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Adam D. Switzer, S. Srinivasalu, N. Thangadurai and V. Ram Mohan

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Bedding structures in Indian tsunami deposits that provide clues to the dynamics of tsunami inundation

ADAM D. SWITZER1*, S. SRINIVASALU2, N. THANGADURAI2 & V. RAM MOHAN3

1Earth Observatory of Singapore, Nanyang Technological University, 639798 Singapore
2Department of Geology, Anna University, Chennai 600025, India
3Department of Geology, University of Madras, Chennai 600025, India

*Corresponding author (e-mail: aswitzer@ntu.edu.sg)

Abstract: The 2004 Indian Ocean tsunami deposited an extensive sandsheet on the coastal plain of SE India. At particular sites, the sedimentary bedding in the sandsheet provides evidence of variable energy conditions and flow during inundation of the coast. Trenching of the deposits at sites where only unidirectional flow was observed allowed the investigation of changes in hydrodynamics recorded in bedding structures without the added complexity of return flows and reworking. A high-velocity initial surge is recorded as upper flow regime (UFR) plane bedding. Following the initial high flow a period of falling flow velocity and quiescence occurs where sediments settle out of suspension, often resulting in a reverse graded bed that transitions to a graded (fining-up) bed. As water levels begin to decline after maximum inundation sheet flow caused the formation of inversely graded (coarsening-up) beds or a return to UFR conditions. At one site the final stages of tsunami inundation is recorded as small channels that have an erosional base and are filled with graded sediments that exhibit complex patterns of sedimentation. Pits excavated in areas of unidirectional flow allow the development of a sedimentary model for tsunami sediment dynamics across flat topography under unidirectional flow conditions.

Despite recent advances, the hydrodynamics of tsunami inundation and the inherent relationship between inundation hydrodynamics and sedimentary bedding in tsunami deposits remain poorly understood. Much can be learnt from the careful study and interpretation of modern tsunami deposits as they provide a valuable and powerful analogue to palaeostudies, and provide insights into the dynamics of erosion and deposition during tsunami inundation and back flow (e.g. Le Roux & Vargas 2005; Dawson & Stewart 2007; Hawkes et al. 2007; Jaffe & Gelfenbaum 2007; Morton et al. 2007; Paris et al. 2007, 2008; Srinivisalu et al. 2007; Choowong et al. 2008a, b; Komatsubara et al. 2008; Naruse et al. 2010). Owing to the relative rarity and geographical distribution of tsunami, few descriptions are available of the sedimentary structures and facies of onshore tsunami deposits (e.g. Gelfenbaum & Jaffe 2003; Nanayama & Shigeno 2006; Bahlburg & Weiss 2007; Hawkes et al. 2007; Hori et al. 2007; Morton et al. 2007; Paris et al. 2007; Umitsu et al. 2007; Choowong et al. 2008a, b; Naruse et al. 2010). Investigations of sedimentary processes associated with modern tsunami are extremely important in the interpretation of tsunami deposits in the geological record as many identified tsunami signatures or features can be equally attributed to storm surge or other depositional processes (Witter et al. 2001; Switzer et al. 2005; Dawson & Stewart 2007; Jaffe & Gelfenbaum 2007; Kortekaas & Dawson 2007; Morton et al. 2007; Switzer & Jones 2008a, b; Switzer & Burston 2010). Recent studies on tsunami-deposited sandsheets, such as those deposited by tsunami events in 1983 at Nihonkai-chubu (Minoura & Nakaya 1991), the 1992 Flores (Shi et al. 1995; Minoura et al. 1997), 1993 at Hokkaido–Nansei-oki (Nishimura & Miyaji 1995; Sato et al. 1995; Nanayama et al. 2000), 1994 in Java (Dawson et al. 1996), 1998 in Papua New Guinea (e.g. Gelfenbaum & Jaffe 2003) and the recent 2004 Indian Ocean tsunami (e.g. Szczucinski et al. 2005, 2007; Bahlburg & Weiss 2007; Hawkes et al. 2007; Hori et al. 2007; Morton et al. 2007; Paris et al. 2007; Srinivasa et al. 2007; Umitzu et al. 2007; Choowong et al. 2008a, b; Naruse et al. 2010), are of considerable importance in understanding the dynamics of tsunami inundation in different coastal settings.

The tsunami run-up process is very complex, and it is pertinent to any study of onshore tsunami deposits that analysis of the likely pre-event morphology, sedimentary environments and sediment dynamics of the seabed, nearshore and onshore systems be considered. One of the most widely recognized sedimentary signatures for tsunami inundation is landwards-tapering wedges.
of marine material, often in the form of extensive sheets of marine sand (e.g. Minoura & Nakaya 1991; Dawson et al. 1996; Minoura et al. 1997; Jaffe & Gelfenbaum 2007; Morton et al. 2007; Matsumoto et al. 2008). Often these sandsheets contain sequences of normal (fining-up) or inversely (coarsening-up) graded beds (Dawson et al. 1991; Nishimura & Miyaji 1995; Benson et al. 1997; Gelfenbaum & Jaffe 2003; Morton et al. 2007), non-graded (massive) or multiple graded sandsheets (Benson et al. 1997; Gelfenbaum & Jaffe 2003; Moore et al. 2006; Paris et al. 2007), and sharp erosional bases (Nanayama et al. 2000; Switzer et al. 2006; Switzer & Jones 2008b). Some deposits contain ‘bioclasts’ or rip-up clasts of muddy soil and, in some locations, mud caps or rafted debris (Dawson et al. 1996; Goff et al. 2001, 2004a, b; Gelfenbaum & Jaffe 2003; Dawson & Stewart 2007; Naruse et al. 2010). Current ripples and dunes in onshore tsunami deposits, formed by tsunami inflows and outflows, have also been reported by Sato et al. (1995), Nanayama et al. (2000) and Nanayama & Shigeno (2006).

A large earthquake on Sunday 26 December 2004 occurred 160 km west of Sumatra, Indonesia at a depth of approximately 25–30 km (Fig. 1a). The earthquake generated a tsunami that caused over 280,000 fatalities across the entire Indian Ocean Basin (Lay et al. 2005; Stein & Okal 2005; Grilli et al. 2007). On the Indian coast the tsunami consisted of three large waves, with the first making landfall 3 h after the initial earthquake, followed by two more waves approximately 5 min apart that flowed over the low-lying coast before the first wave completely receded (Srinivasalu et al. 2007). Tsunami run-up levels ranged from 0.7 to 6.5 m above sea level, and inundation distance varied from 30 to more than 850 m from the swash zone (Chadha et al. 2005; Jayakumar et al. 2005; Ramanamurthy et al. 2005). The average landwards inundation distance was approximately 250 m. The tsunami waves extensively transformed the morphology of the Tamil Nadu coast as they inundated estuaries, overtopped dunes and resulted in considerable alteration to the coastal morphology (Narayana et al. 2007; Mascarinho & Jayakumar 2008; Pari et al. 2008). In many places waves ripped large trees out of the ground, and moved both traditional wooden and modern brick and mortar structures off of their pilings or foundations tens to hundreds of metres away from the coast (Srinivasalu et al. 2007; Mascarinho & Jayakumar 2008).

This paper looks at the sedimentary bedding characteristics of tsunami overwash deposits from four specific pits excavated on the SE coast of India. Trenching and coring elsewhere on this coast has allowed mapping of the extent of the 2004 tsunami deposits, and investigation of the affects on coastal topography and indicators of sediment sources (Thangadurai et al. 2006; Srinivasalu et al. 2007). This work focuses on two sites where unidirectional flow occurred, and investigates the relationship between sedimentary bedding, flow regime, bedform morphology and flow velocity. The four pits (of 12) were chosen to minimize the added complication of reworking during back flow (Nanayama & Shigeno 2006; Hori et al. 2007; Choowong et al. 2008a, b; Naruse et al. 2010). Sedimentary beds identified here are representative of different stages of flow change during unidirectional tsunami overwash across relatively flat topography (relief less than 1 m change over more than 150 m) at 2–3 m above present mean sea level.

**Study sites**

The study area consists of approximately 160 km of coastal tract from Vedarranniym in the south to Cuddalore in the north (Fig. 1). The landforms of the northern part of the study area are characterized by low-angle (<3°) siliclastic beaches with an average width of about 50–100 m that are backed by a coastal dune system usually of less than 5 m elevation (Anbarasu 1994; Pari et al. 2008). In the northern study area, two prominent sets of well-developed beach ridges that are almost parallel to the shore lie landwards of the modern dune system (Fig. 1). The southern part of the study area shows more complex delta morphology, and is dominated by silty floodplain sediments and strandlines and a coastal morphology of beach ridges and tidal flats that overlie the prograded deltaic system of the Kaveri (Cauvery) River. These ridges are dissected by the numerous small rivers and estuaries along with the two large rivers, the Pellar River and the Kaveri River (Fig. 1). Two main sites are presented here: Silver Beach near Cuddalore (Fig. 1b) and Kallar near Nagipattinum (Fig. 1c).

**Methods**

The study focuses on the bedding structures, bioturbation and sediment particle-size variation observed in tsunami-deposited sediments in two areas affected by unidirectional flow. Unidirectional flow was confirmed by eyewitness accounts and geomorphic indicators, such as grassy debris wrapped around scattered trees or the presence of erosional scour marks behind trees. The study sites were also located on local topographical highs (50–80 cm higher than surrounds) seawards of a slope that ran into the creeks at the back of the sites. Flow depths at Silver Beach and Kallar were estimated to be around 2–3 and 3–4 m,
Fig. 1. (a) Regional map of India and the Bay of Bengal. The epicentre of the 24 December 2004 tsunami was situated offshore of Banda Aceh in northern Sumatra, Indonesia. The yellow dotted line is the 1500 km + rupture. The tsunami wave generated struck the Indian coast approximately 3 h after generation. (b) Map of the SE coast of India. Maximum inundation was up to 2 km at Verdarranniyam. (c) The study site at Silver Beach near Cuddalore. Here the tsunami waves washed into a small estuary. Two pits were excavated, SB-I and SB-II. Pit SBI shows a clear tsunami deposit of marine sand. Eyewitness accounts suggest that tsunami waves passed over the site of pit SB-II, no tsunami deposit was identified. (d) The study site at Kallar near Nagapattinam. Two pits were excavated here to investigate the unidirectional washover dynamics where eyewitness accounts stated that the waves washed across the dunefield and into the low-lying floodplain below before draining out through Nagapattinam Port.
respectively, based on eyewitness accounts of levels on walls and estimations based on debris in trees. Inflow velocities in the area are believed to have been in excess of 3 m s\(^{-1}\) based on eyewitness accounts and videos from sites nearby. These velocities are consistent with those derived from videos in studies of inundation in Banda Aceh (Sakakiyama et al. 2005; Fritz et al. 2006).

Although many pits have been excavated and described for this coast (Srinivasalu et al. 2007), the four study sites chosen here were selected because they show clear bedding structures that are the result of variation in unidirectional flow or evidence of significant bioturbation, which was deemed to be the most important aspects of this study. For this purpose, several pits of approximately 40 \(\times\) 40 cm were excavated in October 2005. Excavations extended through the tsunami deposit and into the underlying soil at sites where no evidence of bidirectional flow was found. Samples were collected at 2 cm intervals, with extra samples taken across stratigraphic contacts and in areas of key interest. Sedimentary bedding features along with sediment grain-size characteristics were used to define facies within the tsunami deposit and the underlying units with the aim of developing a model that relates grain-size patterns, sedimentary bedding and tsunami flow dynamics. Grain-size parameters, including the percentage of sand, silt and clay along with graphic mean, inclusive graphic standard deviation, inclusive graphic skewness and graphic kurtosis (after Folk & Ward 1957), were obtained using a Malvern Mastersizer 2000 (laser diffraction particle-size analysis) and a method modified from Chivas et al. (2001) and Switzer et al. (2005).

**Results**

**Silver Beach**

At Silver Beach the tsunami waves inundated the coastal plain at depths estimated to be around 2 m and flowed up the estuary towards the town of Cuddalore. Two pits (SB-I and SB-II) were excavated on the northern bank of the estuary behind a small car park that lies on the heavily modified (anthropogenically flattened) beach ridge (Fig. 2). Small pits were excavated along a transect from the dune and car park to a grassy berm with a small wall 1.6 m high that was partially destroyed in the tsunami. The distance from the shore to the wall was approximately 600 m. Local residents outlined the extent of the tsunami deposit and it was identified as a thin sandsheet that started approximately 50 m from the shore. The deposit thickness increased landwards to a maximum thickness of about 32 cm approximately 200 m from the coast before thinning and becoming patchy at about 350 m from shore.

![Fig. 2. Photographs of excavated pits SB-I and SB-II near the town of Cuddalore on the SE coast of India. In pit SB-I, the tsunami deposit is identified as a thin layer of fine- to medium-grained sand 32 cm thick. In pit SB-II, the facies are predominantly estuarine mud and sand. The upper 12 cm may be a tsunami deposit but it has been heavily reworked by aeolian activity and affected by soil development.](http://sp.lyellcollection.org/)
Pit SB-I

Pit SB-I was excavated close to the area of maximum thickness (c. 200 m from shore) where the sedimentary record of the tsunami is identified as a thin deposit of fine- to medium-grained sand 32 cm thick, which exhibits several layers and complex bedding patterns (Figs 2a & 3). At this site the deposit sharply overlies the muddy fine sand (c. 2.06\(\phi\)–2.10\(\phi\)) of the coastal plain. The base of the tsunami deposit found in pit SB-I exhibits complex bedding with low-angled cross-bedding occurring in a basal layer of fine sand (c. 2.17\(\phi\)–2.21\(\phi\)) that is approximately 5 cm thick. The basal layer is composed of a facies that contains abundant heavy minerals. This layer is sharply overlain by a lighter coloured (tan) relatively massive fine- to medium-grained sand (c. 2.08\(\phi\)–1.95\(\phi\)) layer with noticeable bioturbation (burrows). This facies exhibits little variation in grain size, showing only a slight coarsening-up trend (reverse grading), and becomes slightly coarser (1.79\(\phi\)) and more poorly sorted (0.71\(\phi\)) towards the top of the light coloured layer. The light coloured layer is sharply overlain by a layer of sediments that has a higher proportion of heavy minerals (>10%) (including abundant zircons, ilmenite and rutile) and undetermined lithic clasts (indicated by a dark colour). The top layer is composed of fine- to medium-grained sand (c. 1.95\(\phi\)–1.79\(\phi\)), and exhibits complex bedding that is recorded as small cross-bedded channels and micro-bars outlined by dark coloured beds composed almost entirely of heavy minerals. The deposit then grades to a muddy sand (c. 2.05\(\phi\)–2.35\(\phi\)) that is topped by a sandy soil (c. 1.88\(\phi\)). The top of the tsunami deposit is poorly defined, although grain-size data of the overlying layer shows considerable contrast with the underlying (tsunami) layers (much coarser) and are dissimilar to that of

![Photograph of face and grain-size data from pit SB-I. The base of the tsunami deposit contains a laminated facies (LF) that exhibits complex bedding that is approximately 5 cm thick and contains abundant heavy minerals. Laminated facies is sharply overlain by fine- to medium-grained sand facies (GMF) with noticeable bioturbation. This bed exhibits little variation in grain size, showing only a slight coarsening-up trend and with only a slight increase in sorting towards the top of the bed. This bed is sharply overlain by a bed that has a higher proportion of heavy minerals (ROF), where complex bedding includes small cross-bedded channels and micro-bars outlined by dark coloured beds. The uppermost unit (Soil) is a muddy sand that is topped by a sandy soil. The top of the tsunami deposit is poorly defined, although the overlying bed shows considerable contrast with the underlying (tsunami) beds, and is similar to that of the underlying muddy soil of the coastal plain.](#)
the underlying muddy soil of the coastal plain. This may represent post-depositional aeolian reworking of the sediments deposited by the tsunami.

**Pit SB-II**

Pit SB-II (Figs 2b & 4) was excavated near the reported landward extent of the deposit. Here the only deposit considered as a ‘suspect tsunami’ deposit is a poorly defined thin muddy sand (c. 3.01σ–3.34σ) unit approximately 12 cm thick that overlies an interbedded series of muddy sand and silts. The ‘suspect tsunami’ deposit appears to have been considerably modified by soil development. All units show considerable variation in grain size but they are all muddy-sand units that are considerably finer and more poorly sorted than the tsunami sediments identified in face SB-I. If the top unit in the sequence is, indeed, the deposit of the tsunami event, then it provides some evidence of landwards fining within the deposit. If not, then it may suggest that, even if tsunami deposits are identified by eyewitnesses, the preservation and differentiation from confining facies can remain problematic.

**Kallar**

At Kallar, south of Nagapattinam town, the tsunami waves inundated the coastal plain at depths of 3–4 m. Unidirectional inundation at the study site was across two poorly defined, low-relief (<2 m), well-vegetated beach ridges before flowing into the Uppanar River flood plain and out through the heavily modified entrance of Nagapattinam Port (Fig. 1b). No evidence of return flow was observed at this site and, although vegetation is likely to have affected flow characteristics to an extent (Dahdouh-Guebas et al. 2005), the sediments deposited here are likely to have been emplaced under flow directions that were close to unidirectional (Fig. 2c). Two pits, Kallar-I and Kallar-II (Fig. 5), were excavated in a fenced area that had been sealed off by the local community and the environment had been well preserved since the tsunami some 5 months earlier. Pits Kallar-I (Figs 5a & 6) and Kallar-II (Figs 5b & 7) were excavated along a transect perpendicular to the shore at distances of approximately 420 and 580 m from the shore, respectively (Fig. 2c). Local residents described the tsunami deposit as a thin sandsheet that started approximately 120 m from the shore and ran into the low-lying floodplain (Fig. 2c).

**Kallar-I**

The pit Kallar-I was excavated at a site away from surrounding vegetation where the tsunami deposit...
was thought to be the thickest. Here the sedimentary record of the tsunami was identified as a thin deposit of fine- to medium-grained sand, which consists of four sedimentary layers that exhibit considerable horizontal lamination and complex bedding patterns, and sharply overlie the muddy sand of the coastal plain (Fig. 5a). The base of the tsunami deposit shows a 15–20 cm-thick layer that exhibits prominent thin, laterally continuous, laminations between 0.5 and 2 cm thick, which are well defined by heavy mineral horizons. The grain-size characteristics of the basal layer show considerable variation in the lowest parts (Fig. 6) before exhibiting a well-defined trend of increased sorting (c. 1.0–0.6φ) and fining-up (c. 2.6φ–2.2φ). The basal layer is sharply overlain by a massive layer of fine- to medium-grained sand with very few sedimentary features, and is 14–22 cm thick. This unit exhibits subtle variation in mean grain size and it becomes slightly coarser from its base value of approximately 2.3φ to a maximum mean grain size of 1.9φ (reverse grading) before fining up to about 2.1φ. The relatively massive unit is sharply overlain by a laterally discontinuous layer of laminated fine- to medium-grained sand similar to the basal layer that varies between 0 and 4 cm thickness.

Fig. 5. Pits Kallar-I and Kallar-II were excavated south of Nagapattinam town where tsunami waves 2 and 3 inundated the coastal plain across two poorly defined low-relief (<2 m), well-vegetated beach ridges before flowing into the Uppanar River flood plain and out through the entrance of Nagapattinam Port. No evidence of return flow was observed at this site, although vegetation is likely to have affected flow characteristics to some extent. The sediments deposited here are likely to have been emplaced under flow directions that were close to unidirectional, and the two pits Kallar-I and Kallar-II were excavated at distances of approximately 420 and 580 m from the shore, respectively, along a transect perpendicular to the shore (Fig. 1d).
At times, this layer has been incised and reworked at its upper boundary. Overlying the relatively massive unit is a thin prominent layer with a higher proportion of heavy minerals resting unconformably on the erosional boundary (Fig. 5a). Complex bedding is recorded above this boundary with poorly defined cross-bedding and evidence of small infilled channels that, at times, exhibit a slight coarsening-up in mean grain size. This complex layer is overlain by a massive fine- to medium-grained sand layer that exhibits little variation in grain size. The combined thickness of this unit varies between 4 and 11 cm.

**Kallar-II**

The pit Kallar-II was excavated approximately 160 m further inland than the site of the Kallar-I pit. The basal layer of the tsunami deposit in Kallar-II is an 8–13 cm-thick sand layer that exhibits prominent, thin, laterally continuous laminations between 0.5 and 2 cm thick that are well defined by heavy mineral layers (LF). The basal unit is sharply overlain by a massive bed of fine- to medium-grained sand that exhibits few sedimentary features (GMF). The massive unit is overlain by a laterally discontinuous bed of laminated fine- to medium-grained sand similar to the basal unit, and has been incised and reworked at its upper boundary. The base of the overlying bed rests unconformably on the underlying bed and exhibits complex bedding. This complex unit is overlain by a massive fine- to medium-grained sand that exhibits little variation in grain size.

At times, this layer has been incised and reworked at its upper boundary. Overlying the relatively massive unit is a thin prominent layer with a higher proportion of heavy minerals resting unconformably on the erosional boundary (Fig. 5a). Complex bedding is recorded above this boundary with poorly defined cross-bedding and evidence of small infilled channels that, at times, exhibit a slight coarsening-up in mean grain size. This complex layer is overlain by a massive fine- to medium-grained sand layer that exhibits little variation in grain size. The combined thickness of this unit varies between 4 and 11 cm.

**Kallar-II**

The pit Kallar-II was excavated approximately 160 m further inland than the site of the Kallar-I pit. The tsunami imprint was identified as a thin deposit of fine- to medium-grained sand that sharply overlies the muddy sand of the coastal plain (Fig. 5b). The deposit here consists of four layers and shows a similar vertical variation as the
laminations similar to those found in the basal layer. A series of small incised channels unconformably overlie this unit and contain complex bedding with occasional low-angle cross-beds. This complex channel unit is overlain by a thin prominent bed that has a higher proportion of heavy minerals (Fig. 5a). The unit exhibits poorly defined lamination and grades into a massive fine- to medium-grained sand (GMF) with very few sedimentary features. This unit exhibits very little variation in mean grain size and, in contrast to the same unit in Kallar-I, it fines-up slightly. The massive unit is sharply overlain by a laterally discontinuous unit of fine- to medium-grained sand that is similar to the basal unit. A series of small incised channels unconformably overlie this unit and contain complex bedding with occasional low-angle cross-beds. This complex channel unit is overlain by a thin prominent bed that has a higher proportion of heavy minerals.

Other sites with laminated (plane-bedded) facies

At many places along the SE coast of India post-tsunami surveys identified tsunami deposits (Fig. 8) with laminated or plane bedding (Thangadurai et al. 2006; Srinivasalu et al. 2007). In places (Fig. 8a, b), the tsunami deposit is entirely composed of thin, 1–4 cm-thick, lamina sets of fine- to medium-grained sand. The laminated or partially laminated deposits are primarily found closest to the coast in the seaward one-third of the tsunami deposit. Figure 8a shows a photograph of a deposit from Velankanni, where the deposit was identified as a strongly laminated sequence of heavy-mineral-rich sands. Here a prominent rounded boulder, approximately 15 cm in diameter, was also found in the base of the deposit.

Discussion

Understanding the key transport mechanisms and depositional processes of tsunami deposits is a basic requirement for explaining and predicting the dispersal of sediment in coastal settings during tsunami inundation (Moore et al. 2007; Paris et al. 2007; Szczucinski et al. 2007; Choowong et al. 2008a, b; Naruse et al. 2010). Although geological investigations of former tsunami are a relatively new research area, many papers on the topic have...
been published over the last 20 years. From these studies, a wide range of sedimentary evidence from different locations has been attributed to a series of former tsunami (see reviews by Dawson & Shi 2000; Goff et al. 2001; Scheffers & Kelletat 2003; Dawson & Stewart 2007; Kortekaas & Dawson 2007; Morton et al. 2007; Bryant 2008; Switzer & Jones 2008b). Many authors have

Fig. 8. The laminated facies identified at Silver Beach and Kallar are not local anomalies. Similar deposits with laminated or plane bedding are found at many places along the SE coast of India. In places, the tsunami deposit is entirely composed of thin 1–4 cm-thick lamina sets of fine- to medium-grained sand. The laminated or partially laminated deposits are usually found in the seaward one-third of the tsunami deposit. (a) and (b) show the tsunami deposit from Velankanni near Nagapattinam where the deposit was identified as a strongly laminated sequence of heavy-mineral-rich sands. In (a), a prominent rounded boulder approximately 15 cm in diameter was also found in the base of the deposit. (c) shows a partially laminated sequence near Karaikal and (d) shows a sequence from the dunes at Vedarranniyam, the southern most part of the area.
argued that tsunamis are frequently associated with the deposition of continuous and discontinuous sediment sheets across large areas of the coastal zone, provided that there is an adequate sediment supply. More recent research has demonstrated that the deposition relationships found in tsunami deposits are more complex than that first described. Such research has only recently yielded significant insights on the understanding of tsunami dynamics during inundation (e.g. Choowong et al. 2008a, b; Naruse et al. 2010). The distinction of depositional units within tsunami deposits formed by different stages and flow characteristics will assist in extending our understanding of the relationship between tsunami inflow, sediment deposition and bed preservation.

Deposit characteristics depend on a number of factors, including: tsunami height and period; local bathymetry and topography; sediment source; and vegetation and other roughness elements (Bourgeois 1993; Morton et al. 2007; Moore et al. 2007; Choowong et al. 2008a, b). All tsunami deposits are inherently different, some deposits exhibit evidence of multiple waves (Dawson et al. 1991), but others do not, even where eyewitnesses described more than one significant wave (Bourgeois 1993). Early descriptions of tsunami deposits suggested that the vertical profile of most tsunami deposits consisted of a series of fining-up units often attributed to individual tsunami waves (e.g. Dawson et al. 1991; Shi et al. 1995; Dawson 1999). These simple descriptions have evolved through time, and over the last decade the internal sedimentary structures of tsunami deposits have been used extensively to infer flow directions and changes in hydraulic behaviour during inundation (e.g. Fujiwara et al. 2003; Panegina et al. 2003; Nelson et al. 2004; Cisternas et al. 2005; Williams et al. 2005; Moore et al. 2006, 2007; Nanayama & Shigeno 2006; Jaffe & Gelfenbaum 2007; Choowong et al. 2008a, b; Paris et al. 2008). Prior to 2004, sharp contacts between layers of normal grading deposits were considered good criteria to separate inflow and outflow units (e.g. Nanayama et al. 2000); however, recent work (e.g. Paris et al. 2007; Choowong et al. 2008a, b; Naruse et al. 2010) has demonstrated the complexity of the deposition relationships found in tsunami deposits. Tsunami deposits are a product of the source environment, and grain size and sorting will commonly reflect the source material available (Bourgeois 1993; Switzer & Jones 2008b). Where unconsolidated sediment is available, tsunamis can erode significant amounts of sediment from the coastal zone and offshore; such material will also consist of coastal sediments but will also often include large amounts of displaced and reworked coastal vegetation and fauna. Several authors have identified large volumes of sediment sourced from the continental shelf incorporated into the tsunami deposit. For example, Gelfenbaum & Jaffe (2003) noted that, in several locations, the 1998 Papua New Guinea tsunami deposit was composed of more than 65% offshore sediment. Similar findings were presented by Babu et al. (2007) and Paris et al. (2008) in reference to the 2004 Indian Ocean tsunami. In these cases, both studies identified that more than 75% of the sediments came from offshore. The tsunami deposits of the SE Indian coast directly relate to their source, and all contain abundant fine- to medium-grained sand (Fig. 8) with minor heavy minerals and relatively low carbonate content.

Flow characteristics and sedimentary facies

Three main facies are identified in the Indian tsunami deposits (Figs 3–8) and are thought to reflect different stages of inundation, energy dissipation and changes in flow regime for the specific sites investigated. The majority of deposits are associated with the much larger second wave that struck the coast at approximately 9.35 a.m. local time (Srinivasalu et al. 2007). The dominant facies is a massive sand (GMF) that exhibits subtle evidence of reverse grading (coarsening-up), followed by normal grading (fining-up) that is usually the thickest of the units and is often found in the middle section of the deposits. The second prominent facies is a plane-bedded or laminated facies (LF) composed of numerous lamina sets that dominate the most seaward areas of the deposits and are also often found in the lower parts of the middle section of most transects. The final facies is termed the runout facies (ROF) and consist of complex bedding with laminated sediments and evidence of channelized flow including complex low-angle cross-bedding. In some places, including the Kallar sites, deposits from a later, possibly third, wave are found overlying the sequence deposits from the initial inundation.

Deposition of plane-parallel laminated facies (LF).

Laminated sediments segregated into multiple discrete lamina sets are often found in sandy storm deposits and rarely in tsunami deposits (Morton et al. 2007; Choowong et al. 2008a, b). Most storm deposits exhibit at least some subhorizontal planar stratification and may have inverse or normal grading (Leatherman & Williams 1977; Morton 1979; Schwartz 1982; Tuttle et al. 2004; Switzer & Jones 2008a). The number of layers or lamina sets inherently depends on the thickness of the deposit and there is often no clear correlation between the number of layers within a bed and the number of waves either for tsunami or storm deposits (Morton et al. 2007).
The presence of plane-parallel lamination or plane bedding in deposits gives clues to the dynamics of sedimentation. The presence of parallel or flat bedding in sandy sediments is often presented as evidence of deposition by a strong unidirectional, turbulent, high velocity flow (Bridge & Best 1988; Cheel 1990; Tucker 2001; Fielding 2006). At many localities along the southeast coast of India, sandy tsunami deposits exhibit planar-parallel lamination occasionally throughout the entire deposit, but more often in the lower and upper parts of the deposit where the plane bedded units often confine beds of massive or graded fine- to medium-grained sand. The presence of these beds is thought to be indicative of upper flow regime (UFR) plane bedding during period of high velocity, turbulent flow. The grain size range of the planar-parallel laminated deposits studied here indicate that the mean grain size is generally between 1.5 and 2.8 φ (Figs 5, 7 & 8). UFR plane bedding is often the result of unidirectional high velocity flows. Although plane bedding is a common sedimentary feature in modern depositional environments, the physical conditions and hydraulic process that form plane beds under UFR conditions remains poorly understood (Fielding 2006). Some suggest that the dominant controlling factor is shallow flow depth (Smith 1971). In contrast, Paola et al. (1989) cited turbidites and deep fluvial channels as examples where UFR plane beds occur but flow depth is not a factor. In coastal settings plane or laminated bedding is found in storm deposits (Leatherman & Williams 1977; Sedgwick & Davis 2003; Switzer & Jones 2008) where it is attributed to repeated inundation by storm waves and not due to UFR high velocity turbulent flows. The presence of these laminated beds is peculiar within tsunami deposits and is most likely associated with UFR plane bedding at high velocities during the initial stages of shallow heavily sediment-laden flow.

**Deposition of the massive or graded facies (GMF).** In a recent review Morton et al. (2007, p. 202) stated that ‘most modern tsunami deposits consist of one layer or only a few layers or lamina sets’ and usually contain a sequence of less than five normally graded beds, citing references to studies by Nishimura & Miyaji (1995), Nanayama et al. (2000), Gelfenbaum & Jaffe (2003), Jaffe et al. (2003) and Tuttle et al. (2004). Morton et al. (2007) also suggested that extremely rapid deposition occurs when flow decelerates between the up-rush and back-wash phases of inundation, often resulting in single-layer, homogeneous and structureless tsunami deposits where inverse grading is rare. In contrast, Choowong et al. (2008a, b) suggested that the reverse grading found in tsunami deposits could be attributed to high grain concentration and mutual collisions among grains within a traction carpet or grain flow, as described by Hand (1997). Choowong et al. (2008a, b) suggested that reverse grading in tsunami deposits indicates a very high grain concentration within the tsunami flow. They theorized that this was possibly formed at the initial stages of inundation at a shallow water depth. This is consistent with the findings of this study, where a slight coarsening-up pattern is found in the lowermost parts of the GMF facies. Although the tsunami deposits do contain a structureless fine- to medium-grained sand unit, the presence of confining plane-bedded or laminated sediments or sediments exhibiting complex bedding or small channels suggest that tsunami sedimentation is significantly more complex than reverse grading followed by normal grading.

The massive (Figs 5–7) or slightly graded facies identified at Kallar is most probably due to settling from suspension during the final stages of inundation. In tsunami deposits, fining-up units have been recorded in many instances, and are attributed to deposition during periods when flow wanes and sediments drop out of suspension, often depositing fining-up units (Dawson et al. 1991; Dawson & Shi 2000; Gelfenbaum & Jaffe 2003; Dawson & Stewart 2007; Morton et al. 2007). In pits Kallar I and Kallar II, the GMF facies shows initial fining-up but then coarsens towards the top of the unit. This may reflect a slight increase in flow strength and shear stress as the runout sequence begins.

**Deposition of runout facies (ROF).** The final facies identified in the tsunami deposits of the SE Indian coast is the runout facies. This facies is thought to be deposited during the final stages of tsunami inundation and is identified as two sandy facies. The first exhibits complex bedding that often has small channels that have incised and reworked the upper boundary of the underlying unit. The lower contact of this unit rests unconformably on the erosional boundary and is defined by a thin prominent bed that has a higher proportion of heavy minerals (Fig. 5a). Complex bedding is recorded above this boundary with poorly defined cross-bedding, and is attributed to channelization of the flow during the final stages. The second subfacies, is a planar laminated unit that occurs at the base of the unit in Kallar I. This subfacies is attributed to a return to UFR plane bedding as the area drains by sheet flow. It is likely that, where preserved, the UFR plane bedded subfacies of the runout facies will be incised by the channelized flow subfacies during the final stages of flow.

**Bioturbation.** Considerable evidence was found in several areas along the SE Indian coast for
Fig. 9. Schematic model for the sedimentary processes, facies and bedform associations observed at sites of unidirectional flow under tsunami conditions on the SE coast of India.
bioturbation of the deposits from the 2004 tsunami. At Silver Beach, the excavated face SB-I (Fig. 3) shows significant bioturbation in the form of crab burrows up to 4 cm in diameter that are observed to mix sediments of the differing sedimentary layers. The crab burrows destroy bedding and are present as elongate structures in vertical profile, which shows obvious evidence of sediment mixing. Some bioturbation is also present in the faces of Kallar-II (Fig. 5), where bedding has also been destroyed and sediments appear to show considerable mixing. The identification of significant bioturbation features indicates that the preservation of these deposits may be problematic, reinforcing the point of Nichol & Kench (2008) who indicated that bioturbation is a significant issue when considering older deposits of unknown origin. When studying prehistoric tsunami deposits, bioturbation by animals and plants and other post-depositional modification due to extraneous factors such as groundwater movement must all be considered (Switzer & Jones 2008b; Nichol et al. 2010). It is possible that much of the bedding described in this paper will be destroyed over the next few years due to burrowing organisms and the re-establishment of vegetation.

**Depositional model.** The tsunami-deposited sediments at Kallar reveal a series of unique characteristics that allow the development of a modified depositional model for unidirectional tsunami washover on low-lying siliclastic coasts (Fig. 9). As tsunami strike the shoreline they experience very large growth in wave amplitude and very high velocity at the shoreface. Tsunami waves then inundate the coast causing rapid short-duration inundation and high shear stress and erosion. Sediments are mobilized from a variety of onshore and offshore environments during the high-energy passage of tsunami waves, and they can easily breach small coastal dune systems and carry sediment into the coastal plain. It follows that the internal sedimentology of any washover deposits on the coastal plain will, at least in part, reflect the conditions of the source area immediately preceding the depositional event. The offshore sediments in the study area are predominantly siliclastic fine- to medium-grained sands with a relatively high (5–15%) component of heavy minerals, and the deposits of the 2004 tsunami share similar composition (Stephen-Pichaimani et al. 2008).

Complex bedding in tsunami deposits has been reported previously by Nanayama et al. (2000) and Nanayama & Shigeno (2006) but that was associated with back flow. The sites studied here allow the study of unidirectional flow, and provide clues to the changes in hydrodynamics as the tsunami inundates the landscape and runs towards topographical lows. Although initial tsunami inundation is known to be characterized by high velocity and unidirectional flow at the shoreline, surprisingly, UFR plane bedding has rarely been reported for tsunami deposits. It is also likely that sheet flow during the initial stages of tsunami runout may also deposit sediments under UFRs resulting in plane-laminated bedding. The final stages of tsunami runout will often involve the development of channelized flow. Such channels will often range from several centimetres to several metres in width and exhibit distinctive complex sedimentation patterns including the formation of small bars.

**Conclusions**

The facies and bedding features identified in the tsunami deposits of SE India indicate several key features about the dynamics of tsunami inundation on this coast. Analysis of the sediment composition indicates a dominance of marine sand, which suggests that a considerable proportion of sediments were carried from offshore during the tsunami. The presence of different bedding features allowed the study of flow regime and grading pattern variation in sites that experienced unidirectional flow. At these sites, the presence of laminated beds attributed to UFR plane bedding that confine graded or massive beds is of note. The laminated sequence shows that tsunami deposits can and do contain horizontally laminated beds, a feature of vital importance to palaeo-overwash studies. The laminated appearance is most probably related to periods of high shear stress during high-velocity flow that results in UFR plane bedding. Further analysis of other deposits may yield valuable information on the dynamics of tsunami inundation and the preservation of features that indicate changes in flow regime and flow conditions.

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References


SE INDIAN TSUNAMI DEPOSITS


