

Erosion and sedimentation in Kalpakkam (N Tamil Nadu, India) from the 26th December 2004 tsunami

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Received 26 August 2006; received in revised form 18 January 2007; accepted 1 February 2007

Abstract

Laterally extensive sand sheets deposited by the 26th December 2004 Asian tsunami provide a valuable modern analogue for comparison with wash over deposits of unknown origin. In many places on the east coast of India, distinct deposits of marine sand drape the landscape and overlie the muddy soils of the coastal plain. This paper discusses detailed measurements of coastal topography, tsunami flow height, and deposit thickness made at Kalpakkam, India. Five transects were examined in detail to assess the sedimentology and spatial distribution of the tsunami deposit. Near the mean water line, the tsunami eroded approximately 10–25 cm of sand from the beach and berm. At Kalpakkam the sand sheet deposited by the tsunami begins 25 m from the shore extending 420 m inland where it becomes thin and patchy approximately 30 m from the limit of inundation. In some cases, the deposit consists of 2 to 4 normally graded units, with coarse sand near the base and fine sand at the top, a characteristic observed in many tsunami deposits worldwide. In many places, the deposits also contain numerous thin laminated units, a characteristic usually associated with storm over wash. The presence of the laminated beds is indicative of the complexity of tsunami sedimentation on the coast. Such observations are essential to the formation of definitive facies models for palaeo-overwash studies that are capable of distinguishing between sediments deposited by storms or tsunami.

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Keywords: Tsunami deposit; Kalpakkam; coastal sedimentation; erosion; sedimentology

1. Introduction

The term tsunami is a collective noun, meaning that it may be used as singular or plural, that is derived from the Japanese word meaning harbour wave (Dawson,

1994; Bryant, 2001). Often originally called tidal waves, the phenomenon has little to do with tides and the term refers to waves which have a characteristically long wavelength. They can now be generally defined for the scientific literature as long period waves generated by a sudden displacement of the water surface (De Lange and Fraser, 1999). Such waves have sufficiently high velocities and bed shear stresses to suspend and transport large quantities of sediment (Gelfenbaum and Jaffe, 2003). Within the geological timescale, tsunami can be

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considered low-frequency, high-magnitude events. Several studies of sedimentation associated with contemporary tsunami inundation have been undertaken, for example by Dawson (1994), Nishimura and Miyaji (1995), Sato et al. (1995), Shi et al. (1995), Yeh et al. (1993). These studies reveal the complex patterns of erosion and sedimentation associated with large-scale movement of sediment both in onshore and seaward direction.

Since 1992 there have been 10 major tsunami worldwide, including Nicaragua (1992), Flores (1992), Okushiri (1993), East Java (1994), Shikotan (1994), Mindoro (1994), Irian Jaya (1996), Peru (1996), Papua New Guinea (1998), Peru (2001) and most recently South Asia in 2004. Studies of these events have led to an improved understanding of tsunami generation, propagation, and inundation. In particular, studies of the sedimentary deposits from the Okushiri, Japan tsunami (Nishimura and Miyaji, 1995; Sato et al., 1995), the Flores Island, Indonesia tsunami (Dawson, 1994; Shi et al., 1995), and the Papua New Guinea (Gelfenbaum and Jaffe, 2003) describe the pattern of sedimentation associated with a tsunami. For example, both Shi et al. (1995) and Gelfenbaum and Jaffe (2003) find that the grain-size fines landward in the deposit on Flores Island. The purpose of this manuscript is to describe the erosion and sedimentation associated with the 26th December 2004 south Asian tsunami. Sedimentation on this siliclastic coast yields some interesting contrasts with other tsunami deposits such as those found in Papua New Guinea and Japan thus adding to the observations of modern tsunami sedimentation that will ultimately improve the identification and interpretation of palaeotsunami in the geologic record.

1.1. The description of 2004 Asian tsunami

On Sunday 26 December 2004, a large earthquake occurred off the west coast of the Indonesian island of Sumatra (Fig. 1A) generating a tsunami that caused over 200,000 fatalities in 12 countries across the Indian Ocean basin (Ghobaraha et al., 2006). Tens of thousands were also reported missing and over a million left homeless (Kawata et al., 2005; Yalciner et al., 2005). The tsunami was a truly global event, with significant wave activity recorded around the world (Titov et al., 2005).

The tsunami was generated by the third largest earthquake ever recorded, with a moment magnitude of approximately 9.0 (Ammon et al., 2005; Lay et al., 2005; Park et al., 2005; Stein and Okal, 2005). The main shock occurred at 0 h 58'53" GMT, with hypocenter,

located, i.e., 160 km west of Sumatra (3.32N and 95.85E), at a depth of approximately 25–30 km (Grilli et al., in press). The main shock epicenter is marked on Fig. 1A.

The amount of uplift (seafloor displacement) is debated (Bilham, 2005; Lay et al., 2005; Stein and Okal, 2005) but is thought to be average 7–10 m (Bilham, 2005) and is centered at northwest margin of Sumatra, around 5N. Sea level changes in Andaman and Nicobar Islands, in the north, indicate that the coseismic crustal deformation extended that far north (Kayanne et al., 2005), further confirming the source length. The sea floor motion displaced an estimated $\sim 30 \text{ km}^3$ of water on the ocean surface, causing the tsunami in the process.

On the Indian coast, the tsunami involved of three large waves, the first making landfall approximately 9.25am (Indian local time) some 3 h after the initial earthquake. The tsunami comprised three waves that arrived at 5-minute intervals. According to eyewitnesses, the second and third waves flowed over the low-lying coast before the first wave completely receded. In many places, waves ripped large trees out of the ground by the roots and moved both traditional wooden and modern brick and mortar structures off of their pilings or foundations tens to hundreds of meters away from the coast.

1.2. The past tsunami in Indian Ocean

Unlike the Pacific region where many damaging tsunami have occurred tsunami are rare in the Indian Ocean. The occurrence of large tsunami in Bay of Bengal is relatively infrequent. The Bay of Bengal has experienced 5 tsunami during the period from 1881 to 2004, including the 26th December 2004 tsunami. Previous tsunami in the Bay of Bengal were in 1881, 1883, 1907 and 1941 (NOAA compilation). Tsunami were also generated by Sumatran earthquakes of 1833 and 1861 but before the introduction of harbour tide gauges in most parts of the world including India. In most cases no scientific data are available and such events are only recorded in local history.

2. Study area

The study area consists of approximately 60 km of coastal tract from Injambakkam to Kadalore, south of Chennai (Fig. 1B). The study area is one of the most important and sensitive areas in the country and is also the site of the Madras Atomic Power Station (MAPS) which consists of two reactors of 235 MW. The area also contains a coastal township associated with MAPS,

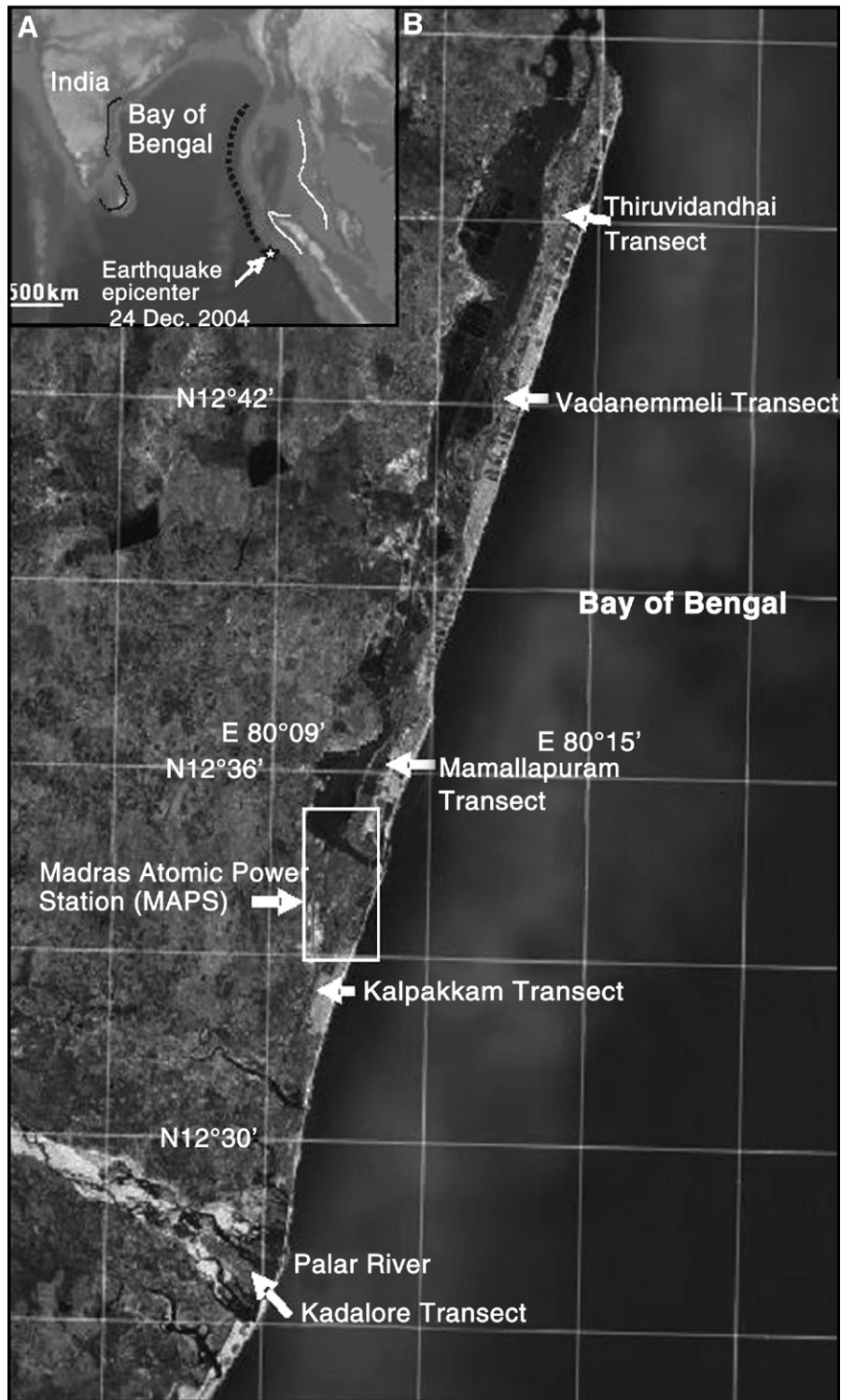


Fig. 1. Location map of the Kalpakkam coast of southeast India struck by the 2004 tsunami. A) Shows the areas most devastated by the tsunami (thin line) and the epicenter of the M9 earthquake that occurred at 12.58am (GMT) on December 24 2004. B) Shows the location of five transects that were conducted at Thiruvidadandai, Vadanemmeli, Mamallapuram, Kalpakkam and Kadalore.

many coastal villages and an important tourist attraction Mamallapuram, which attracts tourists from all over the world. This coastal tract is represented by low angle, siliclastic beaches with a width of about 50 to 100 m which are backed by coastal sand dunes usually of less than 5 m elevation. The back barrier morphology consists of a variety of geomorphic units such as stranded beach ridges, palaeo-lagoons, palaeo-tidal flats and palaeo barriers (beach ridges) (Anbarasu, 1994). These are the features mostly formed due to the recent and ongoing emergence of the coast (Mohan and Rajamanickam, 1998). Two prominent sets of well developed beach ridges, exhibiting typical strand line features almost parallel to the shore are present along much of the study area. These ridges are dissected by the Palar River near Kadalore (Fig. 1B).

3. Tsunami deposit transects

Deposits from the 2004 tsunami were investigated along shore-normal transects at 5 locations along a 60 km stretch of coast centered on Kalpakkam (Fig. 1B). The transects presented here were located at Thiruvidadanhai, Vadanemmeli, Mammallapuram, Kalpakkam, and Kadalore (Fig. 1B). At each transect, deposits were trenched, measured, described, photographed and push core and extraction method were used for sampling. Small trenches were dug at approximately 50-m intervals and were augmented by additional trenches where necessary to trace layers. Topography was measured using a total station and values are reported relative to mean sea level. Water inundation was estimated by measuring the height of broken branches, debris found in trees, debris found piled on the ground (Fig. 2A), or water marks on buildings (Fig. 2B and C). Tsunami deposits were common and identified as fine to medium-grained, grey to tan coloured sand that was usually found to overlie a brown muddy soil (Fig. 2D–H) characteristic of the coastal plain. In the field, bulk samples of the deposit were taken, and, at a few locations, samples were taken at 1-cm intervals down through the deposit. Grain size analysis was undertaken, using a set of 11 sieves with mesh size ranging from 0.25 Φ to 4.25 Φ . Grain-size statistics were calculated using methods described in Carver (1971). Information on grain size characteristics can be used to interpret the depositional environment and transport mechanism of a deposit.

3.1. Thiruvidadanhai transect

Thiruvidadanhai is a coastal village having both sandy and muddy setting. Maximum landward inundation was

300 m and run-up was 4 m. (Fig. 3A). The inundation was restricted to the sandy beach only. Trenching revealed multiple sand layers, an erosional base, and normal grading. Total thickness of deposits ranged from 0 to 40 cm (Fig. 3B), which is at 100 m away from the coast line. The beach face and berm showed no evidence of deposition from the tsunami. On the berm the exposed roots of some shrubs indicated the erosion of sediments down to depths of 30 to 40 cm. The zone of erosion extended up to 50 m from the coast. At about 100 m from the shore line, the thickness abruptly increased up to 40 cm before gradually decreasing in the landward direction. Approximately 300 m from the mean water line the tsunami deposit becomes patchy before terminating. Coastal vegetation was also observed to be bent in the direction of flow and no evidence of a return flow is recorded in the sediments at Thiruvidadanhai.

Surface sediments along this transect are very well sorted and the mean grain size varies from 1.1 to 1.7 phi (Fig. 3C). In this transect from 50 to 100 m from the mean water line the mean grain size gradually reduce and deposit gets finer. After that distance (100–300 m), the mean grain size and sorting values remain relatively constant.

At a distance of 230 m from the mean water line, a core sample was taken to quantify the vertical variations in grain size within the deposit. The vertical distribution in mean grain size reveals both coarsening and fining upward trends. The decrease in the grain size in the middle is problematic and cannot be explained simply as fining upward trends, as it is confined vertically by 2 coarsening upward deposits (Fig. 3D).

3.2. Vadanemmeli transect

The topography along the Vadanemmeli transect undulates with sandy ridges and low lying troughs. Inundation was about 230 m and run-up was 3.8 m. (Fig. 3E). The sand sheet grades upward from coarse sand at the base to fine sand near the top a characteristic which was only observed in deposits more than few cm thick. The zone of erosion extended to the landward side of the berm, about 50 m from the mean water line and within the span of few tens of meters, the deposit thickness increased to about 3.8 cm (Fig. 3F) and decreased in the landward direction over the next 125 m. Surface sediments along this transect are very well sorted and the mean grain size varies little from 1.1 to 1.6 phi (Fig. 3G). This transect also suggest that the mean grain size gradually decreases in a landward direction with sorting of the deposit remaining more or less constant.



Fig. 2. The direction of water flow is marked with an arrow (A) and the water level can be observed on the white wall (B). Water level and considerable erosion is also noted in front of the concrete foundations (C). The tsunami deposits were generally identified as grey sands that overlies the soils of the coastal plain (D–H).

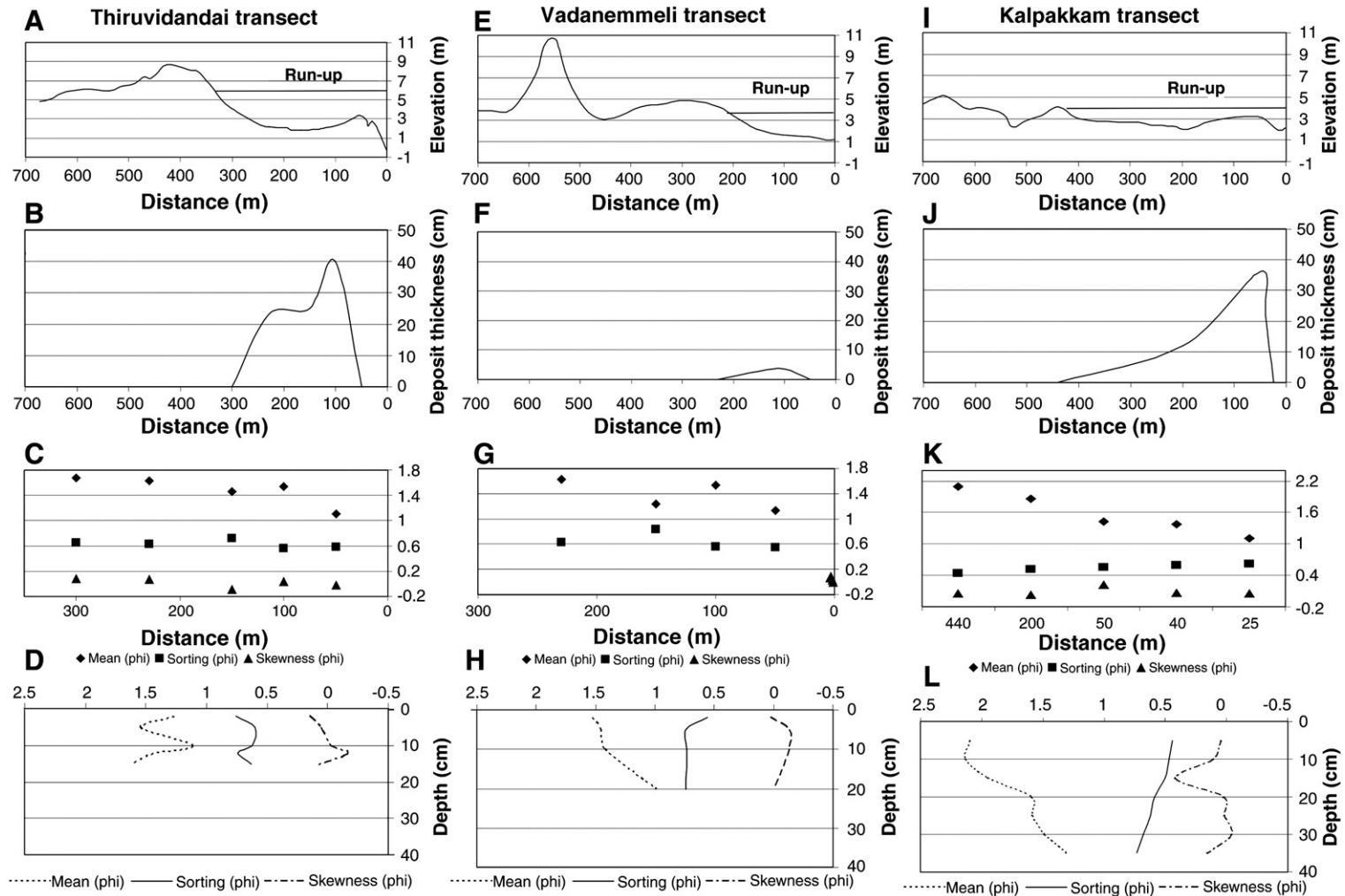


Fig. 3. Topography (A) and tsunami deposit thickness (B) along with standard grain-size statistics (inclusive mean, standard deviation and skewness) taken from transects (C). The vertical trends in grain size parameters for cores taken from the tsunami deposit are shown in (D). From left to right along the transects are Thiruvandandai (I), Vadanemmeli (II), Kalpakkam transects (III).

No pit sample was collected as the limited thickness of the deposit precluded trenching in this transect as the thickness of the deposit is very thin. However, a pit sample was collected in a low lying area near to this transect, where a berm was eroded at a distance of 150 m from the mean water line. The tsunami deposit was 20 cm thick. The vertical distribution in mean grain size confirms the fining upward deposit (Fig. 3H). The mean grain size smoothly decreases from 1 to 1.5 phi. The surface layer contained mud which was not included in the distribution pattern. The standing tsunami waters allowed fines to settle out after the event.

3.3. Kalpakkam transect

On this transect, the maximum inundation was 420 m and run-up was 4.2 m. (Fig. 3I). Here the trenching revealed multiple sand layers, an erosional base and narrow banding in the deposits. The maximum thickness of tsunami deposits here was 36 cm observed at 50 m from the mean water line (Fig. 3J). Trenching on this transect revealed multiple laminated sand layers in the lowest parts of the deposit and an erosional base. The

laminated sequence showed no trend in mineralogy or grain size although this may be a result of the coarse sampling interval. The mean grain size varies from 1.1 to 1.6 phi (Fig. 3K). In this transect the mean grain size gradually decreases from the mean water line and the deposit fines landward.

A pit sample was taken at a distance of 50 m from the shore line to study the vertical distribution pattern. The mean grain size reveals two coarsening and fining upward sequences (Fig. 3L).

3.4. Mammallapuram transect

Mamallapuram is a historical coastal town and it is well known for its heritage. The contrast between the tsunami deposit and the underlying sediments made identifying the deposit easy and allowed investigation of the contact between the sand sheet and the underlying soil. The maximum inundation was 650 m and run-up was 4.3 m. (Fig. 4A). On this transect laminations are there and no trends were identified due to coarse sampling intervals.

Tsunami deposition here was patchy in the area immediately behind the foredunes, no continuous

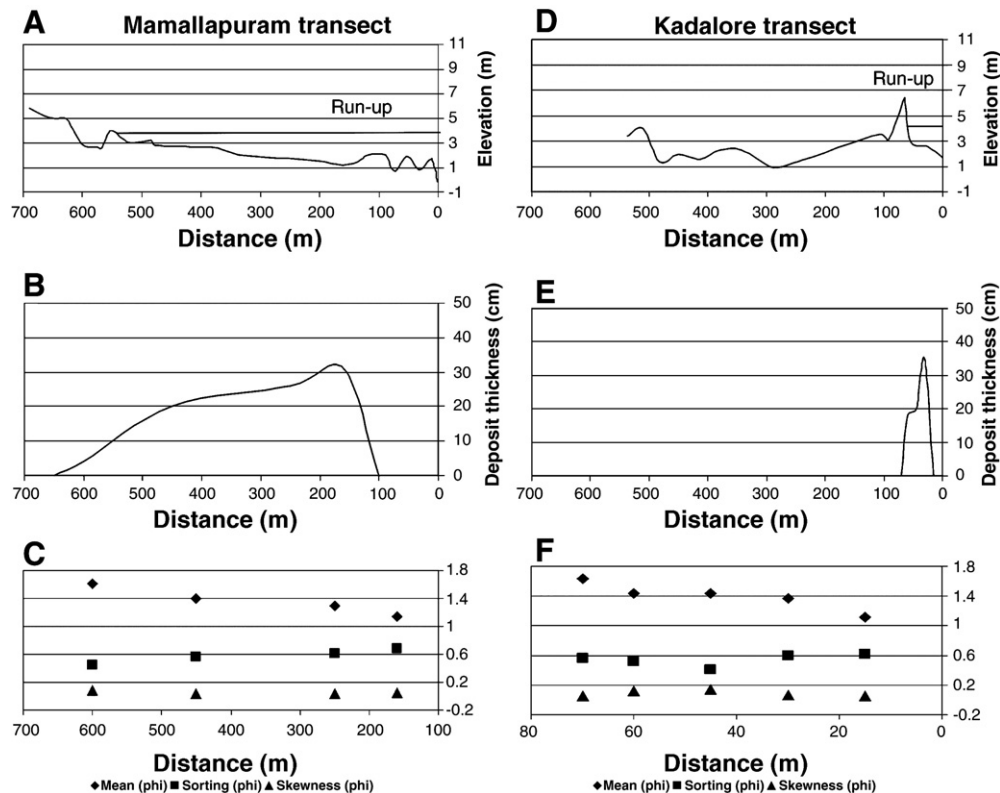


Fig. 4. Topography (A) and tsunami deposit thickness (B) along with grain-size statistics (C) of the beach sand and of the tsunami deposit along the Mamallapuram (I) and Kadalore (II) transects.

deposit was identified at Mamallapuram until approximately 100 m from the mean water line. The deposit became thicker from 100 to 160 m to a maximum thickness of 32 cm. The tsunami deposit then thins from its maximum thickness to a minimum of 0–2 cm at a distance of 620 m from the mean water line (Fig. 4B).

The deposits at Mamallapuram exhibit considerable lateral variation, in some places the deposit occurs as a single fining upward layer, but in other places the deposit is composed of some laminated as noted above. The mean grain size of the deposit decreases landward (Fig. 4C), and the surface sediments along this transect are very well sorted with a mean grain size that varies from 1.1 to 1.6 phi. From 50 to 100 m along this transect the mean grain size gradually reduces and deposit gets finer. In contrast samples taken 150 to 230 m along this transects suggest the mean grain size slightly increases. The well sorted nature of the sand in the tsunami deposits of along this transect remains relatively constant.

3.5. Kadalore transect

Kadalore is a small village near the river Palar mouth. The maximum inundation was 70 m and run-up was 4.2 m (Fig. 4D). The maximum thickness of tsunami deposits was 35 cm, which is observed 30 m from the mean water line. The zone of erosion extended up to 15 m from the shore line (Fig. 4E) and an erosional contact was observed at the base of the tsunami deposit. Surface sediments along this transect are very well sorted and the mean grain size varies from 1.1 to 1.8 phi (Fig. 4F). In this transect the mean grain size decreases landward and the sorting of the sediments exhibits little variation.

4. Discussion and summary

4.1. Shore-normal trends in deposit

The tsunami waves that struck Kalpakkam made landfall with velocities high enough to erode, suspend and transport large quantities of sand into the coastal environments. Despite their destructive power which uprooted trees and destroyed many structures, the tsunami waves left behind a sandy deposit as the flow dissipated in a landward direction. The sandy deposit was usually identified as a continuous sandsheet that varied in thickness depending, in part, on local topography, the presence of obstructions, and the density of vegetation. Such features are common in tsunami deposits (Dawson and Shi, 2000; Scheffers and

Kelletat, 2003) and have been identified in tsunami deposits at Sissano Lagoon, Papua New guinea (Gelfenbaum and Jaffe, 2003) on the Japanese coast (Nanayama and Shigeno, 2006). A tsunami deposit was found at every site along the Kalpakkam coast where it usually extends from approximately 15 m landward of the mean water line, across the coastal plain to very near the limit of inundation (indicated by debris), in places a distance of up to 620 m. Tsunami inundation distance or the distance measured from the mean water line to the landward limit of inundation, varied in a similar manner to the wave height, with the maximum inundation at Vadanemmeli. The maximum inundation distance that we observed over land, at the Mamallapuram transect, measured about 650 m. The deposit often shows variable thickness and can be patchy nearer the shore before it tapers inland from a zone of maximum thickness usually found approximately 1/3 of the distance of inundation.

At Thiruvudanthai, however, the deposit is more nearly tabular, with a rapid increase in thickness near the coast, a long nearly flat middle section, and then a gradual decrease on the landward side. The maximum thickness is not near the coast, but farther inland. Along each of the transects in which both the landward limit of sand deposition and the landward limit of the tsunami could be identified, the landward limit of the deposit fell short of the limit of tsunami inundation. Dawson (1994) and Gelfenbaum and Jaffe (2003) measured similar distances between the deposit and the maximum inundation for the 1994 Java and 1998 Papua New Guinea tsunami respectively. Along all five transects the areas with net onshore erosion as a result of the tsunami were limited to portions of the beach and berm close to the ocean. The amount and depth of erosion offshore were not quantified but the presence of marine microfauna in the deposit suggests a variable amount offshore material was incorporated into the deposit. Further investigation of the heavy mineral suite and microfaunal populations is currently being undertaken. Initial results indicate the presence of some immature platy heavy minerals which may indicate erosion of material from below storm wave base (Switzer et al., 2005). Such information may provide valuable criteria for distinguishing between storm over wash and tsunami deposits in the geological record.

4.2. Alongshore trends in deposit and inundation

The zone of inundation from the 2004 tsunami in Kalpakkam covered about 60 km in the alongshore

direction. Within this 60-km long stretch of coast the maximum inundation level was 11 m at Vadanemmeli in the north and 6.5 m at Kadalore in the south. A section of coast spanning about 20 km long sustained water levels over 4 m high. This focusing of wave energy may reflect several factors, including the proximity of the source disturbance and the focusing nature of the bathymetry on the shelf and slope (Matsuyama et al., 1999). Tsunami run-up, or the elevation relative to sea level at the landward limit of inundation, does not appear related to tsunami wave height. This is most likely a reflection of topographic roughness (the presence of ridges, dunes and vegetation) where a rough surface such as a series of beach ridges acts on the flow to limit inundation distance. In contrast tsunami deposit thickness does appear related to wave height on a regional scale.

Deposit thickness is smallest at Vadanemmeli where the wave height was smallest and greatest at Thiruvandanthai, Mamallapuram and Kadalore, where the wave height was largest. At many of the study sites the thickness of the sand layer deposited by the tsunami varies locally as well as regionally. Locally, the tsunami deposit thickness varies in response to variations in local topography. In general, deposit thickness increases slightly in local depressions and decreases over local highs in the topography. Mean grain size of the tsunami deposit seems unrelated to deposit thickness or wave height. The grain size of the deposit inherently reflects the grain size of the sediment available to be transported. Bedding relationships and vertical trends in sediment characteristics that relate to transport and depositional processes can be studied by examining the detailed vertical trends in the tsunami deposit.

Most of the deposits contain vertically (normal) graded sediments, meaning the grain size varies increases with depth in the deposit. Some transect had one continuously graded bed others had two normally graded beds one atop another. Each graded bed implies deposition from suspension as flow velocity decreases. Normal grading is a common sedimentary structure associated with deposition from a turbulent suspension in tsunami deposits (Shi et al., 1995; Goff et al., 2001; Gelfenbaum and Jaffe, 2003; Smith et al., 2004). In a turbulent flow there is a sediment grain-size gradient, with coarse material proportionally concentrated near the bed and finer material more evenly distributed throughout (Smith, 1977; Gelfenbaum and Jaffe, 2003). As the flow wanes and the sediment settles out of suspension, the coarse material will settle first and the finer material will follow. At Thiruvandanthai, the normally graded deposit suggests deposition from a

single event or wave. At Kalpakkam, the two layers of normally graded sediment may imply deposition from two tsunami waves. However, at both locations, the number of graded beds is less than the number of waves reported by eyewitnesses. Throughout the region, eyewitnesses consistently reported three waves inundating the coast. Apparently, each wave that struck the coast either did not deposit a sandy layer, or each wave deposited a sandy layer that was subsequently resuspended with the passage of the next wave. Unfortunately, there does not appear to be a one-to-one relationship between the number of waves inundating the coast and the number of sandy layers in a deposit.

In places the deposit contains laminated sequences of sand, a feature which has been studied in the 2004 tsunami deposits on other parts of this coast (Thangadurai et al., 2006; Switzer et al., 2006). The laminated facies are most likely associated with upper flow regime plane bedding during the high velocity stages of initial flow and occasionally in the final stages of waning flow. This inference is supported by the presence of these beds in the lower and upper parts of deposits at Kalpakkam and Mamallapuram. At other places on the coast no graded sequence is observed within the deposit and the entire deposit consists of laminations particularly in parts of the deposit closest to the mean water line (Switzer et al., 2006).

5. Conclusions

The 2004 Indian Ocean tsunami has left significant sand deposits along the coastal tract of Tamil Nadu. The study of these deposits provides a better understanding of the effects of tsunami on coastlines. The evidence left by the tsunami in the coastal stratigraphy can assist in providing modern analogs for the identification and interpretation of palaeotsunami in the geologic record. Shore-normal transects show signs of flow, erosion, and deposition from the south Asian tsunami of 26th December, 2004:

1. A distinct deposit was left by the tsunami. The deposit was distributed continuously across the coastal plain and varied in thickness. The average thickness along the transect was 18 cm and the maximum thickness was 40 cm.
2. Upward fining sediments dominate the deposits and suggest sediment fell out of suspension before the water retreated. Some deposits show multiple graded beds suggesting multiple waves. The presence of laminated beds is also noted and requires further examination. These beds are most likely upper flow

regime plane beds deposited during high velocity conditions.

3. Erosion of the beach and berm generally extended 50–150 m inland from the mean water line.
4. The incoming tsunami flowed nearly perpendicular to shore, but a slower backwash, or return flow, was directed obliquely to the shore, toward local lows in the topography.
5. Tsunami deposit thickness and inundation distance varied along the coast. They were greatest where the tsunami wave height was greatest and decreased with decreasing wave height.

Acknowledgements

We thank the Department of Science and Technology, Ministry of Science and Technology, Government of India for the financial support. This work was carried out as a part of Tsunami research programme. The authors are grateful to Prof. S. P. Mohan, Head, Department of Geology, University of Madras for providing laboratory facilities and The Director, CPEES, Anna University for providing the transportation and support for the fieldwork. A.D. Switzer obtained financial assistance from the DES at Hong Kong University to participate in this study.

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