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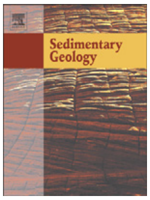

Thickness and grain-size distribution of the 2004 Indian Ocean tsunami deposits in Periya Kalapuwa Lagoon, eastern Sri Lanka

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ABSTRACT

In this paper we describe the sedimentary characteristics of the 2004 Indian Ocean tsunami deposits in and around Periya Kalapuwa Lagoon, Sri Lanka. Periya Kalapuwa is a coastal lagoon of about 13 km^2 area and has an average depth of about 1 m. It is separated from the Indian Ocean by coastal barrier sand dunes of up to 9-m elevation through which two inlet channels open the lagoon to the ocean. This region was hit by three waves during the 2004 Indian Ocean tsunami. The second wave was largest (4–6 m) and entered the lagoon not only via the two inlet channels, but also by flowing over the sand dunes. Erosive scars were found on the sand dunes adjacent to the two inlets. Twenty-seven core samples, along with trenching and hand-auger data, show that the tsunami deposits are 9 cm thick on average (up to 35 cm in the lagoon and up to 66 cm on the shore) and are composed mainly of medium sand (mean grain size 1.06 φ) with low mud content (0.61 wt.%), which is similar to the composition of sand from near the erosive scars in the sand dunes (mean grain size 0.94 φ), but different from the lagoon deposits (mean grain size 1.68 φ; mud content 4.7 wt.%). The distribution of the tsunami deposits was limited to within about 1 km from each inlet. The tsunami deposits become thinner and finer grained with increasing distance from the inlets. Most of the tsunami deposits are massive, but some show sedimentary structures: single or multiple-graded bedding structures, parallel laminations defined by layers of heavy minerals, and muddy laminations. Our observations and analyses suggest that the tsunami deposits were formed mainly from sand eroded from sand dunes near the two inlets. We estimated the total volume of tsunami sediments to be 83 000 m^3. By assuming that the sediments of the tsunami deposits were supplied only by erosion of sand dunes from near the two inlets, this is equivalent to erosion of 83 m^3 of sand per meter of sand dune traversed by the tsunami wave.

1. Introduction

Tsunami deposits have been reported in environments ranging from coastal lowlands to shallow and deep seafloors (e.g., deep-sea: Kastens and Cita, 1981; shallow-marine: Matsumoto and Masuda, 2004; Fujino et al., 2006a; lagoon and coastal lakes: Minoura and Nakaya, 1991; Bondevik et al., 1997; marsh: Atwater and Moore, 1992; Nanayama et al., 2003; coastal plain: Matsumoto et al., 2008; Fujino et al., 2009). In particular, tsunami deposits in otherwise quiet environments, such as marshes and lagoons, have been preferred in studies attempting to reconstruct the behavior and recurrence intervals of tsunamis, largely because marshes and lagoons are commonly adjacent to the ocean but are little influenced by sediment reworking by waves or rivers. Therefore, the preservation potential of undisturbed tsunami deposits in the geological record is greater in these environments.

Although there are a few studies of tsunami deposits in coastal lakes (e.g. Minoura and Nakaya, 1991; Bondevik et al., 1997; Kelsey et al., 2005), very little is known on modern tsunami deposits in large lagoons like Periya Kalapuwa Lagoon in eastern Sri Lanka. Bondevik et al. (1997) attributed multiple-graded tsunami deposits in core data from uplifted coastal lakes to successive tsunami waves generated by the Storegga Slide in the Norwegian Sea, and proposed a tsunami sedimentation model. Minoura and Nakaya (1991) described five sand layers in lacustrine and marsh sediments from northwestern

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Japan and related them to the 1983 Japan Sea Earthquake and other historical earthquakes. Donato et al. (2009) reported on the grain-size distribution of inferred tsunami deposits from intertidal environments in Sur Lagoon in Oman. However, few modern tsunami deposits in lagoonal environments have been studied. Unlike paleo-tsunami events, modern tsunami deposits can be reliably identified, and they also make it possible to quantitatively estimate the hydraulic conditions associated with tsunamis from observations and from witnesses.

The purpose of this study was to describe characteristics such as sedimentary structures, thickness distributions and grain-size distributions of modern tsunami deposits in a lagoonal environment, with the aim of improving the identification and interpretation of paleo-tsunami deposits in the geological record. To achieve this, we carried out field investigations of deposits in the Periya Kalapuwa Lagoon in eastern Sri Lanka that were deposited by the 2004 Indian Ocean tsunami.

2. Description of the 2004 Indian Ocean Tsunami in the study area

We conducted field surveys of the Periya Kalapuwa Lagoon and surrounding areas in March 2005, three months after the 2004 Indian Ocean tsunami (Fig. 1). The lagoon is on the east coast of Sri Lanka (7°10′N, 81°50′E), around 1500 km from the epicenter of the Sumatra–Andaman Earthquake (Fig. 1). It covers an area of about 13 km^2, and its bottom surface is generally flat (average depth = 1 m) over the extent of our survey. Coastal barrier sand dunes of about 9-m elevation occupy a strip up to 600 m in width between the lagoon and the Indian Ocean, except where two inlets pass through the dunes (Figs. 2 and 3). The ridge line of the sand dunes is almost flat between the two inlets, and declines near the inlets. The northern inlet is approximately 300 m wide, while the southern inlet is approximately 200 m wide.

The 2004 tsunami struck the east coast of Sri Lanka approximately 2 h after the earthquake (Satake et al., 2005) and caused immense damage in coastal communities. The studied area was hit by three large tsunami waves, according to eyewitnesses and Inoue et al. (2007). The first wave arrived at 0845 local time (Inoue et al., 2007); the second wave had the highest runup of 4–6 m.

The second wave inundated the lagoon from east to the west, flowing both over the sand dunes and through the two inlets, with a runup height of 4–6 m above ground level even at the crest of the sand dunes in Tampaddai Village (Fig. 2), according to eyewitness reports and our measurements of damaged trees and other watermarks. The Rise in water level was witnessed at the shore opposite of Tampaddai during the tsunami, which suggests the tsunami waves flooded the entire lagoon. Erosive scars caused by tsunami waves were observed at only two sites, on the sea side of the sand dunes near each of the two inlets (Fig. 4A). On the sand dunes beside the inlets, eyewitness reports and the observed orientation of prostrated trees (Fig. 4B) suggested that backwash from the tsunami waves was less significant as the incoming flow, probably because the volume of water by tsunami was small compared to that of the lagoon.

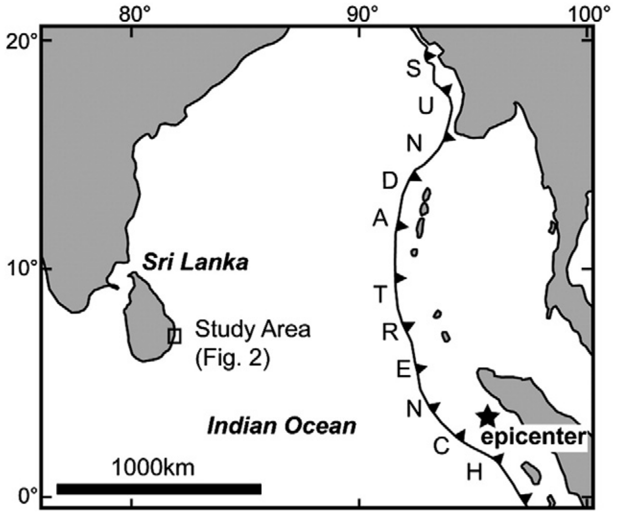

Fig. 1. Overview map showing the study area (Periya Kalapuwa Lagoon) and the epicenter of the Sumatra–Andaman Earthquake. Detailed map of the study area is shown in Fig. 2.

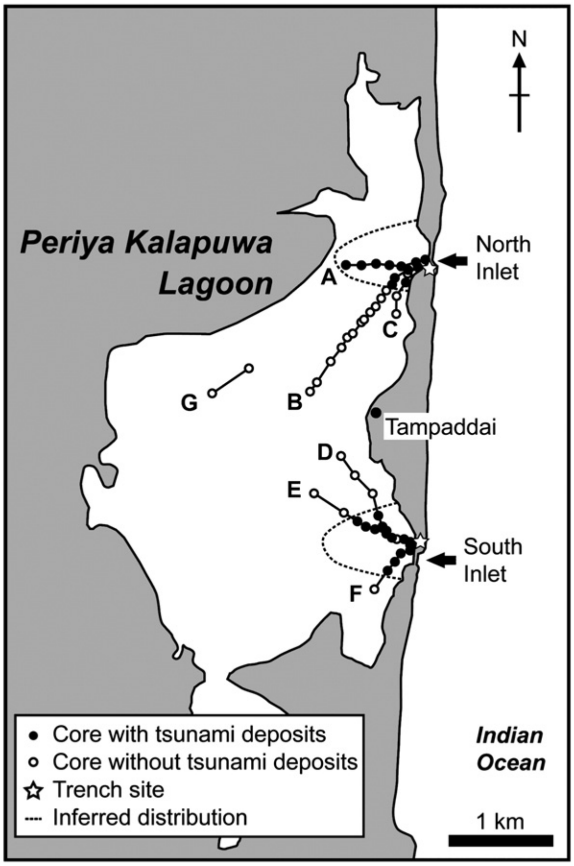

Fig. 2. Core sampling sites in the Periya Kalapuwa Lagoon. Cores were collected at a total of 51 sites (circles) on seven transects (A–G). Tsunami deposits were inferred to show two fan-like distributions from the two inlets (dash line).

3. Method

3.1. Sampling sites

We interviewed people to establish the hydraulic conditions (e.g., wave height and direction) and investigated damages caused by the tsunami. We then selected our sampling sites and transects to investigate the distribution of tsunami deposits in the lagoon and on the sand dunes. A GPS system was used to determine the exact locations of sampling sites, supplemented by corrections from triangulation data from some reference points on the sand dunes.

A total of 51 core samples were collected along seven transects across the tsunami deposits in the lagoon (transects A–G; Fig. 2). Transects A, B, and C were arranged radially into the lagoon from the northern inlet (Fig. 2). Transect A (60–1060 m from the northern inlet) had 7 sample sites, transect B (300–2300 m from the northern inlet) had 15 sample sites, and transect C (180–830 m from the northern

Fig. 3. Photograph of the northern inlet of Periya Kalapuwa Lagoon. A road bridge crosses the inlet.

inlet) had 5 sample sites. Similarly, transects D, E, and F were arranged radially from the southern inlet (Fig. 2). Transect D (420–1440 m along the sand dunes from the southern inlet) had 6 sample sites, transect E (110–1440 m from the southern inlet) had 11 sample sites, and transect F (200–870 m along the sand dunes from the southern inlet) had 5 sample sites. Transect G (2700–3270 m from the northern inlet) was farther offshore in the lagoon than the other transects, more than 2 km landward (westward) of the northern inlet (Fig. 2), and had 2 sample sites. This transect was used to determine whether there is any difference between offshore and nearshore lagoon deposits.

We also set an extra transect for core sampling between the sites C5 and D6 along the shore of the sand dunes to verify whether tsunami deposits were formed. Sampling sites along this transect were set at intervals of between 100 and 500 m, although their exact locations were not determined.

3.2. Sampling of tsunami deposits from the lagoon

Samples were collected by driving a transparent acrylic tube of 4-cm diameter and 1-m length vertically into the floor of the lagoon. A rubber plug was then inserted in its upper end and the tube was gently extracted from the lagoon sediments (Fig. 5A). Water in the tube above the sample was siphoned off using a rubber hose. Next, the sediment sample was extruded from the sampling tube and packed into a pair of longitudinally halved plastic pipes for transport, taking care not to disturb internal structures of the sample (Fig. 5B). In the laboratory, the samples were split lengthwise, photographed, and described (Fig. 5C), and grain-size analysis was performed (described below).

3.3. Trenching and hand-auger surveys

The tsunami deposits were also investigated by trenching at two sites near the inlets on the eastern lagoon shore (Fig. 2) to study their lateral continuous changes in sedimentary structures and thickness that are not confirmed with the core samples. At each site, two trenches (5–10-m long, 50 cm deep) were dug parallel and perpendicular to the inferred runup flow direction (east–west). We also constructed a thickness profile of the tsunami deposits from hand-auger samples. 165-m long transect for the hand-auger samples was set from the southern inlet to the west along the inferred flow direction (Fig. 2).

3.4. Grain-size analysis

Grain size of the sediments was analyzed with a laser granulometer (Mastersizer 2000, Malvern Instruments). The tsunami deposits and lagoon deposits from the core samples, and samples from the erosive scars in the sand dunes at the northern inlet were analyzed. Core samples of the tsunami deposits were first separated vertically into 1-cm intervals. Lagoon deposit was sampled from immediately beneath the boundary of the tsunami deposit in each core. After drying, coarse grains ($>-1\ \varphi$) were sieved out of each sample. The samples were weighed before and after sieving to allow calculation of the weight percentage of the coarse fraction. Subsamples (1–2 g) of the dried and sieved samples were analyzed with the granulometer, which provides volume percentages for 100 grain-size fractions ranging from about 16.5 to $-3.2\ \varphi$. For each sample, we calculated the 5th, 25th, 50th, 75th, and 95th percentiles, as well as mud ($<5\ \varphi$) and coarse-grain ($>-1\ \varphi$) contents. Mean grain size of the tsunami deposits in each core was calculated by averaging the result of the individual samples.

4. Results

4.1. Tsunami deposits in the lagoon

Tsunami deposits were found in two fan-shaped areas extending approximately 1000 m inland from the two inlets, regardless of the distance from the coastline. That is to say, tsunami deposits were not formed at places distant from the inlets, even close to the coastline, as near Tampaddai. They were present in 27 of the 51 core samples along all lagoon transects except transect G (Figs. 2 and 6). Typically, they consisted of well-sorted sand layers that are easily distinguished from the muddy lagoon deposits. Local fishermen witnessed that the entire lagoon floor was muddy before the tsunami and that it became sandy after the tsunami only in the areas near the two inlets.

Fig. 4. Remaining evidence of the 2004 Indian Ocean tsunami. (A) Erosive scars on sand dunes near the northern inlet. Note that tree roots are exposed. (B) Trees prostrated in the downstream direction of runup flow.

Tsunami deposits were found in cores from sites A1-7, B1-3, C1, 3 on the three northern transects, and from sites D1-D3, E1-3, 5–9, F1-4 on the three southern transects (Figs. 2 and 6, Table 1). They were found farther from the northern inlet on transect A than on transects B and C, and farther from the southern inlet on transect E than on transects D and F.

The overall range of thickness of the tsunami deposits in core samples was 1 to 35 cm (mean, 9.0 cm; Table 1) and thickness generally decreased away from the inlets. It ranged from 1 to 23 cm (mean, 8.3 cm) in the northern area and from 1 to 35 cm (mean, 9.6 cm) in the southern area. Along transect A, thickness generally decreased from 23 cm (A1, 62 m from the northern inlet) to 1 cm (A7, 1057 m). Further investigation along transect A was impossible because of the presence of shoals and marshes. Along transect C, tsunami deposit thickness was 21 cm at C1 (180 m) and decreased to 7 cm at C3 (429 m). No tsunami deposits were found at C2, 4, 5 (336, 649, 830 m respectively). Along transect D, thickness varied from 10 cm at D1 (421 m) to 14 cm at D2 (478 m), 2.5 cm at D3 (585 m), and no tsunami deposits were found at D4-6 (823–1442 m). Along transect E, the thickness of tsunami deposits generally decreased from 35 cm (E1, 114 m from the southern inlet) to 6 cm (E9, 804 m) and were not found at E4, 10, 11 (283, 999, 1439 m). Along transect F, thickness increased from 8 cm (F1, 203 m) to 17 cm (F2, 308 m), then decreased to 7 cm (F3, 436 m) and 5 cm (F4, 605 m); no tsunami deposits were found at F5 (875 m). Along transect G, no tsunami deposit was found at G1-2 (2700–3270 m). The trend of thickness along transect B was an exception to the rule; the tsunami deposits thickened markedly with increasing distance from the northern inlet, from 1 cm (site B1, 307 m from the inlet) to 15 cm

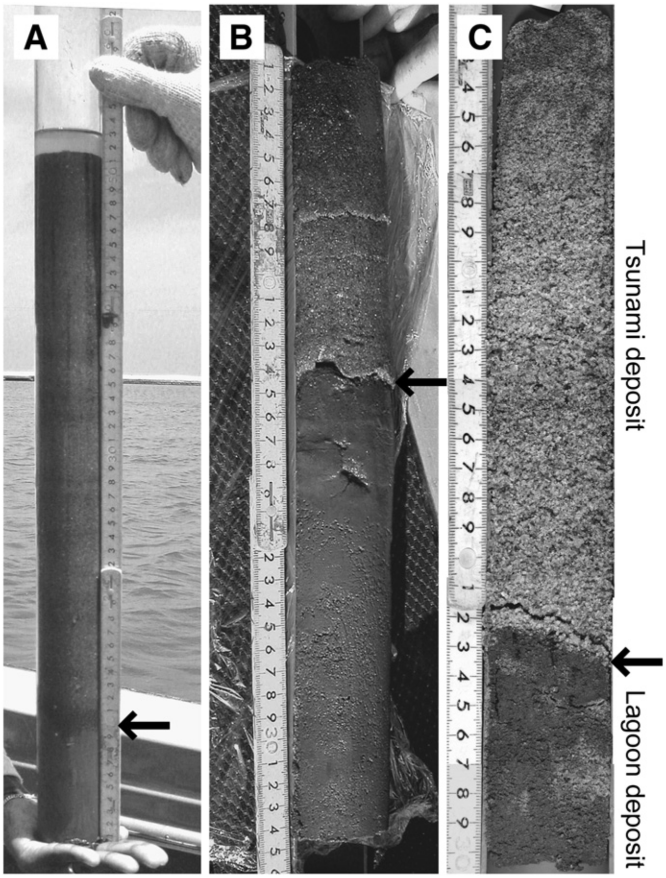

Fig. 5. Photographs illustrating the core sampling procedure. (A) Transparent coring tube immediately after sampling. (B) Storage of core in half-cut pipes. (C) A core sample after splitting in the laboratory. Arrows indicate boundary between the tsunami deposit and lagoon deposit.

(site B3, 581 m from the inlet), but no tsunami deposits were found at sites B4-15 (684–2290 m from the northern inlet). Tsunami deposits extend farthest along transects A and E, possibly because these transects are oriented along the supposed flow direction through the inlets.

The tsunami deposits are typically composed of well-sorted fine to coarse sand. They sometimes include granules and shells of brackish-water gastropods and overlie muddy lagoon deposits at a sharp erosional contact. In contrast, underneath lagoon deposits are generally charcoal gray-colored, and composed of more poorly-sorted, muddy fine to coarse sand. Inhabitant traces and gastropods are sometimes found in them. Any microfossils are not detected through an abbreviated microcopy. Offshore lagoon deposits found in G1 and G2 were somewhat darker in color and finer than those in the other sites. However, these distinctions are unremarkable.

Mean grain size of the tsunami deposits from the core samples ranged from 0.64 to 2.35 φ (1.06 φ on average) and mud contents (<5 φ) were low (0.61 vol. % on average), whereas mean grain size of the lagoon deposits ranged from 0.93 to 2.45 φ (1.61 φ on average) and mud content was high (4.7 vol. % on average). For the northern transects, mean grain size of the tsunami deposits ranged from 0.74 to 2.35 φ (1.00 φ on average), and for the southern transects, it ranged from 0.64 to 2.07 φ (1.11 φ on average). The mean grain size tended to become finer with the distance from the inlets; this trend was not apparent for the lagoon deposits (Fig. 7). The fining trend is clearly evident for transects A, C, E, and F, but not for transects B and D.

Most of the tsunami deposits are massive sands with little internal structure. For those samples that do show internal structures, graded bedding and parallel lamination of heavy minerals are the most common (Table 1). Multiple-graded bedding structures and muddy laminations (intercalations) are also evident in some cores, generally those from within about 500 m of the two inlets (Table 1). An exception to this is an instance of a single-graded bedding structure at site E9 (804 m from the southern inlet). Single-graded bedding structures and parallel laminations were found only in the southern area at distances of 203–804 m and 114–478 m from the southern inlet, respectively. Multiple-graded bedding was found only in the northern area at distances of 62–581 m from the northern inlet. Muddy laminations were found only at site A1 (62 m) in the northern area and at site D2 (478 m) in the southern area. Generally, thick-bedded tsunami deposits (>10 cm) show single or multiple-graded bedding structures, except those at sites E1, E3, and D1, which are close to the southern inlet (114–421 m). Distant from the inlets, the tsunami deposits are thin and it is difficult to identify any sedimentary structures other than indistinct single-graded bedding structures.

4.2. Tsunami deposits on the lagoon shore

Tsunami deposits on the eastern shore of the lagoon were found only within limited areas close to the two inlets. Trenching and hand-auger investigations near the inlets showed that the tsunami deposits overlay peaty soil with an irregular erosional boundary where wetland plants were prostrated, and were overlain by a thin sand layer (Fig. 8). The base of the tsunami deposits is just below the water level of the lagoon, meaning that they were formed in lagoonal environments as is the case with core samples.

Thickness of the deposits decreases landward (westward) from 66 to 5 cm within 165 m (Fig. 9). The tsunami deposits are composed mainly of medium sand (mean grain size of 1.51 φ) and include rip-up clasts from the underlying soil. There is little vertical change in grain size, and there are distinct parallel laminations composed of heavy minerals (Fig. 8). These features represent lateral continuity within each trench. The mean grain size of the sand on the ocean side of the barrier dunes where the tsunami created erosive scars was 0.94 φ (Fig. 10).

Wider investigation of the sand dunes revealed that there were tsunami deposits on land only near the two inlets. Somewhat firm soil was exposed at the surface of the sand dunes with vegetation between the two inlets, and no tsunami deposits were found there. Some villagers in Tampaddai also indicated that no sandy deposits were left after the tsunami waves.

5. Discussion

5.1. Landward trends of tsunami deposits

Tsunami deposits in the lagoon show a fining trend with the distance from the inlets as a whole, while the underlying lagoon deposits show no such variation of grain size (Fig. 7). This fining pattern is equivalent to the fining-landward patterns in general cases in terms of travel distance of the tsunami on land. The fining-landward pattern is common in terrestrial tsunami deposits (e.g., Clague and Bobrowsky, 1994; Dawson et al., 1995; Minoura et al., 1997; Goff et al., 2001; Fujino et al., 2006b) and in coastal lakes (Bondevik et al., 1997;). This pattern reflects the preferential deposition of coarse sediments because of the landward decrease of runup flow velocity (Bondevik et al., 1997). Exception to the pattern is found in transects B and D, and this may reflect their oblique directions to the inundating waves or influence of backwash flow which concentrated locally near the inlets.

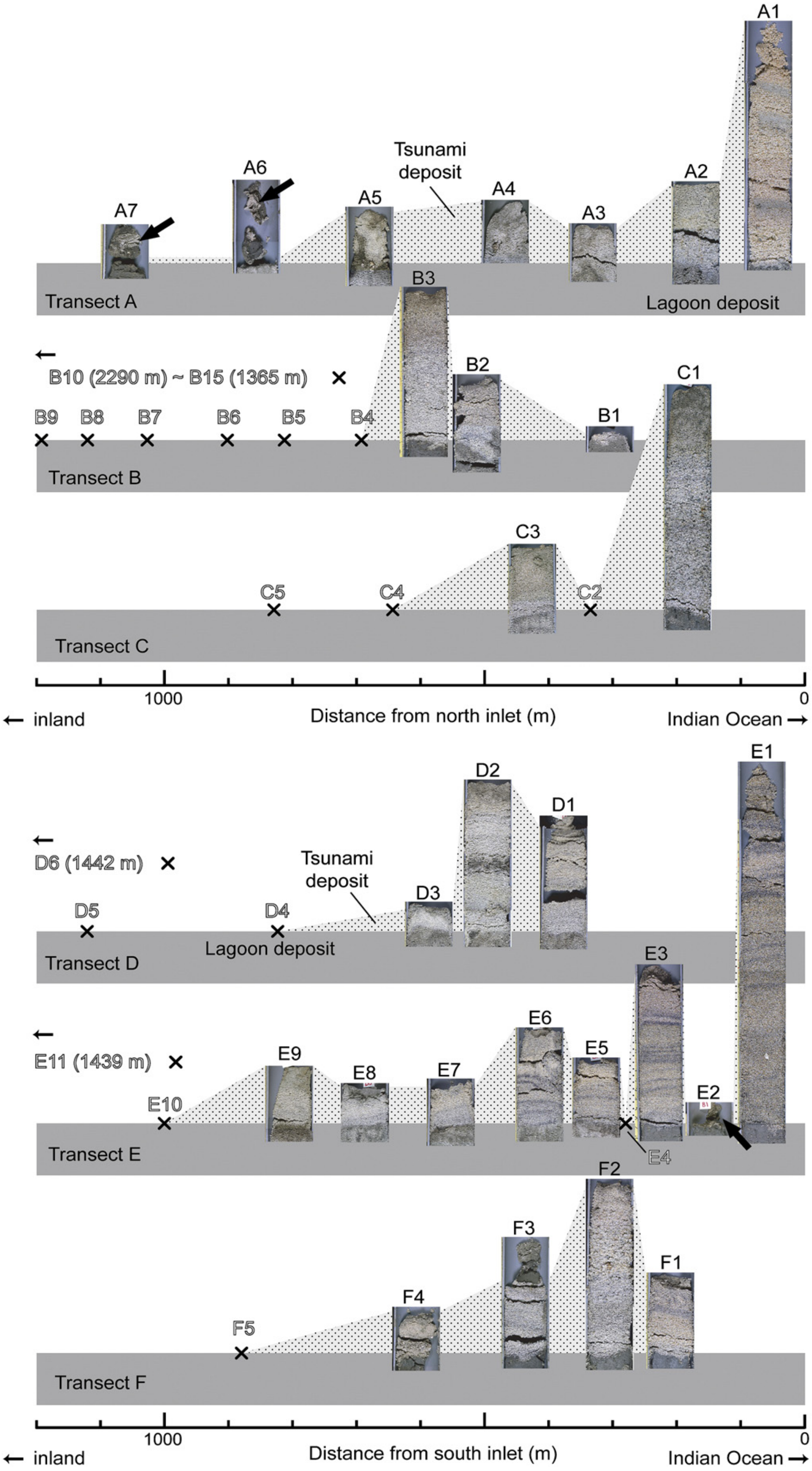

Fig. 6. Correlations of core samples for lagoonal transects A to F. Core sites marked with a black × are those where tsunami deposits were not found. Note that core sites more than 1200 m from the nearer of the two inlets are not shown. Arrows on cores A6, A7 and E2 show fractions of the tsunami deposits.

Entrainment of fine particles from the lagoon floor may also have contributed to the fine sediments found at greater distances from the inlets. Nanayama and Shigeno (2006) showed an example of a mixed grain-size distribution caused by entrainment of substrate during runup. Inclusion of shells of brackish gastropods in the tsunami deposits also suggests occurrence of entrainment at the time.

The spatial variation of thickness of the tsunami deposits in the lagoon and on the lagoon shore shows a clear thinning with the distance from the inlets that can be comparable to thinning-landward trend (Fig. 9). The thinning-landward trend is a common feature of both terrestrial tsunami deposits and those in coastal lakes (e.g., Dawson et al., 1988, 1991; Atwater and Moore, 1992; Bondevik et al., 1997; Kelsey et al., 2005; Fujino et al., 2006b), although deposit thickness is also sensitive to local topography (Nishimura and Miyaji, 1995; Gelfenbaum and Jaffe, 2003). Landward thinning has been attributed to the waning energy of runup flow and decrease of sediment supply from the ocean as a tsunami travels inland. Sugawara et al. (2004) showed experimentally that the thinning-landward trend is characteristic of deposits formed by tsunamis dominated by runup flow, rather than those formed by tsunamis for which runup flow is followed by backwash flow. Thus, we infer that the tsunami sand layer observed in this study was deposited mainly during runup flow, with possible local contribution near the inlets from backwash flow.

The landward extent of tsunami deposits was greater along transects A and E, which suggests that the tsunami deposition was controlled by runup flow through the two inlets. The observed trends of landward thinning and fining, as well as eyewitness reports and the dominant orientation of prostrated trees, suggest that backwash flow was limited to local influence near the lagoon on the tsunami deposits in Periya Kalapuwa Lagoon.

The limited distribution of tsunami deposits within the lagoon itself suggests that estimation of recurrence intervals of tsunamis on the basis of tsunami deposits requires careful investigation. In general, past estimates of the recurrence intervals of tsunamis have assumed that deposits formed by past tsunamis are controlled mainly by runup flow and have been preserved without reworking in the geological record. However, our study has suggested from the examination of the tsunami deposits that they are not necessarily controlled by runup flow alone. Tsunamis deposits, even those from tsunamis of more than 5 m wave height, may be strongly influenced by local landforms and by entrained local bottom sediments in addition to the accepted controls of flow velocity and wave height. To avoid underestimating the number of past tsunamis, future studies should take into account local depositional settings and include survey data over wide areas including representative local landforms.

5.2. Vertical trends and sedimentary structures of tsunami deposits

The single-graded bedding structures found in six core samples indicate deposition from suspension during deceleration of a runup flow (Gelfenbaum and Jaffe, 2003). Thick, massive tsunami deposits without graded bedding structures (core samples E1, E3, and D1 and tsunami deposit samples from the lagoon shore) also indicate rapid deposition from suspension during deceleration of a runup flow (Morton et al., 2007). Well-developed parallel laminations are produced by low-amplitude bedforms that develop under the current of a plane bed regime (Allen, 1984; Best and Bridge, 1992). These structures, and hence the processes that formed them, are limited to the areas near the two inlets where the intense runup flow would once exist and decrease significantly during sedimentation.

Multiple-graded bedding structures indicate deposition from multiple runup (and possibly backwash) flows (Bondevik et al., 1997; Fujino et al., 2006b; Hori et al., 2007; Paris et al., 2007). Our preliminary research indicated that the second tsunami wave had the highest runup and that it inundated the lagoon. It is also possible that the first or third tsunami wave, or both, also inundated the lagoon, which would explain the multiple-graded bedding. However, the multiple-graded bedding was found only in core samples close to the two inlets.

5.3. Sediment source for tsunami deposits

We suggest that the tsunami deposits in our study area were formed mainly from sediments scoured from the sand dunes near the two inlets and that runup flow carried little sediment derived from the Indian Ocean. This is inferred from the limited distribution of the erosional scars on the dunes, as well as the lack of deposits away from the inlets even where the wave inundated over the dunes. Furthermore, this is supported by the similarity of the grain-size distributions of the tsunami deposits and the sand dunes (Fig. 10). This distribution of deposits suggests that incoming tsunami wave was focused on the two inlets leading to a swift flow and local erosion compared to areas on the sand dunes between the two inlets. Tsunami deposits found in the southern area differ from those in the northern area in that they are relatively thick and contain distinct parallel laminations in some core samples. These differences may be controlled by the geomorphological situations including width of the inlets.

There has been considerable research into the source of sediments that make up tsunami deposits. For example, Sato et al. (1995) compared the amounts of erosion and deposition associated with the tsunamis of both the 1993 Southwest Hokkaido and 1983 Japan Sea earthquakes and inferred that the tsunami deposits for both were formed by sediments derived from onshore areas such as beaches and sand dunes. In contrast, Gelfenbaum and Jaffe (2003) investigated the 1998 Papua New Guinea tsunami and argued that the contribution of offshore areas to the tsunami deposits there was twice that of onshore areas. These previous studies indicate that the sediment sources of the tsunami deposits is likely site-specific. Our inference on sediment source agrees with Sato et al. (1995) but not with that of Gelfenbaum and Jaffe (2003). However, this may not be true of tsunami deposits in all lagoonal environments.

From the distribution of the tsunami deposits, we estimated their total volume to be 83 000 m^3. Assuming that the sediment supplied by erosion came from the coast within 500 m of each inlet, we calculated the volume of sediment supply per unit width of sand dunes to be 83 m^3/m. The estimate of 500 m was based on the width of each inlet and visual observations of the area around the inlets where the sand dunes had little vegetation and were relatively low with erosive scars. This volume is approximately twice that reported for the 1998 Papua New Guinea tsunami (36 m^3/m, Gelfenbaum and Jaffe, 2003), where the runup height was about 10–15 m, but is comparable to that of the 2004 Indian Ocean tsunami in southwestern Thailand (around 78 m^3/m, Fujino et al., 2006b), where the runup height was approximately twice as high as that of our field in Sri Lanka. These differences suggest that the volume of sediment in tsunami deposits depends on conditions such as topography and substrate sediment as well as of the magnitude of the tsunami.

6. Summary

Our study provides a detailed description of the distribution, thickness, grain size, and sedimentary structures of modern tsunami deposits in a lagoonal environment. Core samples, trenching surveys, and hand-auger investigations in and near the Periya Kalapuwa Lagoon in Sri Lanka revealed the following characteristics of the tsunami deposits there.

Table 1
Characteristics of tsunami deposits in Periya Kalapuwa Lagoon, Sri Lanka.

Characteristics	A1	A2	A3	A4	A5	A6	A7	B1	B2	B3	C1	C3	D1
Distance[a] (m)	62	181	363	472	683	860	1057	307	505	581	180	429	421
Thickness (cm)	23	8	4	7	6	1	1	1	6	15	21	7	10
Mean grain size (φ)	0.90	0.75	1.41	1.42	1.30	2.18	2.35	1.31	0.73	0.89	0.88	1.23	1.09
Mud content[b] (%)	0	0.47	2.21	3.54	0.94	12.34	8.57	2.32	0.24	0.24	0.72	0.46	0.19
Coarse-grain content[c] (%)	4.04	7.37	6.33	6.27	1.20	1.47	0	2.16	6.60	6.35	11.90	1.18	2.45
Grading	Multiple	No	No	No	No	No	No	No	No	Multiple	Multiple	No	No
Other sedimentary structures?	Muddy lamination	No	No	No	No	No	No	No	No	No	No	No	No

1. Well-sorted sandy sediments deposited by the 2004 Indian Ocean tsunami overlie the muddy deposits of the Periya Kalapuwa Lagoon at a sharp boundary.

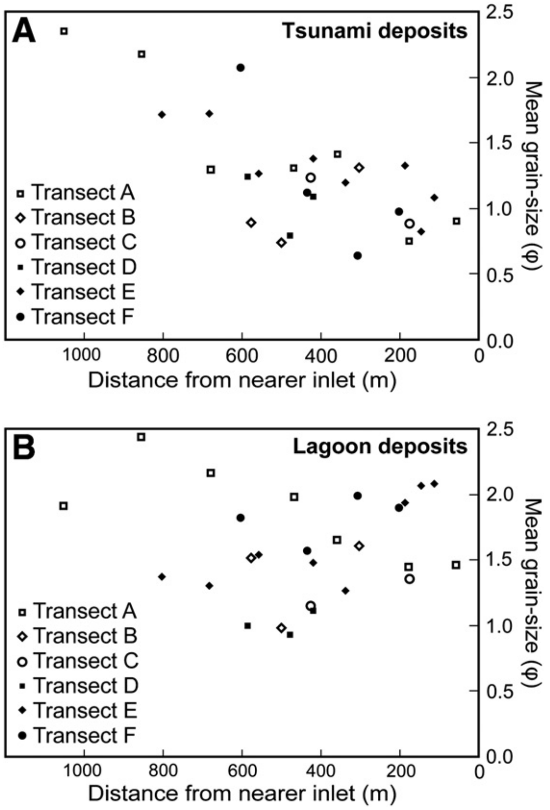

Fig. 7. Mean grain size in core samples of (A) tsunami deposits and (B) lagoon deposits.

2. Despite a runup height of 4–6 m when the 2004 Indian Ocean tsunami reached the barrier sand dunes between the lagoon and the ocean, tsunami deposits were laid only in areas within 1 km from each inlet.
3. The measured thickness of the tsunami deposits in the lagoon was 9.0 cm on average and up to 35 cm, and the deposits were up to 66 cm thick on the lagoon shore. Thickness decreased with distance inland from the two inlets.
4. Mean grain size of the tsunami deposits was 1.06 φ with low mud content (0.61 wt.%), and grain size became finer with increasing distance inland from the two inlets. Mean grain size of the lagoon deposits was 1.66 φ on average with high mud content (4.7 wt.%) and showed no significant change with distance inland from the two inlets. The landward-fining of the tsunami deposits reflects the landward decrease in runup flow velocity.
5. Close to the two inlets, core samples of the tsunami deposits variously showed massive structure, upward-fining structures including multiple-graded bedding, and parallel lamination. These structures are typical of the proximal regions of tsunami deposits. The tsunami deposits farther inland showed no structures or only faint evidence of graded bedding.
6. The results of our investigations of the tsunami deposits in Periya Kalapuwa Lagoon suggest that they were formed mainly during waning runup flow and that their sediment source region is limited to the sand dunes close to the two inlets, where erosive scars were observed. These observations suggest that runup flow transported little sediment from the Indian Ocean.
7. We estimated the total volume of tsunami deposits to be 83 000 m^3.

The findings of our study will assist in the identification of tsunami deposits in the geological record and improve understanding of the formation of tsunami deposits in lagoonal environments. The distribution of the tsunami deposits in this case suggests that sites near the inlets are preferable to detect paleo-tsunami deposits in lagoonal environments especially for reconstruction of recurrence intervals.

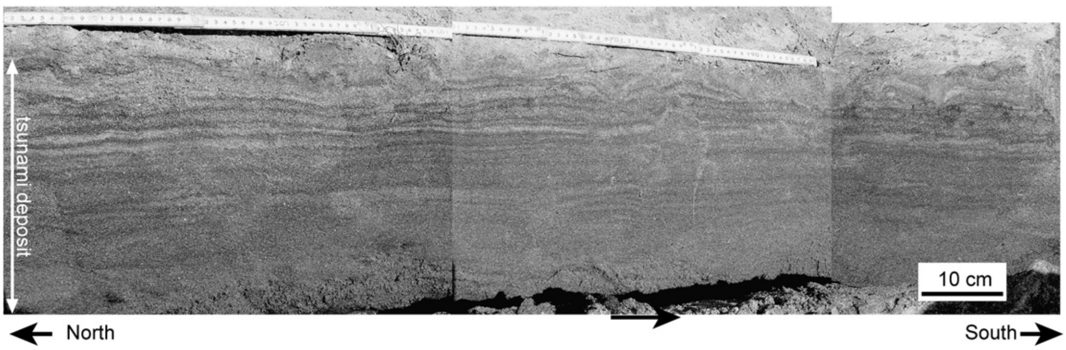

Fig. 8. Photograph of tsunami deposits exposed in a trenching survey on land near the southern inlet.

D2	D3	E1	E2	E3	E5	E6	E7	E8	E9	F1	F2	F3	F4
478	585	114	146	187	339	420	558	682	804	203	308	436	605
14	2.5	35	1	14	6	10	4	4	6	8	17	7	5
0.80	1.24	1.08	0.82	1.33	1.20	1.38	1.27	1.72	1.71	0.98	0.64	1.12	2.07
0.63	0.31	0	0	0.09	0	0.01	0	0.76	0.38	0.30	0.06	1.41	4.04
4.35	3.99	1.58	8.42	1.58	0.80	1.70	4.23	4.11	1.23	1.87	17.57	1.56	0.45
Single	No	No	No	No	No	Faint	No	No	Single	Faint	Single	No	Faint
Muddy lamination	No	Heavy mineral lamination	No	Heavy mineral lamination	Heavy mineral lamination	Heavy mineral lamination	No	No	No	Heavy mineral lamination	No	No	No

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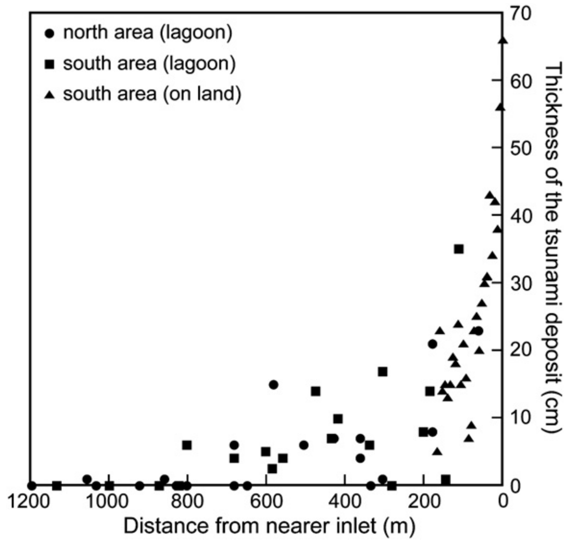

Fig. 9. Relationship of thickness of tsunami deposits to distance from the nearer of the two inlets.

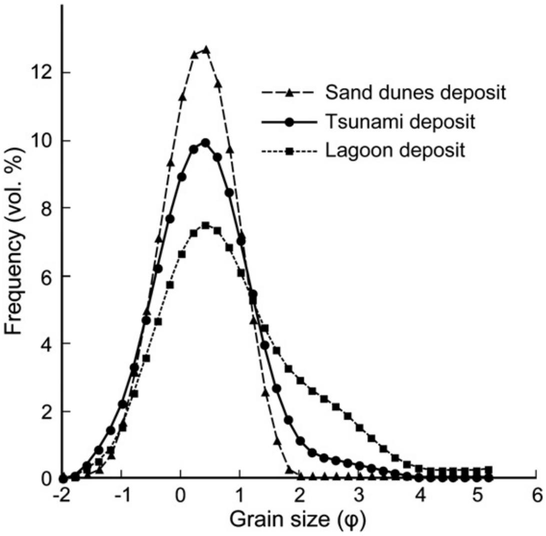

Fig. 10. Comparison of grain-size distributions of the tsunami deposits, lagoon deposits, and sand from the dunes.

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