

Sedimentology of the December 26, 2004, Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya

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Received: 2 May 2006 / Accepted: 18 November 2006 / Published online: 14 December 2006
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Abstract The December 26, 2004 Sumatra tsunami caused severe damage at the coasts of the Indian ocean. We report results of a sedimentological study of tsunami run-up parameters and the sediments laid down by the tsunami at the coast of Tamil Nadu, India, and between Malindi and Lamu, Kenya. In India, evidence of three tsunami waves is preserved on the beaches in the form of characteristic debris accumulations. We measured the maximum run-up distance at 580 m and the maximum run-up height at 4.85 m. Flow depth over land was at least 3.5 m. The tsunami deposited an up to 30 cm thick blanket of moderately well to well-sorted coarse and medium sand that overlies older beach deposits or soil with an erosional unconformity. The sand sheet thins inland without a decrease of grain-size. The deposits consist frequently of three layers. The lower one may be cross-bedded with foresets dipping landward and indicating deposition during run-up. The overlying two sand layers are graded or parallel-laminated without indicators of current directions. Thus, it remains undecided whether they formed during run-up or return flow. Thin dark laminae rich in heavy minerals frequently mark the

contacts between successive layers. Benthic foraminifera indicate an entrainment of sediment by the tsunami from water depths less than ca. 30 m water depth. On the Indian shelf these depths are present at distances of up to 5 km from the coast. In Kenya only one wave is recorded, which attained a run-up height of 3 m at a run-up distance of ca. 35 m from the tidal water line at the time of the tsunami impact. Only one layer of fine sand was deposited by the tsunami. It consists predominantly of heavy minerals supplied to the sea by a nearby river. The sand layer thins landward with a minor decrease in grain-size. Benthic foraminifera indicate an entrainment of sediment by the tsunami from water depths less than ca. 30 m water depth, reaching down potentially to ca. 80 m. The presence of only one tsunami-related sediment layer in Kenya, but three in India, reflects the impact of only one wave at the coast of Kenya, as opposed to several in India. Grain-size distributions in the Indian and Kenyan deposits are mostly normal to slightly positively skewed and indicate that the detritus was entrained by the tsunami from well sorted pre-tsunami deposits in nearshore, swash zone and beach environments.

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Keywords 2004 Sumatra tsunami · India · Kenya · Sedimentology · Tsunami deposit · Grain size

Introduction

The December 26, 2004 Indian ocean tsunami dramatically increased the awareness of the global public that tsunami pose a serious threat to humans. This recognition, however, should not have come as a surprise. It is estimated that approximately 330,000 people died in 15

major earthquake triggered tsunami events on the coasts of the Pacific Ocean between 1293 and 1976 (Bryant 2001). A major tsunami occurred accordingly on average every forty-five years. The high number of victims indicates that these tsunami flooded considerable parts of the impacted coasts during run-up. It is therefore likely, and in some cases documented, that the tsunami left an imprint on the geological record of the affected coasts in the form of changes to the coastal morphology and sediment deposited onshore during run-up and return flow. Bourgeois et al. (2006) derived from Holocene tsunami deposits preserved at the coast of Kamchatka a frequency of more than five tsunami per 1000 years having been triggered north of the Kuril-Kamchatka trench alone.

Between 1992 and 2006, seven major tsunami occurred in the Pacific and eastern Indian oceans, notably in Indonesia at Flores 1992 and Java 1994, at Chimbote, Peru, 1996, Papua New Guinea 1998, Camaná, Peru, 2001, the December 26, 2004 Sumatra tsunami discussed in this contribution, and at Pandangaran, Java, Indonesia in July 2006. All of them left behind onshore tsunami deposits. This tsunami frequency corresponds to an averaged recurrence interval of only two years.

The high number of historical and recent tsunami along the coasts of the Pacific Ocean suggests that sediment-depositing tsunami are quite a common feature in ocean basins containing significant lengths or numbers of subduction systems. Recalculated in terms of geological time scales, the historical examples (Bryant 2001) amount to a rate of more than 22,000 sediment-depositing tsunami per million years. The recent examples would indicate a rate of 500,000 sediment-depositing tsunami per million years. As a first approximation, the former can be considered a minimum rate, the latter a maximum rate.

It is therefore of paramount importance to realize not only in countries bordering the Pacific and Indian oceans that tsunami pose an everyday threat to coastal civilization (Bryant 2001; Jaffe and Gelfenbaum 2002; Borrero et al. 2005). The study of tsunami deposits, even though their preservation potential is somewhat limited, is the only means by which the historical and geological tsunami record of a coast can be reconstructed to establish the long-term hazard risk (e.g., Jaffe and Gelfenbaum 2002; Bourgeois et al. 2006).

Introduction to tsunami deposits

The December 26, 2004, earthquake of Sumatra and the resultant large tsunami drew renewed attention to

the fact that processes connected to tsunami run-up and return flow are still poorly understood (e.g., Hindsen and Andrade 1999; Goff et al. 2001). Studies of recent onshore tsunami sediments immediately after they were deposited have given insights into the original sedimentological features of such deposits (Bourgeois et al. 1999; McSaveney et al. 2000; Gelfenbaum and Jaffe 2003; Jaffe et al. 2003). This is of particular importance because: (1) the sedimentary features directly reflect the hydrodynamic regime immediately prior to deposition, and (2) the obtained data help in recognizing ancient tsunami deposits as evidence of a more extensive past tsunami record. However, even though the literature on tsunami deposits is growing rapidly no tsunami facies model can yet be distilled from the accumulating sedimentological evidence.

Depending on the grain sizes available on shelves and beaches, and the run-up characteristics of the tsunami, a wide range of depositional features can be observed in onshore tsunami deposits. They are commonly thin; thicknesses of over 30 cm are rare. They can consist of extensive sandsheets (Dawson and Smith 2000), more restricted layers of mud associated with sand (Goff and Chagué-Goff 1999) or of strings of boulders several metres across that have come to rest on floodplains or beaches tens to hundreds of metres inland from the swash zone (Paskoff 1991; Dawson 1994; Heartley et al. 2001; Scheffers 2002; Morhange et al. 2006; Mastronuzzi and Sansò 2004; Mastronuzzi et al. 2006). Deposits are usually massive or parallel-laminated. Cross-bedding was seen as being restricted to return-flow sediments (Nanayama et al. 2000). Only a few cases are known where run-up and return flow deposits can be distinguished (Dawson et al. 1996; Nanayama et al. 2000; Goff et al. 2001).

Considering offshore tsunami deposits, marine environments below the wave base of severe storms are theoretically much more likely to preserve tsunami deposits than shallow settings (Weiss and Bahlburg 2006a). There are only a few descriptions of marine, and particularly subtidal tsunami deposits (Pratt 2001, 2002; Bussert and Aberhan 2004; Cantalamessa and Di Celma 2005; Schnyder et al. 2005).

In the past decade, studies increasingly focussed on modern tsunami and tsunami deposits directly in the aftermath of the tsunami incident. Notably the Indonesian 1992 Flores and 1994 Java tsunami (Shi et al. 1995; Dawson et al. 1996), the Chimbote 1996 tsunami (Bourgeois et al. 1999), the 1998 Papua New Guinea tsunami (McSaveney et al. 2000; Gelfenbaum and Jaffe 2003), and the 2001 Peru tsunami at Camaná (Jaffe et al. 2003) provided first-hand data on geometries,

sedimentary structures and grain-size trends of the resulting deposits along coasts dominated by siliciclastic sediments. Those studies showed that many deposits display fining-upward trends in individual sandy layers, and overall fining-inland trends in sheet-like deposits.

Grain size and spatial distribution of tsunami deposits are commonly the only parameters available to infer the magnitude of fossil tsunami. Actualistic studies therefore are of paramount importance: (i) in defining and interpreting the characteristics of a tsunami; (ii) in quantifying the natural hazard for future vulnerability studies; and (iii) by providing analogues for recognizing tsunami sediments in ancient successions and estimating the nature of past tsunami.

Storm deposits, as further examples of high-energy event deposits, are characterised, for example, by hummocky cross bedding (Aigner 1985; Nanayama et al. 2000; Jaffe et al. 2006). The recognition of tsunami sediments is hampered by the apparent absence of unique sedimentary structures or other unequivocal tsunami features. In many cases tsunami sediments are only interpreted as such because of their occurrence in coastal plain soil or peat profiles as “exotic” intercalations often rich in shell debris of marine organisms (Clague and Borbrowsky 1994; Cisternas et al. 2000, 2005; Dawson and Smith 2000; Nanayama et al. 2000; Moore 2001; Peters et al. 2001). Furthermore, tsunami commonly both advance farther inland over coastal plains and inundate larger areas than storm waves (e.g., Tuttle et al. 2004).

The key parameters defining the characteristics of a tsunami impacting on a shore are the sublittoral and coastal morphology, run-up heights and distances, flow

depth over land and the type and distribution of sediments eroded and redeposited during run-up and inundation. Consequently these are the parameters determining the natural hazard threatening coastal civilisation (Synolakis and Okal 2005). Run-up is determined by the wave-length and amplitude of the tsunami, and by the bathymetric profile of the sublittoral shelf and slope regions across which the tsunami is approaching the coast (Heinrich et al. 1997; Bourgeois et al. 1999; Tappin et al. 2001; Weiss et al. 2006). Consequently, run-up heights, distances and flow depths of inundation can vary significantly along a shoreline. For example, run-up heights on the west-coast of Banda Aceh, northern Sumatra, which was hit by both the December 26, 2004 earthquake and the tsunami, varied between 5 and 32 m along distances of only tens of kilometres (Yalciner et al. 2005).

To determine the run-up parameters of the Sumatra tsunami and to study the deposits laid down by it we selected coasts of the Indian ocean in intermediate (India) and large distances (Kenya) from the source that were not noticeably affected by the earthquake itself. Because the sublittoral seafloor morphology significantly influences the run-up of a tsunami and local interferences and modifications are minor at ocean margins with ramp-like bathymetrical profiles and straight coastal morphologies of low relief, we consider the tsunami deposits along such coasts to best reflect the original tsunami characteristics. These criteria are met by the coasts of eastern India between Chennai and Pondicherry (Fig. 2), and by the Kenyan coast north of Malindi that is not sheltered by reefs (Fig. 3; Weiss and Bahlburg 2006b). An obvious target in northeastern Africa would have been the coast of

Fig. 1 Map of the Indian Ocean with the epicentre of the tsunami-producing earthquake

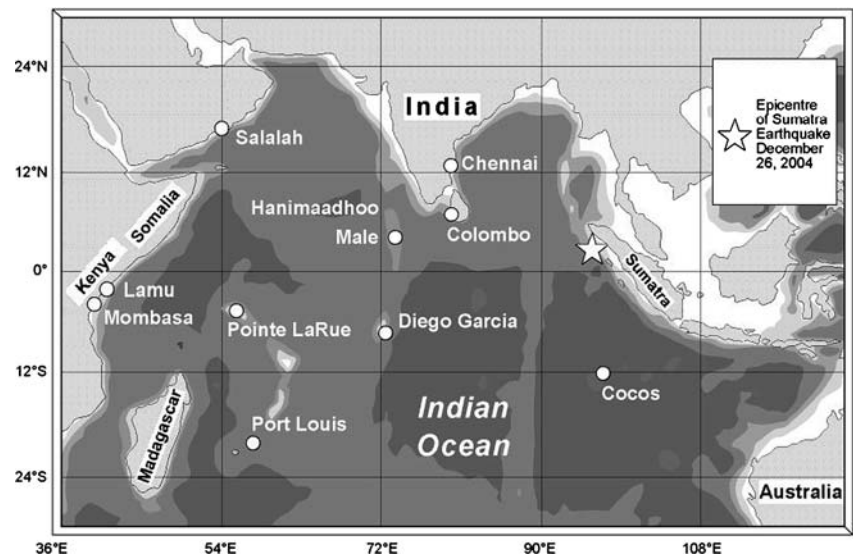
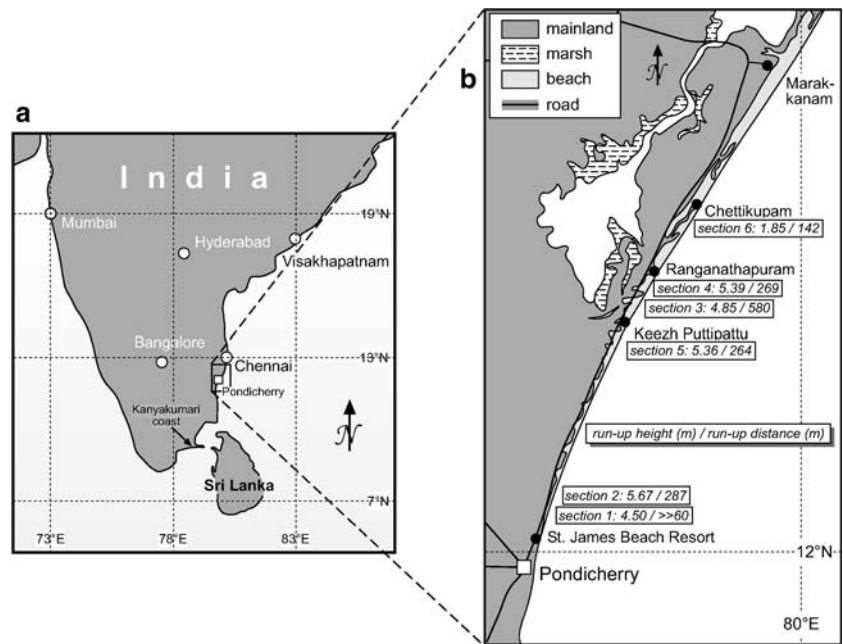


Fig. 2 **a** Southern India, and **b** Chennai to Pondicherry area and locations of sections. The boxed values indicate maximum run-up height and run-up distance in (meter)



Somalia, which suffered the severest tsunami impact (Fig. 1; Fritz and Borrero 2005). However, for reasons of personal security we were advised against traveling there.

In February and March 2005 we measured run-up characteristics of the December 26, 2004 Sumatra tsunami and sampled the tsunami deposits along beach sections in the southern Indian Tamil Nadu province north of Pondicherry at approximately 12°N (Fig. 2), and in Kenya north of Malindi on the Ngomeni peninsula at approximately 3°S (Fig. 3). We use our field data and grain-size analyses to elucidate the dynamic relationship between tsunami run-up and sedimentation.

The December 26, 2004 Sumatra tsunami

The December 26, 2004 Sumatra tsunami was caused by a magnitude 9.3 earthquake off the coast of northern Sumatra (Fig. 1; Stein and Okal 2005), which released its energy along a 1,200–1,300 km long fault in the Burma plate. Rupture propagated northward in the course of approximately 8 min with a speed of 2.8 km s⁻¹ (Ishii et al. 2005). Vertical slip on the rupture fault averaged 13 m (Ni et al. 2005). The resulting tsunami was global (Titov et al. 2005) and caused severe life loss and physical damage along the coasts of the Indian Ocean (Alovisi et al. 2005).

The Chennai tide gauge recorded the arrival of the tsunami at 9:05 AM local time (= 3:25 UTC, Coordinated Universal Time), shortly after high tide. The

tsunami wave had a tide-corrected height of 2 m (Fig. 4). The Lamu tide gauge north of Malindi recorded the arrival at 1300 hours local time (= 1000 hours UTC) during rising tide. The tide-corrected wave height was almost 1 m (Fig. 5; Merrifield et al. 2005).

At the coast of Tamil Nadu in southeastern India the tsunami inflicted a death toll of ca. 3,000 persons and displaced ca. 80,000. In the region of Pondicherry loss of life was close to 400, and ca. 30,000 were displaced (The Hindu 2004). In Kenya, one person drowned.

Results

We obtained our data by measuring sections perpendicular to the swash zone using a Leica NA730 level. We measured flow depths, run-up heights and distances according to Synolakis and Okal (2005) on sections perpendicular to the swash zone. Along the profiles we dug 0.5–1 m deep pits and trenches through tsunami deposits and the upper parts of the underlying beach sand or soil at regular distances, usually every 10 m. At each locality we sampled the tsunami deposits. If more than one layer was present, we sampled each individual layer.

For the grain-size analysis we used sieves with mesh sizes from 4 mm ($\phi-2$) to 0.063 mm ($\phi+4$) and with mesh-size distances of 1. Some 300 g of each sample were dry-sieved automatically for 10 min. Sieve fractions were weighed to 0.01 g precision. Statistical

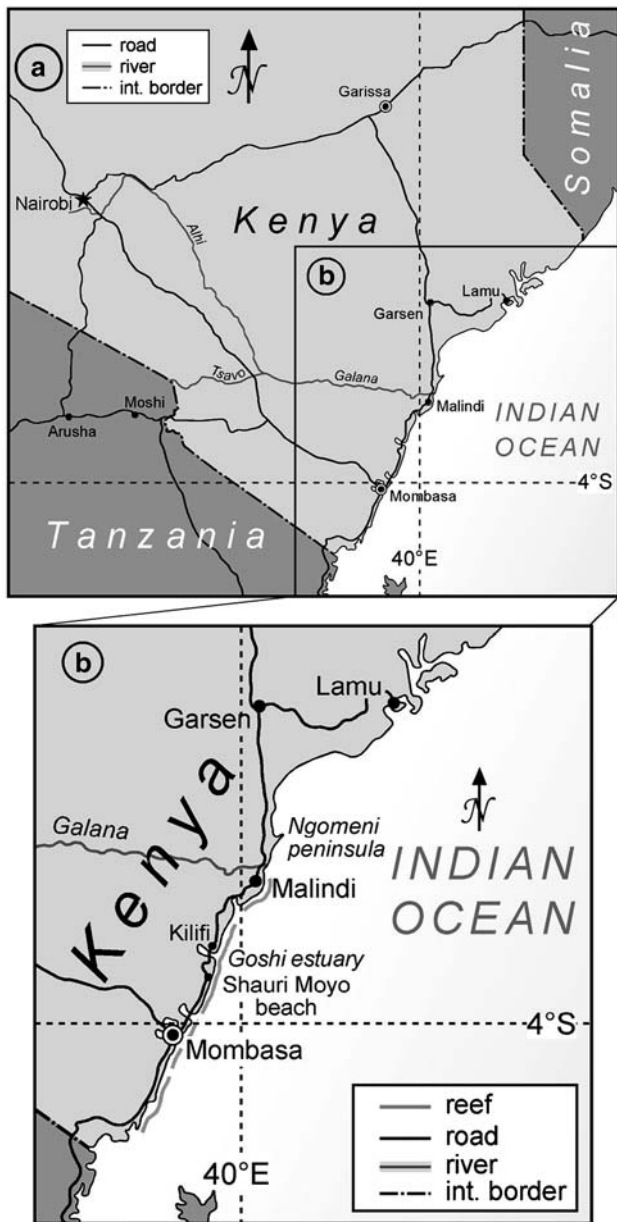


Fig. 3 **a** East Kenya, **b** Mombasa to Malindi area and location of the Ngomeni peninsula

analysis of the grain-size data was performed using the formulas given in Folk and Ward (1957).

India: run-up and sedimentology

The coast north of Pondicherry in southeastern India is of low relief and is characterised by wide and straight beaches (Figs. 2, 6a). Fence posts, shrubs and palm trees were in many cases bent inland by the advancing tsunami (Fig. 6b). The bark of some of the palm tree stems were abraded on seaward-facing sides. Flow depth was recorded both on the vegetation and by thin

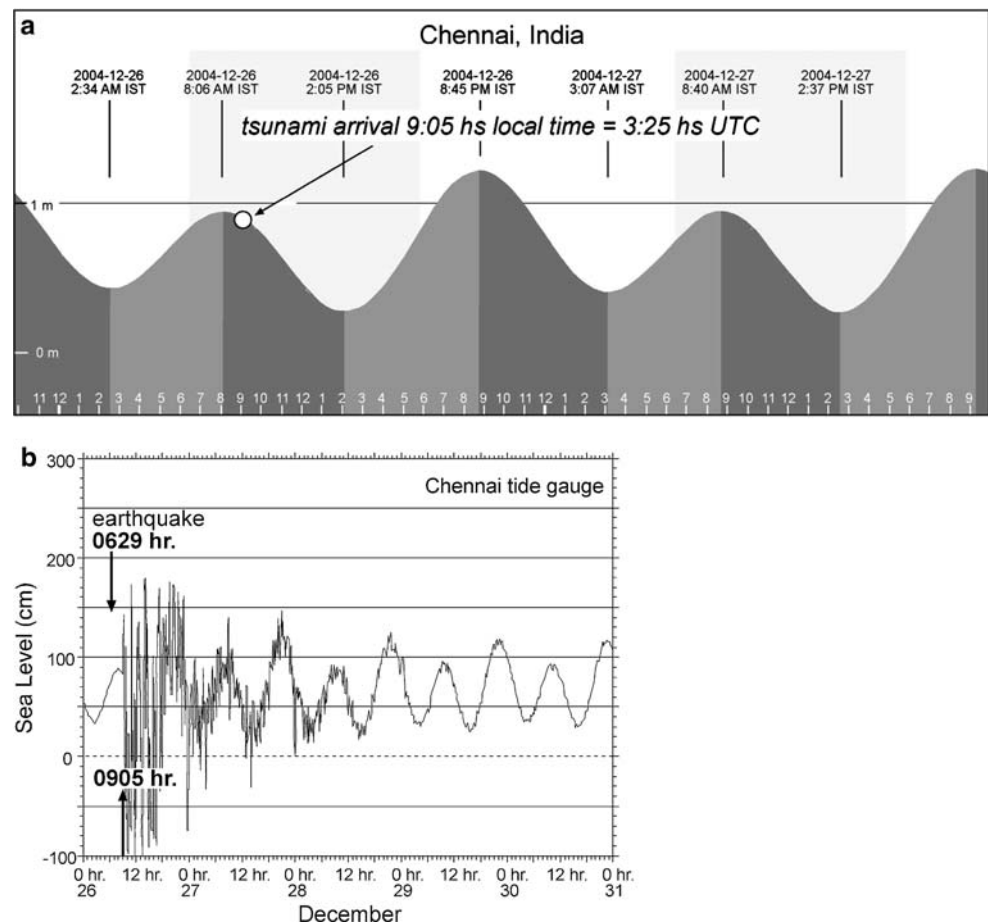
lines of mud, indicating the water level, on the walls of buildings (Fig. 6c). In other cases local villagers indicated the height of inundation (Fig. 6d). Between 100 and 200 m inland from the swash zone, loose groups of palm trees of the species *Borassus flabellifer* grow on the beach. The minimum flow depth of inundation was indicated on most palm trees by brown discolorations of leaves that had been under water. The highest value of the minimum flow depth measured here was 3.5 m (Fig. 6e, f). Watermarks indicated a decrease of flow depth towards maximum run-up.

The position of maximum run-up heights and distances were indicated by displaced fishing boats and accumulations of plant debris and waste (Fig. 7a). At two localities in Ranganathapuram and in Chettikupam we found evidence of the run-up of three waves, in the others indications of only one wave were preserved. As recorded by section 3 at Ranganathapuram, at least two minor waves following the major one left accumulations successively closer to the swash zone (Fig. 7b, c). The three lines of run-up are located at 580, 350 and 130 m (Figs. 2b, 8). At the steeper coast at Chettikupam, three lines of run-up are preserved at 142, 115 and 50 m. Return flow occurred as distributed sheet floods (Fig. 10), or as localised currents in erosional gullies and creeks (Figs. 7d, 9).

On the coast north of Pondicherry large parts of the beach surfaces inland of ca. 50 m from the swash zone are loosely covered by grass runners forming an open network of rootlets (Fig. 10). Near the swash zone the grass runners are covered by sand deposits of usually less than 30 cm thickness, which were only superficially disturbed by foot prints when we sampled (Fig. 11a). The covering sand layers commonly have erosive bases cutting into weathered, reddish to brown-coloured beach soil including rootlets, or older beach sands (Fig. 11b–e). The contacts are frequently marked by buried grass runners. In view of the absence of significant storms after the Sumatra tsunami impacted the Indian coast and before the field work, these field relations lead us to interpret the fresh sand deposits as having been deposited by the Sumatra tsunami.

The Sumatra tsunami left behind sheet-like sand deposits, which taper out landward at a little more than approximately half the distance to maximum run-up. Figures 8 and 12 are representative examples of the several hundred metres long sections 3 and 4 at Ranganathapuram (Fig. 2), sections 1 and 2 north of Pondicherry (Fig. 2) that are shorter than 100 m, respectively. The observed tsunami deposits consist of one to three layers of sand. In particular the distribution of the lower layers is patchy, probably as a function of the beach morphology.

Fig. 4 **a** Chennai (Madras) tides and timing of tsunami impact (<http://www.mobilegeo.graphics.com:81/locations/3522.html?y=2004&m=12&d=26>); **b** The record of the Chennai tide gauge for five days following the tsunami. *IST* Indian Standard Time



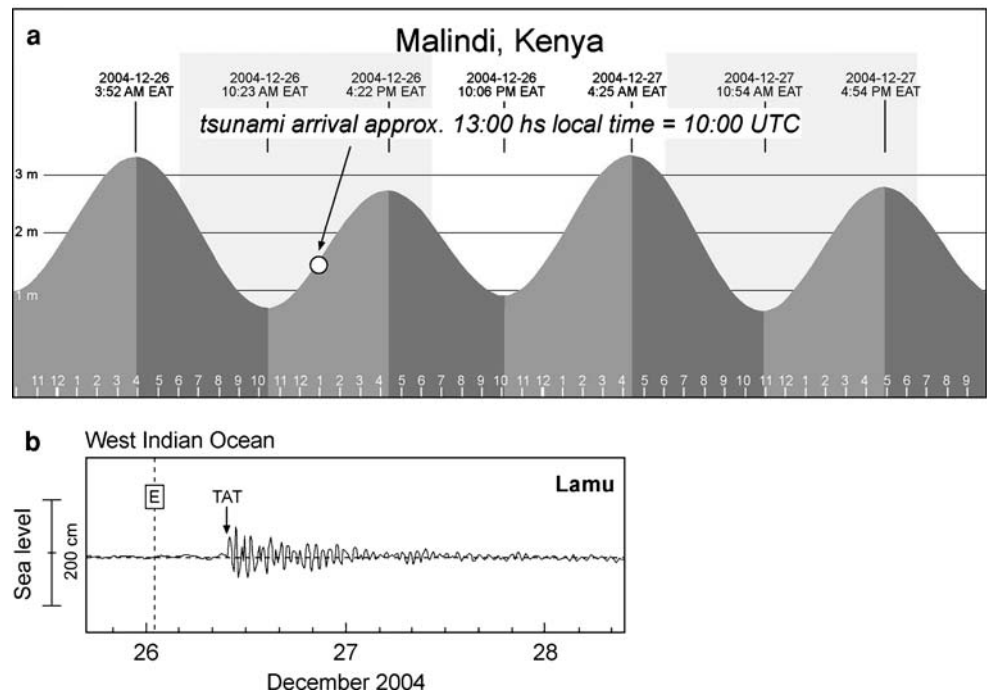
The lower sand layer displays, if present, a faint to distinct cross-bedding in several sample pits in the first 50 m from the swash zones along the Ranganathapuram sections (Figs. 2, 11). All foreset measurements indicate inland flow thus identifying these layers as having been deposited during tsunami run-up (Fig. 11b–d). The layers without cross-bedding have a massive appearance and may be normally graded. Some are faintly parallel-laminated. Successive layers are usually slightly finer grained (Figs. 8, 12, 13). Thin dark laminae rich in heavy minerals frequently mark the contacts between successive sand layers (Fig. 11b–d). Grass runners lying on top of some inner beach surfaces were oriented seaward by return flow of the last tsunami wave on this part of the beach (Fig. 10).

The sands are moderately well to well sorted and have a unimodal grain-size distribution with median phi-values between 0.5 and 1.5 (Figs. 8, 12). This is equivalent to grain-sizes of between 0.7 and 0.35 mm, pointing to a dominance of the medium to coarse sand fraction. The grain-size distributions are mostly mesokurtic to leptokurtic and normal to slightly positively skewed indicating a minor excess of fine particles in the

latter (Fig. 13; Folk and Ward 1957; Friedman 1979). Small variations are present in thickness and grain-size distributions within sections as well as between sections.

Along section 1 there is not much variation in grain-size parameters (Fig. 12, 13). There is an inland tendency to an excess of finer particles producing a positive skew of the grain-size distribution. Section 3 (Figs. 8, 13) shows an initial fining inland trend between section metres 20 and 30 and then a mild fluctuation around a phi value of one. The skewness tends to negative values, i.e. a minor excess of coarse grains, over the first ca. 50 m of the section and then stabilizes in the field of symmetry. Interestingly, along this section, sorting becomes slightly poorer further inland. The grain-size distributions fluctuate between platy-, meso- and leptokurtosis. The individual layers of the three-layered sample at section metre 20 are successively finer-grained. The basal layer is positively skewed, the middle one almost normal and the top one slightly negatively skewed. Along the section, the grain-size distribution goes on average from a mild negative skew to a normal one with a tendency to a

Fig. 5 **a** Malindi tides and timing of tsunami impact, *EAT* East Africa Time (<http://www.mobilegeo.com:81/locations/3557.html?y=2004&m=12&d=26>); **b** Lamu tide gauge, tide-corrected, *E* earthquake, *TAT* Tsunami Arrival Time



positive skew. Generally, the grain-size distributions are laterally uniform and do not show a fining inland trend.

The detritus constituting tsunami deposits is theoretically derived from three main sources, namely the sublittoral sea bottom, the beach, and the flooded coast inland from the beach. Sediment of the sublittoral sea bottom is entrained by a tsunami approaching the coast at some as yet undetermined water depth. Tests of benthic marine organisms, and benthic foraminifera in particular, preserved in the tsunami deposit represent a means to determine at least the minimum water depth of sediment and test entrainment.

The incorporation of older beach sands into the tsunami is indicated by the erosive contacts between the tsunami sheet sands and the older beach deposit (Fig. 11b, c). Some input from mainland sources is indicated by a characean oogonia typical of fresh water environments.

A small number of benthic foraminifera is present in most of the samples. Many tests are significantly abraded and damaged. Some steinkerns are present. This indicates that those specimens had been reworked for some time before deposition on the beach. Pristine tests include several species of *Ammonia* and *Elphidium*, which occur in shallow, protected shelf regions of the Indian Ocean in water depths of less than 30 m (Murray 1991). Our data correspond to those of Rao and Charles (2005) who observed foraminifera that live in at least 18 m water depth in tsunami sands at the coast north of Chennai. Because such depths occur at

an offshore distance of 4–5 km we conclude that the Sumatra tsunami entrained sediment only in shallow marine water depths, which extended, however, to several kilometres' distance from the coast.

Kenya: run-up and sedimentology

Large parts of the coast of Kenya are protected by a reef belt paralleling the coast at distances of some hundreds of metres (Figs. 3, 9a). North of Malindi, the combination of sediment input by the Galana river and coast-parallel northward currents formed the spit of the Ngomeni peninsula, which is not protected by reefs (Fig. 3b). Here the beaches are more strongly inclined than in Tamil Nadu (Figs. 6, 9). The run-up of one tsunami wave is recorded by debris accumulations at a maximum of ca. 45 m from the tidal water line and in front of a dune (Figs. 9b, c; 14). Maximum flow depth was approximately 3 m. Behind the protective barrier of the reef, beaches suffered only minor tsunami effects. In one representative example the beach was inundated up to a height of 0.70 m and the water penetrated laterally 3 m onto the beach (Weiss and Bahlburg 2006b).

Also at NgAAlso at Ngomeni, the Sumatra tsunami left behind sheet-like sand deposits that extend over the entire but narrower beach to the maximum run-up line (Fig. 14). The sandy deposit is well-sorted and consists of two layers only near the swash zone. The lower layer is limited to the zone proximal to the swash zone, probably as a function of the beach morphology.

Fig. 6 Coast morphology and run-up indicators. **a** General view of beach near Ranganathapuram; **b** shrub bend inland; **c** water-level marks on buildings at Chettikupam, *Arrow* indicates highest level; **d** waiter indicating a flow depth of approximately 2 m at the St. James Court Beach Resort, Pondicherry (see also Fig. 12e, f) discoloured palm trees of the species *Borassus flabellifer* at section 3, Ranganathapuram. *Arrows* indicate height above which trees are not discoloured. Person for scale is 1.75 m tall



Fig. 7 Debris accumulations marking the run-up of at least three tsunami waves near Ranganathapuram (section 3); **a** maximum run-up marked by a displaced fishing boat; **b**, **c** run-ups of a second and third wave. The concrete blocks in **c** were very likely deposited by the return flow of a previous wave; **d** creek and erosional return flow gullies. Note shrubs bent inland and discolored trees in the distance

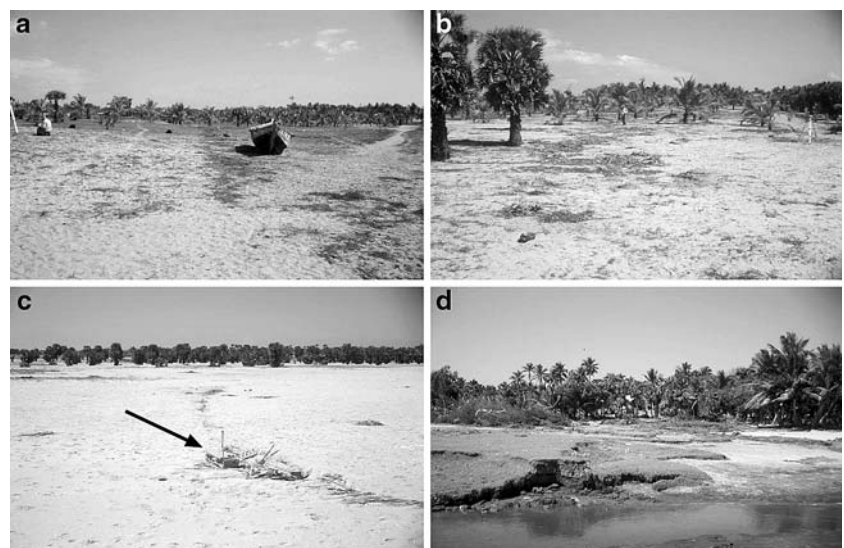
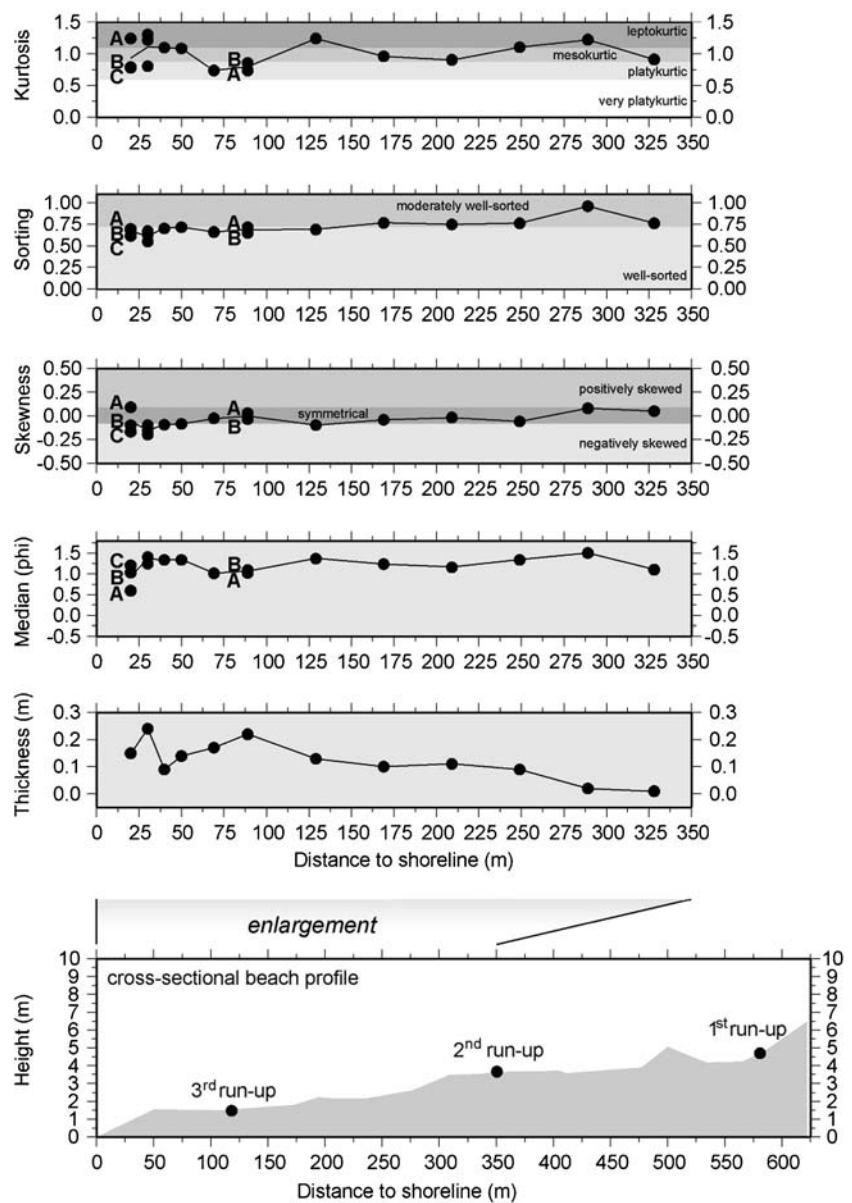


Fig. 8 Ranganathapuram, India, section 3. Synoptical diagram of the cross sectional beach profile, sample locations, run-up positions, thickness of the tsunami deposit and grain-size parameters. The *black lines* represent mean values. The letters *A* and *B*, and *A, B, C* indicate samples of successive layers labelled from bottom to top. Labelling is valid in the same manner for unlabelled twofold or threefold samples



The entire deposit has a maximum thickness of 20 cm landward of the swash zone, which decreases to 8 cm over the next 4 m and then tapers off towards the run-up line (Fig. 14).

The tsunami deposit is dark-coloured and rich in heavy minerals but may contain light-coloured laminae (Fig. 11e). The heavy minerals were most likely derived from abundant placer accumulations on the tidal flat and originally were delivered to the sea by a nearby river and the Galana river to the south (Fig. 3b). The parallel-laminated layers do not contain any current indicators. It is thus unclear whether they formed during run-up or return flow. Large gastropod and oyster shells floated to maximum run-up (Fig. 11f).

The tsunami deposit of the Ngomeni section consists of fine sand, is well sorted and thins inland (Fig. 14). As the lower layer of the deposit tapers off over the first five metres of the recorded section, it is the upper layer that extends up to the run-up line. It shows an increase of the median values from 2.1 to 2.4 and then decreases to 2.2 at the run-up line. The grain-size distribution is normal and varies between leptokurtic and platykurtic.

The Kenyan samples contain abundant tests of benthic foraminifera, which the tsunami deposited together with the mineral grains. Bathymetrically indicative pristine tests include several benthic species of *Quinqueloculina* and *Spiroloculina* belonging to the

Fig. 9 Kenya, **a** run-up debris on the reef-protected Shauri Moyo beach; **b** Ngomeni beach, unprotected by reefs, at low but rising tide as at the time of the tsunami impact; **c** Ngomeni beach, debris accumulations marking maximum run-up



Miliolidae which typically occur in shallow and protected shelf regions in water depth of less than 30 m. Also present are several species of *Amphistegina* including *Amphistegina lessonii* D'Orbigny which may occur down to water depths of 80 m (Murray 1991). They indicate that the tsunami very likely entrained most of the sediment in shallow depths of less than 30 m. However, an additional entrainment in depths less than 80 m seems to be possible.

Discussion

In several aspects, the observed deposits on the beaches of India and Kenya are similar to sandy siliclastic tsunami deposits recorded at several localities in the Pacific and Indian oceans, including Camaná at the

coast of Peru and Papua New Guinea after their respective tsunami in 1998 and 2001 (Gelfenbaum and Jaffe 2003; Jaffe et al. 2003). At Camaná, sandy deposits show a parallel layering as well as the presence of thin heavy-mineral concentrations at the base of individual sand layers. Normal grading within individual layers as well as a grain-size decrease between successive layers is present and also observed in several other tsunami deposits on sand-dominated coasts (McSaveney et al. 2000; Goff et al. 2001, 2004; Gelfenbaum and Jaffe 2003; Jaffe et al. 2003; Bourgeois et al. 2006).

Another feature common to many tsunami deposits and present in the studied sediments both in India and in Kenya is the erosive contact to the underlying beach sand or soil (e.g., Goff et al. 2001; Gelfenbaum and Jaffe 2003). Because the underlying beach and soil deposits are sandy, we did not observe any muddy rip-up clasts which are characteristic of the deposits at Camaná, for example (Jaffe et al. 2003).

At the Kanyakumari coast in southernmost southeastern India (Fig. 2), Chandrasekar (2005) described erosion of up to 2 m over large tracts of beach which he referred to the return flow of the Sumatra tsunami. In that area, the tsunami penetrated up to 1.5 km inland and the flow depth reached ca. 10 m. In comparison to the Pondicherry coast, the comparatively larger force of the tsunami at the Kanyakumari coast is indicated by the redeposition of boulders and the formation of pebble-sized deposits associated with sand sheets.

Tsunami deposits typically thin landward (e.g., Goff et al. 2001) as do the studied deposits. Run-up distances derived from the distribution of tsunami deposits alone are very likely minima (Bourgeois et al. 2006). In India, the tsunami sediments taper off several

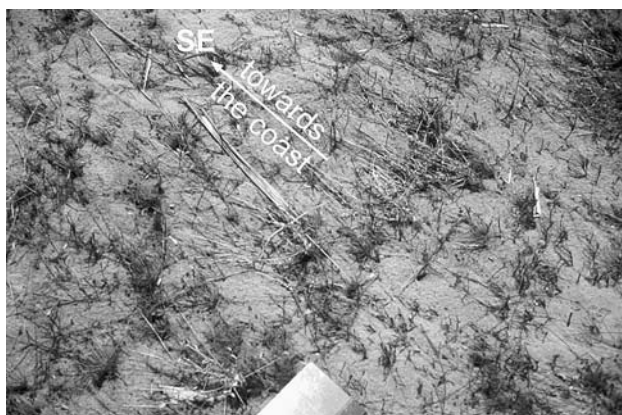


Fig. 10 Ranganathapuram, India, section 4. Loose network of grass runners covering an older inner beach surface. Note parallel orientation of plants caused by tsunami return flow. Note book is 21 cm long

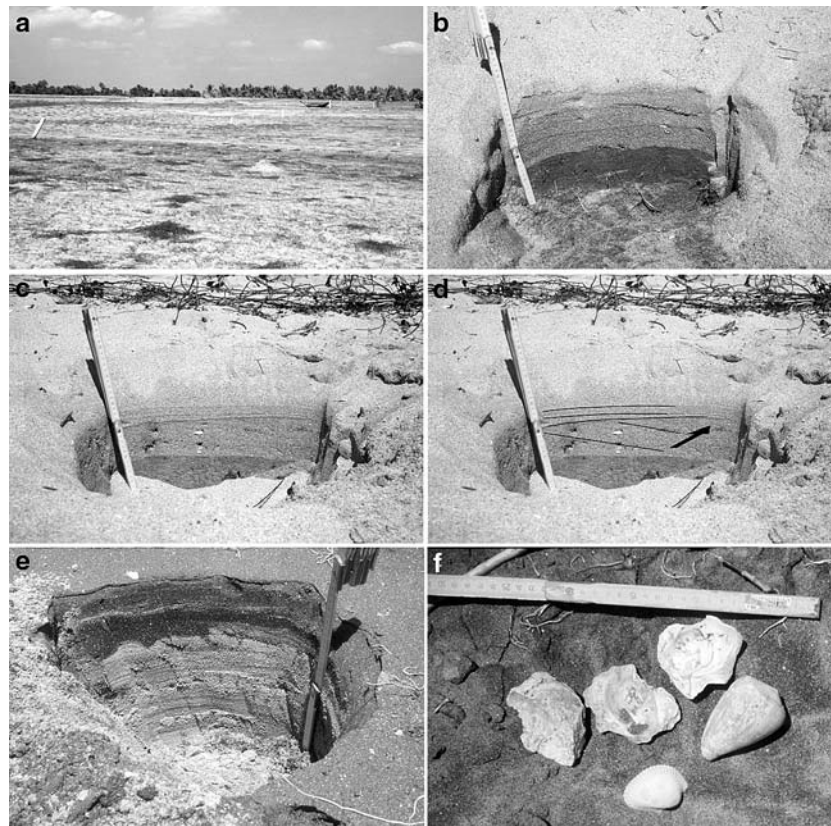


Fig. 11 **a–d** Near-coast area and tsunami deposits near Ranganathapuram, India; **a** grass runners on beach surface; fence posts turned inland by the tsunami; the fishing boat marks maximum run-up; **b** composite tsunami deposit with three parallel layers of sand erosionally overlying older beach soil with rootlets; 50 m inland from the swash zone, section 2 (Fig. 2b); **c, d** composite cross bedded and parallel-laminated tsunami sand erosionally overlying older beach deposit. Forsets

dip landward, the arrow in **d** indicates the current direction; 40 m inland from the swash zone, section 2 (Fig. 2b); **e, f** Ngomeni peninsula, Kenya; **e** black, dark heavy-mineral rich tsunami deposit overlying beach sand with erosional unconformity. It includes a lighter coloured lamina richer in light minerals, which is indicated by the *white arrow*; ca. 10 m from the swash zone; **f** gastropod and oyster shells transported to maximum run-up

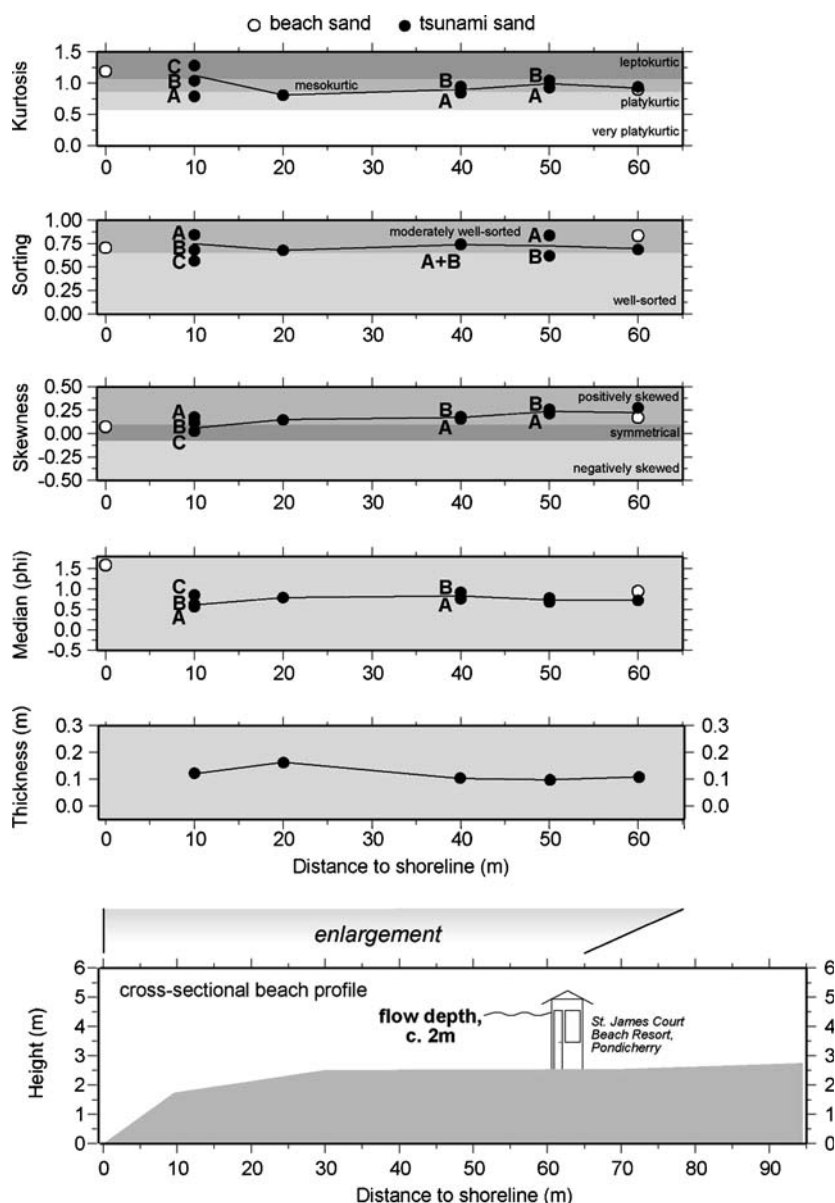
tens to hundreds of metres seaward of the maximum run-up position. In contrast to many other tsunami deposits (e.g., Goff et al. 2001; Gelfenbaum and Jaffe 2003), the studied Indian and Kenyan sediments do not show a fining inland trend.

The deposits have a unimodal composition of coarse to medium sand in India, and of fine sand in Kenya. The grain-size distributions are normal to slightly positively skewed, and mostly mesokurtic to platykurtic. This indicates that the grains constituting the sediment were derived from only one source, which supplied a well-sorted grain population (see Folk and Ward 1957; Friedman 1979), in the Indian and Kenyan cases of coarse to medium, and fine sand, respectively. In the context of the overall beach setting, and in view of the similar characteristics of the underlying beach deposits of both coasts (Figs. 8, 12, 14), it is most likely that the tsunami deposits are made up almost entirely of sediment grains of the pre-tsunami nearshore, swash

zone and beach deposits (Friedman 1961, 1979). It seems that the grain-sizes available for entrainment by the tsunami at the Chennai-Pondicherry coast were restricted to coarse and medium sand down to water depths of ca. 30 m, and to fine sand in water depths similarly less than 30 m at the Ngomeni peninsula in Kenya, as indicated by the re-deposited pristine tests of benthic foraminifera. However, the occurrence of *Amphistegina lessonii* D'Orbigny in the Kenyan deposits may indicate that sediment has been entrained in depths less than 80 m.

Run-up markers point to at least three tsunami waves inundating the Indian coast north of Pondicherry (Fig. 7). It is tempting to correlate the locally present threefold layering of the Indian deposits to each of these waves. This would be a premature conclusion as the three run-up markers are preserved on the beach surface, which theoretically should represent the top either of the uppermost of the three layers or of

Fig. 12 Synoptic diagram of the cross-sectional beach profile, sample locations, run-up positions, thickness of the tsunami deposit and grain-size parameters of section 1 at St. James Beach Resort, Pondicherry, Tamil Nadu, India (see also Fig. 6d). The black lines represent mean values. The letters *A* and *B*, and *A*, *B*, *C* indicate samples of successive layers labeled from bottom to top. Labeling is valid in the same manner for unlabeled twofold or threefold samples



the pre-tsunami inner beach. Because eyewitnesses in India mention at least five waves it is probable that the three identified and vertically stacked sand layers are the product of the first approaching waves and the run-up markers the result of the last three ones. This then would indicate a decrease in the energy of the successive waves.

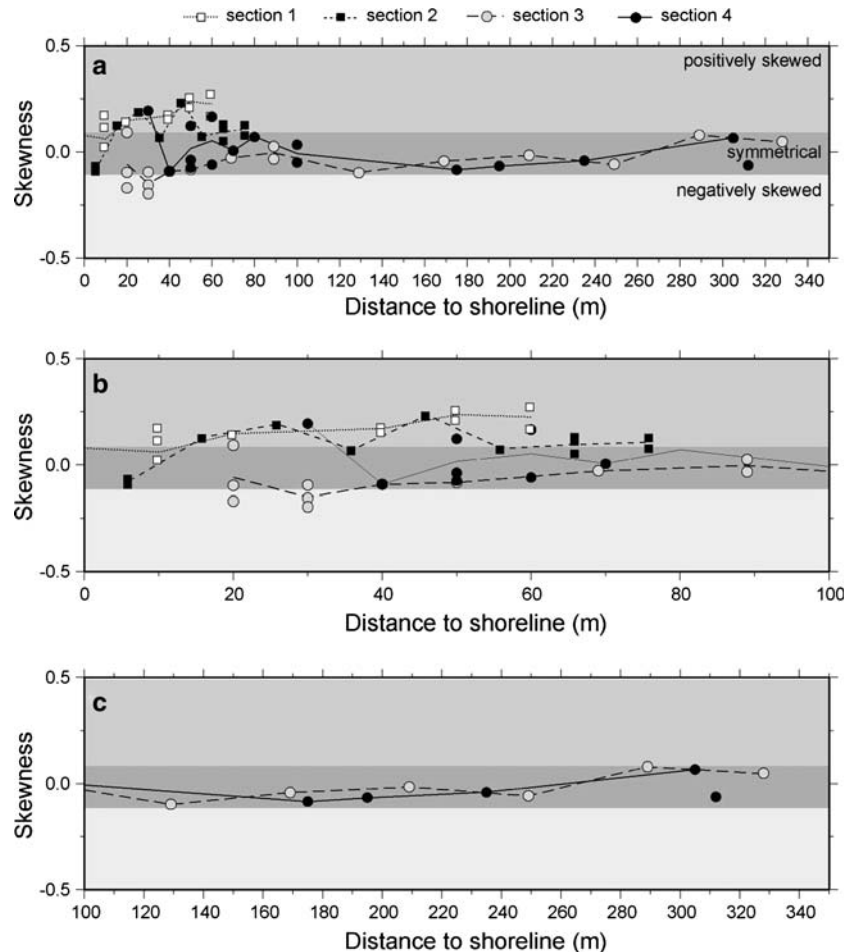
Cross-bedding demonstrates that at least some of the lower layers in India formed during tsunami run-up (Fig. 11c, d). In some cases elsewhere it has been possible to identify both run-up and return flow deposits (Goff et al. 2001). The Indian and Kenyan deposits did not provide evidence linking deposits to return flow, however, even though return flow indica-

tors are preserved in the alignment of grass runners on the beach surface (Fig. 10). Finally, we did not find any fundamental differences between the sandy tsunami deposits in India and Kenya.

Conclusions

The Sumatra tsunami of December 26, 2004 caused severe damage at the coasts of Sumatra and Thailand located in short distances from the source (Alovisi et al. 2005; Gelfenbaum et al. 2005; Yalciner et al. 2005), and also in intermediate distances in India and Sri Lanka (Yalciner et al. 2005), as well as in large

Fig. 13 Synopsis of the skewness values of the Indian sections 1, 2, 3 and 4 (Fig. 2). **a** Overview; **b** and **c** enlargement of **a** black lines indicate mean values along individual sections



distances at the coast of northeastern Africa, particularly in Somalia and less in Kenya (Fritz and Borrero 2005; Weiss and Bahlburg 2006b). At the Indian coast between Chennai and Pondicherry run-up markers indicate maximum run-up at almost 600 m from the coastline and run-up heights of over 5 m. The flow depth was at least 3.5 m. In Kenya the respective run-up heights and distances as well as the flow depth were considerably smaller.

The sediments deposited by the tsunami on the beaches of Tamil Nadu, India and north of Malindi in Kenya overlie older beach deposits or soils with an erosional unconformity. They form blankets of moderately well- to well-sorted sands, which thin inland and in India taper off at a little more than half way between the swash zone and maximum run-up. In Kenya they cover the entire beach up to the run-up line. In contrast to many other examples of sandy tsunami deposits, the sediments studied by us do not fine inland. The detritus constituting the deposits was most likely derived locally by reworking of pre-tsunami nearshore, swash zone and beach deposits.

The deposits may consist of up to three layers. The lower layer may be cross-bedded and formed during tsunami run-up. The overlying layers may be graded or parallel laminated. They do not contain sedimentary structures that permit the derivation of current directions. It remains therefore undecided whether they formed during run-up or return flow. Scarce but well preserved foraminifera tests indicate an entrainment of sediment by the tsunami from a protected shelf environment and water depths less than ca. 30 m. On the Indian shelf these water depths extend up to 5 km from the coast.

Acknowledgments This study was supported by grant Ba 1011/31-1 of the German Research Foundation (DFG). We thank S. Balakrishnan and S. Nathan, Department of Earth Sciences, Pondicherry University, India, for their generous support. T. Dobrzinski and A. Bisaccia, Münster, helped to process the samples. We thank E. Kuropka and M. Kaefer, Münster, for processing and studying the foraminifera, and M. Bertling, Münster, for knowing a lot about plants. The manuscript benefitted from the critical comments by C. Augustsson, Münster, and the reviews by B. Pratt, Saskatoon, and W.C. Dullo, Kiel.

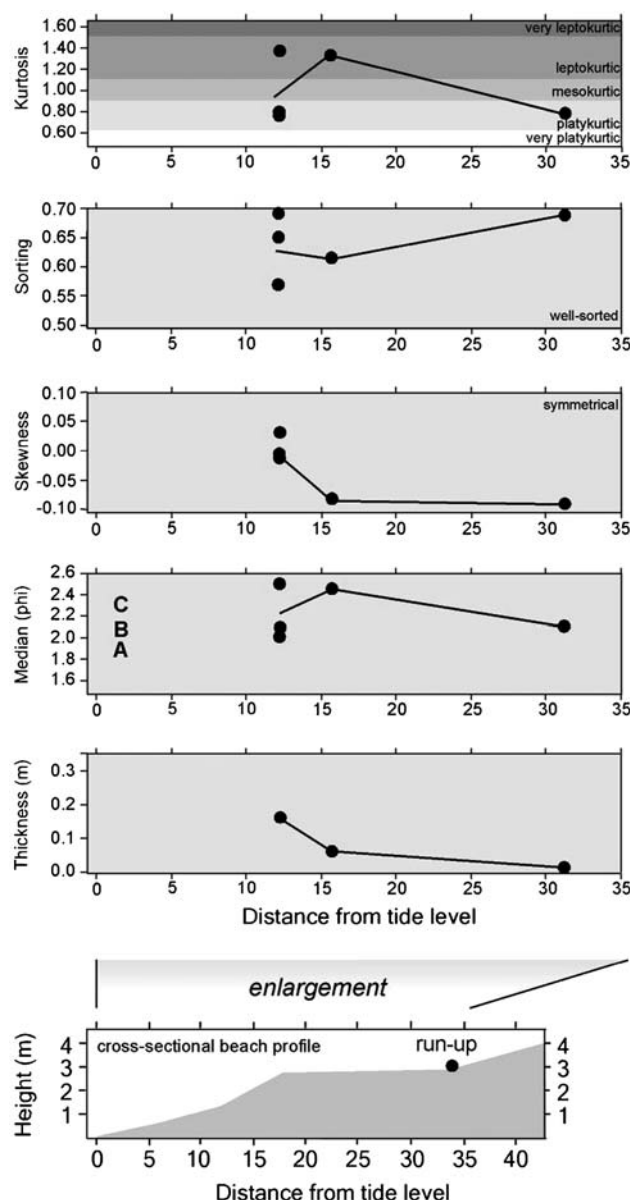


Fig. 14 Synoptical diagram of the cross sectional beach profile, sample locations, run-up positions, thickness of the tsunami deposit and grain-size parameters of the Ngomeni section on the Ngomeni peninsula, Kenya. The black lines represent mean values

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