offshore, while the shoreward-propagating wave energy is dissipated through bottom friction and turbulence. The December 26, 2004 tsunami amplitudes showed wide variations along the Kerala coast, up to 3.5 m in the north (Kurian et al., 2006) and up to 5 m in the south (Narayana et al., 2005) suggesting that the role of bottom topography and friction was significant in channelizing the tsunami to different locations. In spite of the energy losses encountered by waves propagating shoreward, when the tsunami reached the coast it had sufficient energy to cause extensive erosion, stripping sediments from the shelf and beaches and transporting them landwards. The run-up height reached maximum (5 m) at Kayamkulam inlet (Fig. 3) resulting in enormous damage and destruction to life and property.

On several occasions abnormally high, or ‘freak’, wave events were reported on the Kerala coast after the December 26, 2004 earthquake. These were not directly related to local meteorological disturbances like atmospheric low pressure, depression or high wind activities and had periodicities of the order of a few minutes. Narayana and Tatavarti (2005) speculate that the occurrence of these abnormally high waves were the result of the seismic activity due to the aftershocks of the Sumatra earthquake because: (i) during this time, no local meteorological disturbances were present and no strong wind activity was reported; (ii) the times of occurrence of high waves were consistent with the travel times of waves from the epicenter (a time lag of a few hours) to the Kerala coast; and (iii) the periodicity of high waves observed was of the order of 10 min, which is generally the case for tsunami waves and unlike the waves generated by

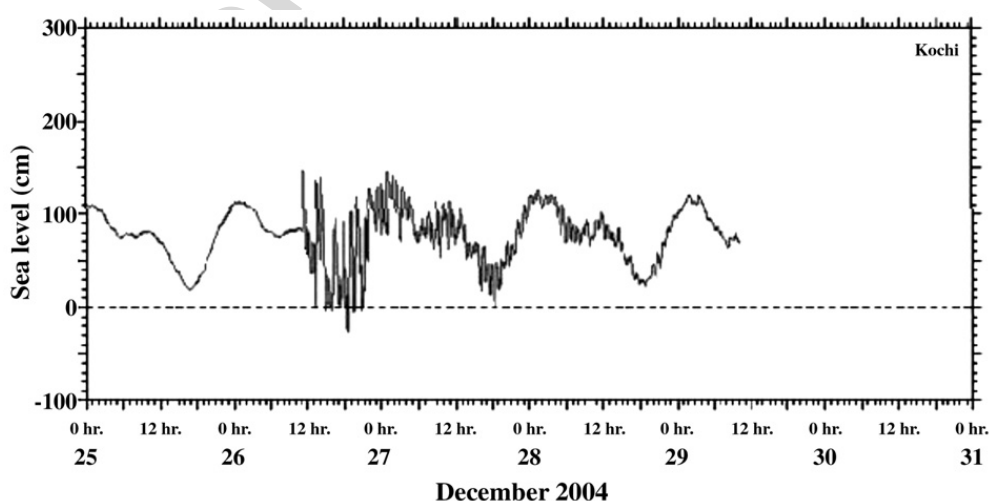


Fig. 2. Tide-gauge record showing sea level variations at Cochin during 25–30 December 2004 (source: NIO website).

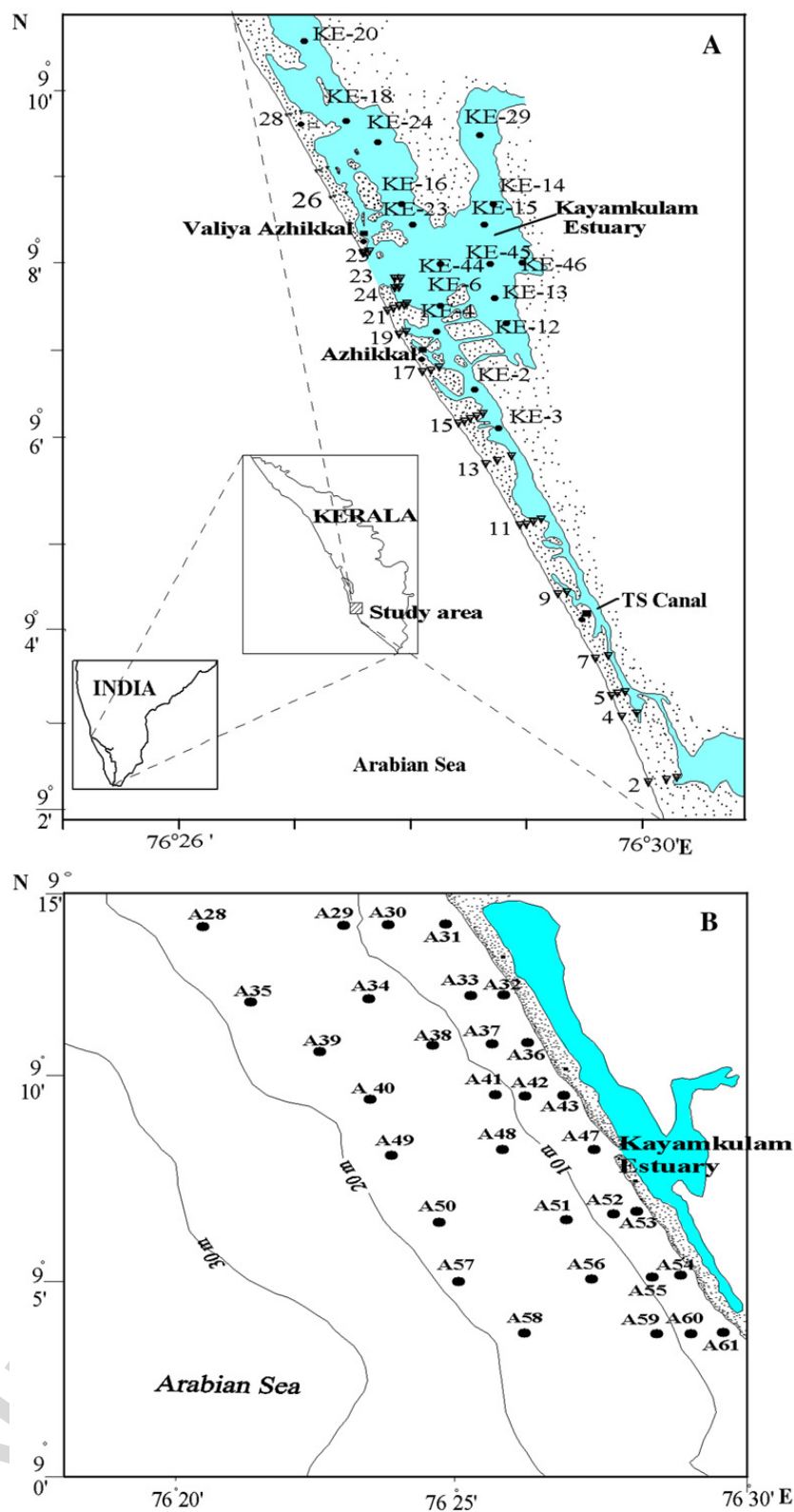


Fig. 3. Map showing the study area and sediment sample locations from different environments in the tsunami-hit Kayamkulam area of Kerala coast. (A) Sample locations from estuary and beach environments (Samples – KE series are from estuary. Sample station nos. 2–28 represent beach environment; at each station, 2–4 samples are collected across the beach). (B) Sample locations in the nearshore region.

meteorological disturbances that have a periodicity of the order of 10 s.

4. Methods and techniques

The present study uses satellite images from the Indian Remote Sensing (IRS) LISS III sensors covering the coastal regions of Kerala during the pre- and post-tsunami events. IRS LISS III is a multi-spectral camera operating in four bands, three in visible and near infrared, and one in the short-wave infrared (SWIR) region. The swath of LISS III sensor has coverage of ~141 km with a spatial resolution of 23.5 m. Radiometric and geometric corrections were applied to the raw digital data. The false colour-coded final product has 7-bit quantization resolution which creates different colours for different reflectance characteristics of the scatterers in the image. A comparison of the satellite imagery from before the tsunami from the LISS III sensor of the IRS 1D satellite uses data acquired on

January 24, 2004. The post-tsunami image data was acquired from the LISS III sensor of the IRS P6 satellite on December 27, 2004 (Fig. 4).

The geomorphological and sedimentological effects observed associated with the December 26, 2004 tsunami include dislodgment/erosion, transport and deposition of boulders, destruction of beach berms, change in shore face elevation and steepness, uprooted trees and thick piles of sediments. Field surveys were conducted in the tsunami-affected area soon after the catastrophic event. Sediment samples using van-veen grab were collected in the inner shelf (30 samples), the estuary (22 samples), and on the beach (40 samples) as depicted in Fig. 3. On the beach, samples were acquired from the top layer only (using a poly vinyl chloride tube of 9 cm diameter, penetrated to a depth of 12 cm from the surface) to study the textural characteristics and the influence of tsunami in modifying the sediment properties. To determine the grain-size distribution, the sediment samples were dried and sieved into 0.5φ

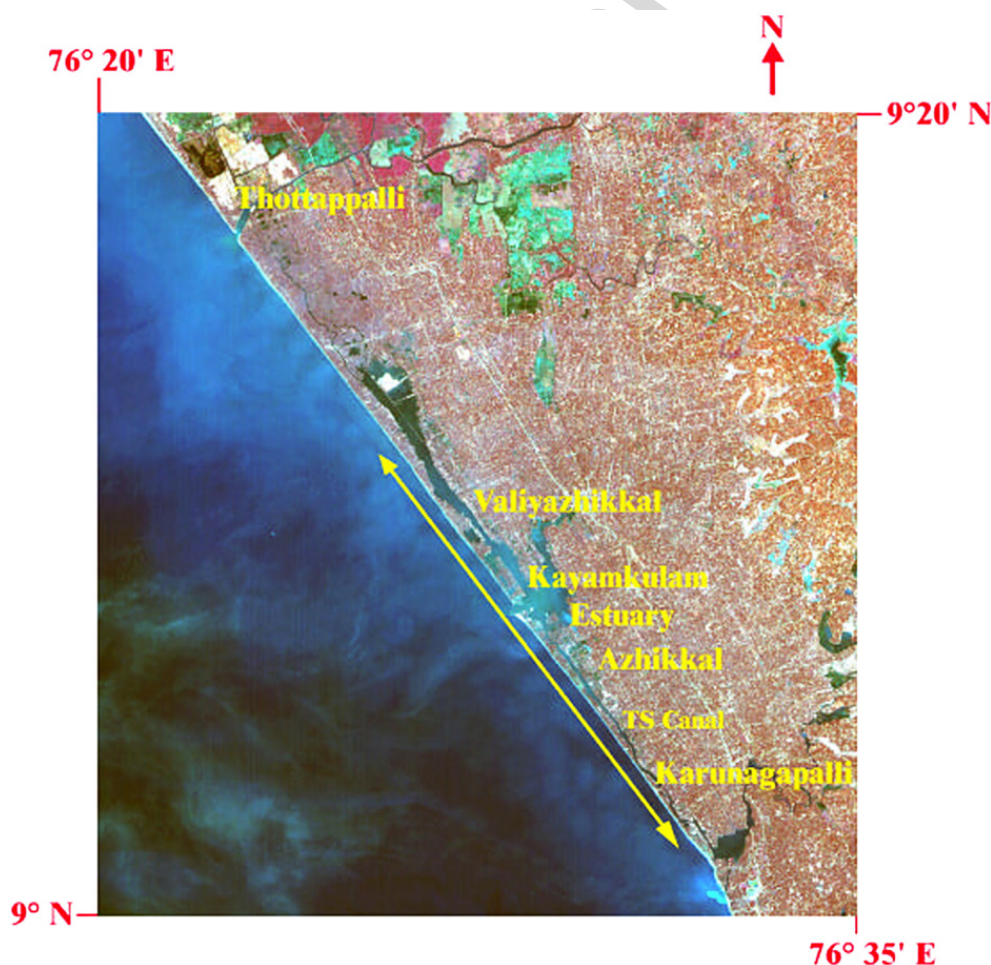


Fig. 4. Satellite imagery showing the tsunami affected coastal Kerala. The image is obtained from LISS III sensor of the IRS P6 satellite on December 27, 2004. The maximum affected area is marked along the coast with arrows. Note the light green colour of waters in the Kayamkulam estuary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intervals. The grain-size statistics (mean, sorting, skewness and kurtosis) were calculated using the inclusive graphic method and the division into different sediment types follows Folk's (1980) classification.

5. Impact of the tsunami on geomorphic features

The geomorphic features (beach dunes, shore-face, berm and the barrier island build up over long years) of



Fig. 5. Post-tsunami geomorphic features along the southwest coast of India. (A) Deep trench cut by the tsunami. Partially filled portion with coir and lateritic soil is seen. (B) Shore face altered by the tsunami and huge dump of black sands on the coastal road. (C) Inundation pathway of tsunami, transported seawall boulders obstructed by the coconut grove and thick black sand concentrates are seen. (D) Dump of black sands in the porticos of coastal homes. (E) Picture shows shore erosion on the northern side of Kayamkulam estuary, disfigured back-berm after the tsunami hit the coast. The displaced boulders from the sea wall are visible in the foreground.



Fig. 5 (continued).

the coastal area adjoining the Kayamkulam estuary on the southwest coast of India were significantly altered by the tsunami of December 26, 2004.

Although the entire Kerala coast experienced the effects of tsunami waves, a stretch of 10 km along the coast, off Azhikkal (from 9°2'N to 9°9.5'N; as in Fig. 4), was the most affected in terms of inundation, run up, and erosion. On this coastal stretch, the

maximum devastation occurred along the Kayamkulam estuary (i.e., 4 km south and 2 km north of Kayamkulam estuary, where a fishing harbor is under construction). Coastal inundation was prevalent along this stretch with run-up extending up to 1.5 km eastward from the shoreline. The main route for inundation was through the estuary into the Travancore State (TS) Canal.



Fig. 5 (continued).

At Azhikkal, the first tsunami wave hit the coast at around 12:30 h, followed by a series of waves with 10- to 15-min intervals. After hitting the coast, the sea receded progressively revealing the seabed up to 1 km from the shore at around 13:00 h. The largest wave then followed immediately and hit the coast at 13:10 h with an approximate height of 5 m, causing inundation along the coast. The run up of largest wave reached a distance of 1.5 km from the shoreline along the 10-km stretch. The predominant run up occurred along both enclosed and open inlets, which acted as natural inundation pathways. Many of the closed inlets were re-opened. The maximum damage occurred across the shore, between beach and TS canal.

Shi and Smith (2003) demonstrated that turbulent flood currents rather than waves characterize the hydrodynamics of run up and backwash resulting from tsunami. Our investigations also revealed that during the run up phase of one episode of inundation, a large amount of energy transferred from the incident offshore wave would dissipate over the coastal topography – destroying, eroding and transporting solid materials. Examining the hydrodynamics of run up processes during the December 2004 tsunami on the southwest coast of India and the accounts of eye witnesses that the tsunami waves broke far away from the coast and turned into horizontal movements of turbulent water running across the near shore zone to strike upon the coastal low lands, we therefore infer that the tsunami inundation was

an ephemeral process and consisted of several episodes of run up and backwash.

The color of the sea as detected from a remote sensing satellite sensor like LISS III on board the IRS P6 provides a good indication of the turbidity of the coastal waters, the intensity of turbulent mixing, and the suspended sediment concentration of the water column brought about by the tsunami. Based on a comparison of satellite images obtained before (January 2004), and after (December 27, 2004) the tsunami, we infer that the entire water body was turbulently churned up. This is manifest as light blue to light green color of the sea in the post-tsunami satellite image, suggesting turbid sediment-laden water (Fig. 4). The tsunami widened the estuarine mouth considerably and brought in sediment-laden water into the estuarine and canal system. It was also observed from the satellite imagery that at many places along the coast, the shore was breached resulting in extensive inundation of the coastal areas and the subsequent run up of sediment-laden water from the continental shelf region.

6. Impact of tsunami on sedimentary processes

During periods of lower than present Pleistocene sea-level, shallow tracts of the modern shelf were exposed to subaerial conditions. The early Holocene transgression and subsequent fluctuations in relative sea level caused the formation and subsequent drowning of sand ridges

and heavy mineral concentrations. Today, black sand placer deposits occur in the inner and mid-shelf region, and along the present beaches such black sands are intercalated with white silica sands (Nambiar and Unnikrishnan, 1987; Suresh Babu and Thirvikramaji, 1993).

The black sand deposits are concentrated in the inner shelf region of Kayamkulam, southwest coast of India. These deposits are characterized by a high concentration of heavy minerals, varying between 65% and 85% (for example, see Rajamanickam, 2000). The placer minerals of these deposits constitute ilmenite, garnet, zircon, rutile, monazite and sillimanite. The reserves of ilmenite and rutile are estimated to be 17 and 1.25 million tonnes, respectively. The thickness of placer bearing black sands ranges from 2 to 10 m, and extend to water depths of 30 m, i.e., up to 15 km offshore.

The run-up caused by the tsunami not only resulted in transport and deposition of sediments from the inner shelf onto the beach and estuary, and also generated erosion pits and trenches along the coast (Fig. 5A). Extensive black sands from the inner shelf were transported and deposited (>1-m-thick layer) across the beach and in the inland area (Fig. 5B and C). The deposits of black sands led to significant changes in the beach morphology, blanketing the entire coastal region between the existing sea wall and the TS canal running along the coast. In some instances, the black sand deposits even blanketed the corridors of coastal homes (Fig. 5D).

Most of the concrete houses were damaged, coastal fishing vessels, and some of the automobiles along the coastal road in this area were uprooted and thrown to distances of 100 to 200 m. Most of the boulders (having an average size of 1 m) of the sea wall, which was constructed to protect the coast from erosion, were thrown ashore to a distance of about 150 m by the tsunami. The inundation and the run-up resulted in some of these boulders and fishing vessels being washed into the neighbouring TS canal, breaching of the seawalls and transport of flotsam and debris from the sea approximately 500 m inland (Fig. 5E).

At some places, the uprooted boulders, fishing vessels and trucks got struck in the coconut groves parallel to the coast, while some were washed into the neighboring flooded TS canal. The floodwaters created large erosion pits along the roadside and also at the basement of the houses. Extensive quantities of black sands also were transported by tsunami blanketing the area between sea wall and TS canal. In the Azhikkal area, the black sand was ~0.6 m thick for a stretch of 2 km of the road. The black sand deposit was more

extensive in Valiya Azhikkal area (i.e., on the northern side of the estuary), where the coastal road was buried by a blanket of 1.2 m thick black sands (Fig. 5B), suggesting that the tsunami hit the coast from a southwest direction. We suspect that this may be the artifact of the alignment of the coast, the predominant tsunami wave direction and the fact that more erosion results on the leeside of an inlet due to waves and associated currents transporting the middle ground shoals located at the entrance of the estuary along with the churned up sediments from the sea bed onto the northern side of the estuary (see Figs. 4 and 5B, C).

7. Sediment texture

7.1. Pre-tsunami

There are few previous sediment textural studies of the Kayamkulam region pertaining to the inner shelf, beach and estuary. In the Kayamkulam region, sands and silty clays, with sand percentages varying from 5% to 75% reportedly cover the inner shelf region, of which the sand fraction, particularly fine (2–3 ϕ) to medium sand (1–2 ϕ) category being predominant (Prakash, 2000). Kolla et al. (1981) studied the sediment distribution pattern in the larger area of the southwest coast of India and reported that beyond the inner shelf region (>50 m water depth) the sediments are predominantly silty clays or clayey silts.

Medium sand is predominant along the present beaches, with coarse sand varying from 2% to 25%, medium sand varying from 70% to 90% and fine sand varying from 1% to 9% (Santosh, 2000). Mean size ranges from 1.2 to 2.25 ϕ , with an average of 1.7 ϕ and the standard deviations range from 0.55 to 0.95 ϕ .

Muddy sands are predominant in the Kayamkulam estuary (Srinivas, 2000). Sand content increases towards the central region, but decreases towards the southern region of the estuary. Silt also increases, where as clay content decreases towards the central region of the estuary. The sediments from the southern region of the estuary is marked by a higher silt and clay content. The mean size of sediments ranges from 2.25 to 3.4 ϕ (standard deviation ranges from 0.47 to 1.55 ϕ).

7.2. Post-tsunami

The post-tsunami sediments were examined using samples collected at different water depths in the inner shelf region, at closely spaced locations across the beach, and in the estuary (Fig. 3).

7.2.1. Near shore environment

Fig. 6 shows the relative proportions of sand–silt–clay at different water depths (0–5 m, 5–10 m, 10–15 m and 15–20 m) in the inner shelf region of the tsunami-hit area. These sediments are predominantly sandy mud, followed by muddy sand. Most of the samples exhibit

bimodal distribution with modal classes in medium-to-fine sand and in silt–clay sizes.

In 15–20 m water depths, silt and clay contents vary from 20% to 50% and 10% to 30% respectively, with the sand content ranging from 20% to 50%. In the 10- to 15-m water depths, silt is dominant closely

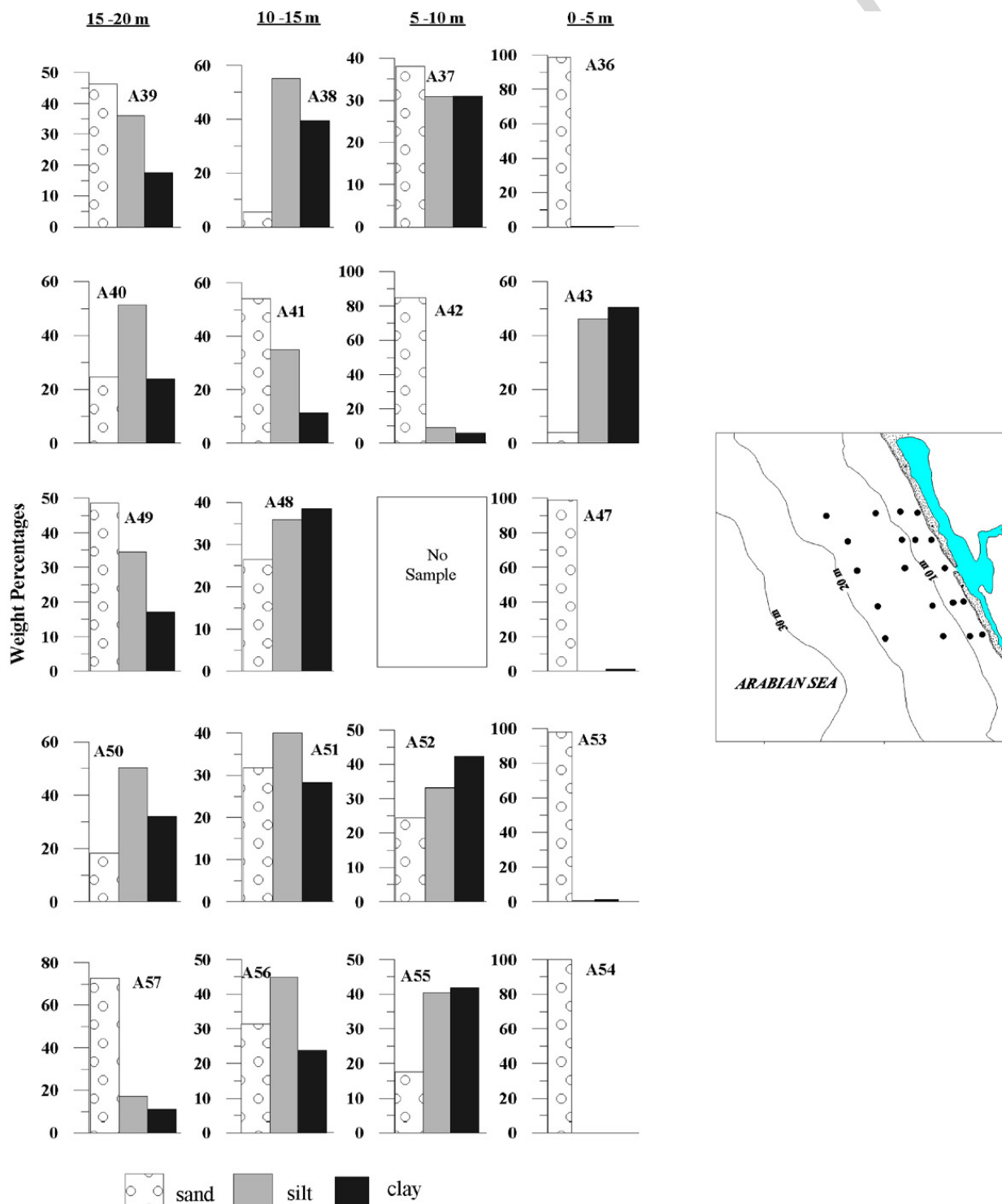


Fig. 6. Sand–silt–clay weight percentages in near-shore sediments at different water depths. Plots pertaining to different locations of the near-shore surface samples are organized left to right in offshore–onshore direction and top to bottom in the north–south direction.

followed by clay content, except in two samples where sand is about 45%. Silt content varies from 30% to 50% and clay ranges from 20% to 40%. In a majority of samples, sand content also ranges from 20% to 45%. The textural data reveal that sand, silt, and clay contents, in general, are almost uniform,

although the silt content is slightly higher in some of the samples. In 5–10 m water depths, the sand content is dominant with low silt and clay contents in half of the samples. The remaining 50% of samples dominantly constitute 40% each of silt and clay fractions. Sand content is dominant from the shore up

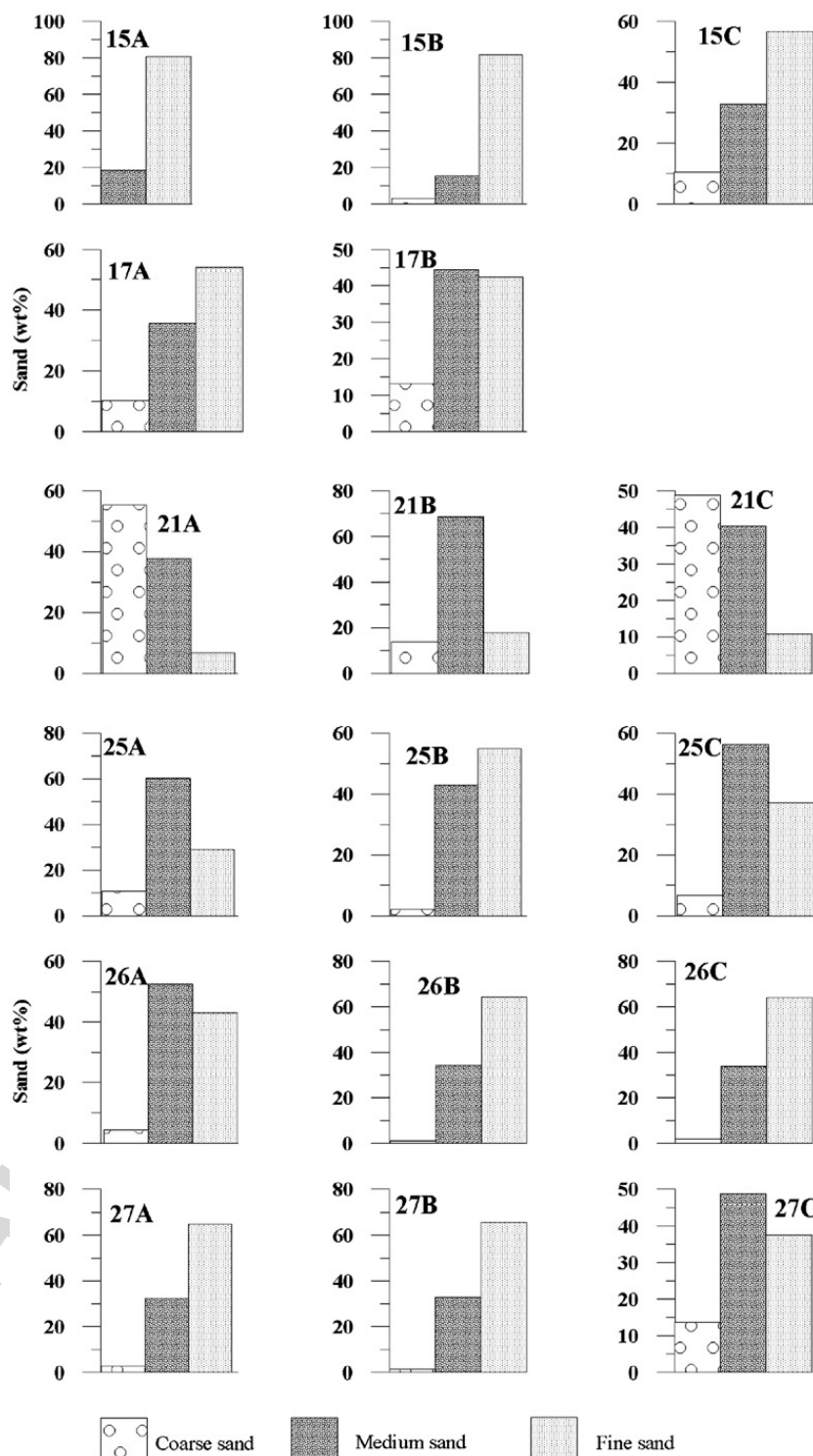


Fig. 7. Distribution of coarse (CS), medium (MS) and fine sand (FS) weight percentages in beach sediments from different locations as shown in Fig. 3.

to 5-m water depths ranging from 50% to 100%, except in one sample. Silt and clay contents are almost uniform and range from 10% to 50%. Mean size of sediments varies from 2.6 to 6.3 ϕ . Most of the samples are poorly-to-very poorly sorted in nature, with standard deviation varying from 1.3 to 2.7 ϕ . Sand-size grade sediments are moderately-to-well sorted, exhibiting the modal class either in 3–3.5 or 3.5–4 ϕ size range, and are skewed towards fine sand. Coarse sand is totally absent in most of the samples.

In summary, the pre-tsunami scenario, the silty clays/clayey silts and sand constituted the predominant percentage of sediment distribution in the outer shelf and the inner shelf regions of the study area, respectively (Kolla et al., 1981; Prakash, 2000). However, the sediment characteristics of the post-tsunami scenario (Fig. 6) clearly show that sandy mud and muddy sands now blanket the inner shelf region. This suggests that

the sediments in the shelf region of the tsunami-hit Kayamkulam coast were significantly reworked, resulting in mixed-size grades of sediments blanketing the near shore area.

7.2.2. Beach

The beach in Kayamkulam region was predominantly covered with black sands. We hypothesise that the tsunami waves eroded the near-shore seabed and transported the black sands onto the beach. Beach sediments predominantly constituted medium- and fine-size sands (Fig. 7). Coarse sand fraction weight percentages range from 4 to 50, medium-size sand from 15 to 60 and fine sand fraction from 10 to 80 (but the majority of samples constitute 40–60% of fine sand). Mean size of beach sands range from 0.9 to 2.9 ϕ . The beach sands are moderately sorted, with modal class varying between 1.5 and 3 ϕ .

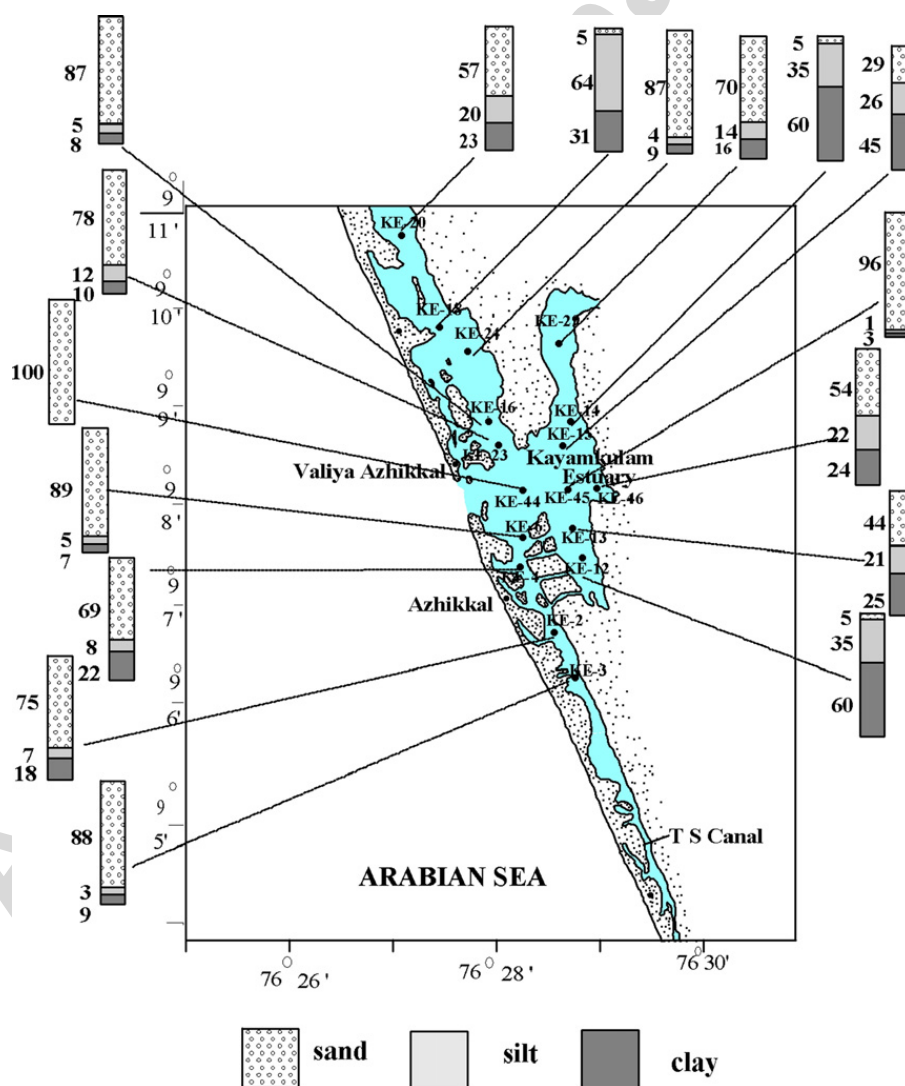


Fig. 8. Sand–silt–clay weight percentages in surface sediments at different locations the Kayamkulam estuary of the tsunami-hit area.

As noted above, prior to the tsunami, medium sand was predominant along the beach. We infer therefore that the black sands, with their higher density (although finer in size) were brought from the inner shelf by the tsunami.

7.2.3. Estuary

It is generally observed that in estuaries, mud dominates in the subtidal regions and low energy areas, whereas sand content is restricted to high-energy environments such as tidal channels and inlets. Typically, the coarse sediments are deposited at the mouth, and finer sediments in the upper part of the estuary because of prevailing low-energy conditions in that region (reference). A tsunami striking an estuary will often deposit a landward-tapering wedge of sand which grades inland into a texturally homogenous single sand layer of decreasing thickness. Andrade et al. (2001) have observed such sediment developed due to 1755 Lisbon tsunami in some of the estuaries in Portugal. The horizontal grading suggests that the tsunami rapidly lost energy as it moved upward the valley and eventually lost the ability to accrete significant amount of sediment brought from inner shelf.

The samples of the Kayamkulam estuary are predominantly sand, followed by silt and clay, except for three samples – two located landward, and the other in the northern part of the estuary (Fig. 8). In general, the sand content comprises 60–90%. Sand-size fractions of samples are dominantly of medium and fine sands. The sediments are muddy sands, followed by sandy mud in texture. Most of the samples exhibit a bimodal grain-size distribution. Mean size varies from 4.6 to 6.2ϕ . Sediments of estuarine environment exhibit moderately-to-well-sorted characteristics, with standard deviation ranging from 0.34 to 0.96ϕ . The sediments are mostly skewed towards medium- to fine-size sand, except a few samples that are skewed towards very fine sizes. We therefore infer that the tsunami was responsible for the landward fining of sediment distribution in the estuary.

8. Impact of tsunami on sediment texture

Tsunami can leave a depositional imprint of their passage that is characterized by varied sorting and mixing of sediments either from different coastal environments or of different grain-sizes (Bryant et al., 1991). Similar depositional characteristics and grain-size variations are observed in the tsunami-hit coastal environments of southwest coast of India. For example, in their analysis of the sediments deposited by the mid Holocene Storegga Slide, Smith et al. (2004) demon-

strated that the deposits of the tsunami are generally consistent; comprising of a sheet of fine or fine-medium sand that overlies a lower coarse deposit at the base of the tsunami sediment sequence.

Our analyses demonstrate that the December 26, 2004 tsunami transported landwards significant volumes of sediment from the mid- and inner-shelf regions of the southwest coast of India. The particle size and distribution patterns of the tsunami sediments reflect the characteristics of the original source material, as well as the processes of transport and deposition. We also observe that the sediments cluster into several size ranges forming subpopulations. The subpopulations in the sand range are readily identifiable in the tsunami sediment deposited on the beach and in estuary. The bimodal characteristics of the tsunami deposit suggest that sedimentation took place rapidly and that particles of different sizes settled out together but at different rates.

9. Conclusions

The tsunami of December 26, 2004 was topographically steered onto the Kerala coast. This resulted in intense turbulent mixing of the entire water column, entraining sediment into suspension that was then transported from the continental shelf onto the beach and estuary. Significant changes in the geomorphic features and sediment characteristics of the nearshore and beach resulted. These included the erosion of pits and trenches on the backshore area and the deposition of black sand deposits across the coastal zone. Nearshore sediments are typically poorly sorted and estuarine sediments became moderately sorted upstream. The sediment characteristics demonstrate that tsunami creates a significant exchange of materials from the shelf and nearshore zones to beach and estuarine environments.

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