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ORIGINAL PAPER

Geochemistry of surface sediments in tsunami-affected Sri Lankan lagoons regarding environmental implications

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Abstract The December 26, 2004 Indian Ocean tsunami was one of the largest in human history, devastating the coastal wetlands of surrounding countries. This study present the chemical analyses of tsunamigenic and pre-tsunami sediments from Hikkaduwa and Hambantota lagoons in southern Sri Lanka, to assess their geochemical composition, their source, and subsequent environmental impacts. Principal component analysis of the tsunami sediments shows that 42% of the total variance is accounted for calcium oxide and Sr. That is, the tsunami deposits are rich in biogenic phases derived from shallow marine sediments. High organic matter contents of the tsunami sediments of up to 80 wt% also support this interpretation. The association of chlorine (<9.4 wt%), brome (<170 mg/kg), arsenic (<17 mg/kg), iron (III) oxide (<12.9 wt%) and sulfur (<7.6 wt%) accounts for 33% of the variance, reflecting higher salinity. This further suggests that the sediments were mainly derived from a marine environment, rather than from non-marine sands and/or soils. Immobile element contents and relations (thorium, scandium and zirconium) suggest that the tsunami sediment source was mostly felsic in composition, with some mafic component, and mixed with predominantly shallow marine shelf or slope sediments. Additional compositional variations in the tsunami sediments in both lagoons may be associated with variations of wave strength along the coast and by the morphology of the continental shelf. Lower elemental abundances in Hambantota lagoon sediments compared to Hikkaduwa equivalents may thus reflect a greater non-marine component in the former, and greater shelf sediment component in the latter.

Keywords Composition · Major elements · Total sulfur · Trace elements

Introduction

The major tsunami that was generated by a massive earthquake on December 26th 2004 struck many South Asian countries bordering the Bay of Bengal, and devastated the coastal regions of Sri Lanka. The tsunami waters over-ran ~60% of the Sri Lankan coastline, and in some areas of flat topography inundation stretched 2–3 km inland. Extensive erosion, transportation of large volumes of marine sediments and subsequent deposition in coastal plains take place within a very short time during tsunami events. Field observations of tsunamigenic deposits have shown that they were generally characterized by presence of mafic mineral layers with landward fining of grain size and presence of shallow and/or deep sea fossils (Nishimura and Miyaji 1995; Shi et al. 1995; Moore et al. 2007; Paris et al. 2007). Well-sorted sands within black organic muds found in coastal wetlands have also identified as tsunami sediment sequences (Minoura et al. 1994). Recent geochemical investigations of 2004 tsunami sediments in Thailand found that content of salts and some trace metals was significantly elevated (Szczuciński et al. 2005). Tsunami sediments in wetlands were also characterized by higher Fe and/or sulfur values, along with higher organic matter contents (Goff and Chagué-Goff 1999). Higher abundances of As, Cl, Br, S and organic matter in sedimentary sequences in some coastal wetland

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environments such as lagoons and marshy lands reflect the influences of tsunami and sea level changes on the coast (López-Buendía et al. 1999; Chagué-Goff et al. 2000, 2002). The presences of higher values of Fe, Sr, Ca and S have also been linked to lagoon subsidence associated with tsunami inundation (Nichol et al. 2007).

In Sri Lanka fine to medium-grained sand containing mafic minerals and deep sea fossils were identified from the recent tsunami sediments on the eastern, southern and southwestern coasts (Dahanayake and Kulasena 2008; Morton et al. 2008). The Sri Lankan coast contains many shallow small- and medium-scale lagoons that comprise important natural ecosystems. These were inundated during the tsunami, with widespread deposition of suspended sediment and debris (Morton et al. 2008; Yan and Tang 2009). However, as on today, no detailed studies of the geochemistry of tsunamigenic sediments in wetlands or the coastal plains of Sri Lanka have been made. Consequently, this study focuses on the geochemistry of the tsunami sediments in two lagoons (Hikkaduwa and Hambantota) situated on the southwestern and southern coast of Sri Lanka. Field survey for sample collection was carried out 18 months after the tsunami.

The geochemistry potentially provides valuable information on the nature and origin of the sediments and the effect of the tsunami on the environment. The results obtained may thus be useful for paleotsunami and paleoclimatic studies. The scope of the present study was to examine the major elements, trace elements and total sulfur of sediments in two tsunami-affected lagoons in order to (a) determine the chemical composition of the tsunami sediments; (b) identify their source; and (c) examine possible chemical changes that subsequently took place in the depositional environment.

Study area and physical setting

Hikkaduwa and Hambantota lagoons were situated on the southern coast of Sri Lanka, 100 and 250 km from the capital city of Colombo, respectively (Fig. 1). Both lagoons were inundated by massive tsunami waves. The tsunami sediments deposited within them were mainly associated with tsunami up-flow, rather than with reverse flow.

Hikkaduwa lagoon is a narrow north-west trending body located 1 km from the coastline. It has an area of about 2.5 km^2 with maximum depth of 2 m, and was connected to the sea through a narrow channel. The lagoon was widened by the tsunami, especially its northwestern corner (Fig. 1), due the action of strong tsunami waves about 7 m in height. Hambantota lagoon is a wider east–west trending lagoon, located half a kilometer from the coast. It has an area of about 3.5 km^2 and water depth of 2.5 m, and is also connected to the sea by a small channel. Heavy tsunami waves hit this coastal site, with maximum inundation height of around 7 m. In general, the tidal ranges around both lagoons are low (mean annual tidal range 0.10–0.18 m), and their narrow connections with the sea limit seawater influence within the lagoons (Wijeratne and Rydberg 2007; Wijeratne and Pattiaratchi-web reference). Average temperature at both sites is 30°C during the dry season (November–January), falling to around 20°C in the wet season (May–September).

The present setting of the coastal wetlands is a result of sea level changes during the Holocene period (Katupotha and Fujiwara 1988). The overburden cover in the area consists mainly of terrigenous sands, biogenic carbonates, and mud (Wijayananda 1994). Lateritic and peaty soils are also common (Dissanayake 1984). Basement rocks at both sites are mainly granulite facies charnockitic and granitic gneisses (Fig. 1) with lesser cordierite gneiss and garnet silimanite gneiss. The chemical composition of rocks in the region shows a bimodal distribution with a marked gap in SiO_2 content between 57 and 62 wt%, and significant enrichment of Fe_2O_3, TiO_2, MnO, P_2O_5 and Sr (Pohl and Emmermann 1991).

Materials and methods

Field survey and sample collection were carried out in both tsunami and pre-tsunami sites. Sample locations were selected based on field observations and information from local people who experienced the tsunami. Sample site selection considered the nature and extent of the tsunami deposits, inundation level, distance from the sea, and the geomorphology of the area.

Physical properties of lagoon water were studied with respect to depth using a drop-down electrode. Temperature, pH, dissolved oxygen (DO), oxidation–reduction potential (ORP), total dissolved solids (TDS), turbidity, salinity, and conductivity were measured at different depths at each location, immediately prior to the collection of the sediment samples (Fig. 1).

Sediment samples were collected from inundated and non-inundated areas using a standard Ekman grab sampler. The sampler typically penetrated to a depth of 15 cm, yielding a 3.5 L sample weighing about 7 kg. Temperature, ORP, and pH of each sample were measured at the time of collection. Textural characteristics of the sediment aggregates were estimated in the field using a texture chart. The surface fraction of the collected samples were stored in 10°C cool boxes and transferred to the laboratory.

The sediment samples were analyzed for major elements, trace elements and total sulfur by X-ray fluorescence spectrometry (RIX 2000) in the Department of

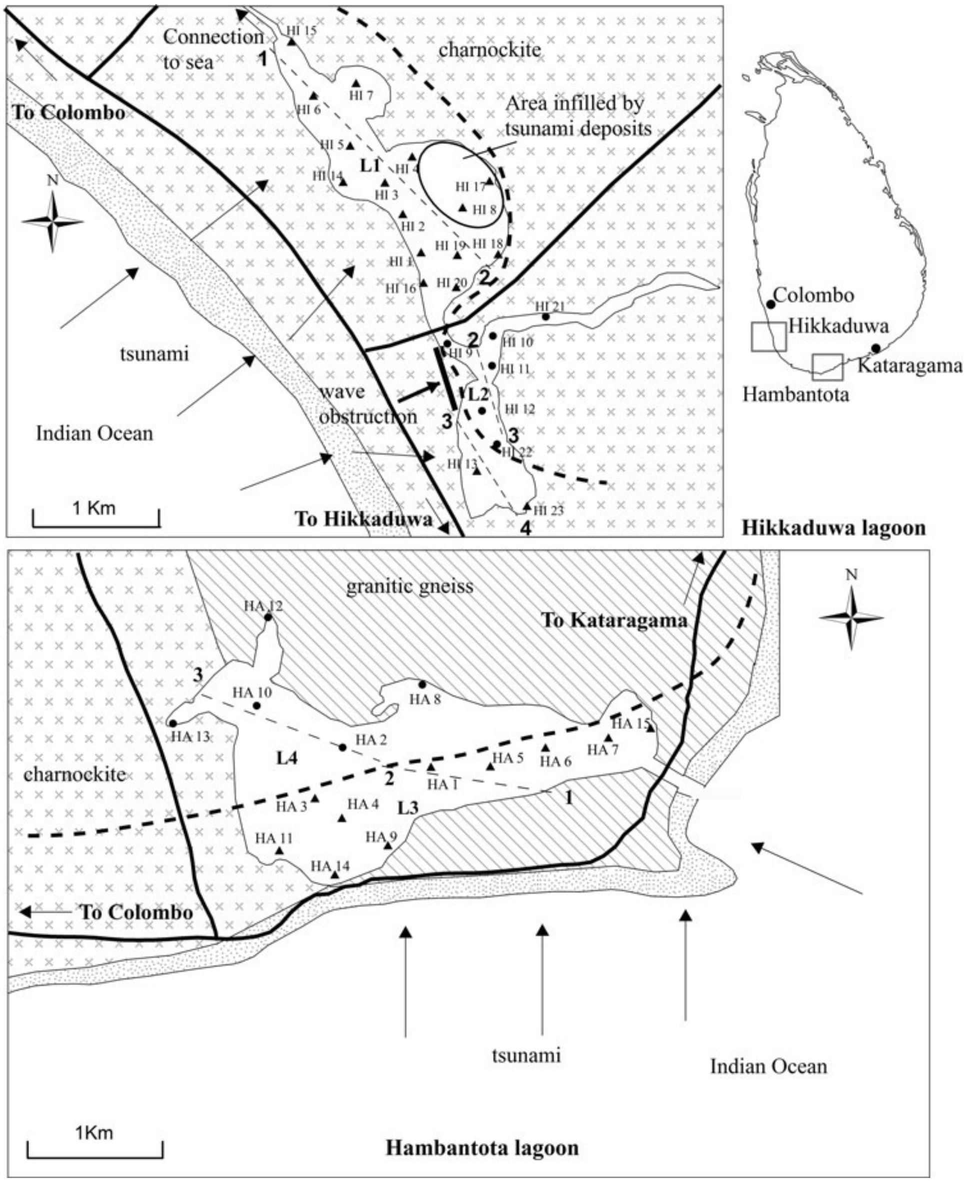

Fig. 1 Maps of the study areas and location of sample sites. *Filled circles* denote pre-tsunami sediment samples, *triangles* denote tsunami sediments. Tsunami flow directions are indicated by *arrows*, *heavy dashed lines* are water inundation levels. *Thinner dashed lines* represent the locations of the schematic cross-sections in Fig. 2

Geoscience at Shimane University. Gravimetric water was first removed by oven-drying for 24 h 110°C. A split of each sample was then oven-dried for 48 h at 160°C to determine organic matter (OM) content, the temperature limit 160°C to prevent the evaporation of carbonates, crushed the dried samples subsequently in an automatic agate pestle and mortar grinder. The crushed samples were then compressed into disk under a force of 200 KN for 60 s. The disk were subsequently analyzed for selected major elements (TiO_2, Fe_2O_3, MnO, CaO and P_2O_5), trace elements (As, Pb, Zn, Cu, Ni, Cr, V, Sr, Y, Nb, Zr, Th, Sc, Br, I and Cl) and total sulfur (TS) under powder diffraction method. Average errors for these elements are less than ±10%.

Major and trace element data are key components of geochemical studies of sediments. Elemental normalization against upper continental crust (UCC) can assess the extent to which sediment compositions diverge from normal crustal composition (Taylor and McLennan 1985). Trace metal correlation with Fe_2O_3 and total sulfur are important relationships for studying the behavior of metals in the natural environment. Fe_2O_3 is typically positively correlated with most trace metals, but abundances may vary according to several factors such as pH, ORP and anthropogenic impacts. It can, therefore, used to examine both the extent of contamination and the source of sediments (Ishiga et al. 2000; Gurung et al. 2005; Ahmed et al. 2005). Strong positive correlation between total sulfur and Fe_2O_3 indicates the temporary formation of pyrite within sediments (Berner 1970; Ishiga et al. 2000). Correlations between immobile element ratios are also useful for determining the source of sediments and the potential role of heavy mineral concentration (Bhatia and Crook 1986; McLennan et al. 1993; Roser 2000). Moreover, principle component analysis for the correlation matrix which obtained from geochemical data is useful to understand underlying data structure.

The nature of marine sediments provides a lever for the study of tsunami sediments, because, the geochemical composition of the latter is characterized by a largely physical mixture of lithological constitutents such as continental and oceanic detritus (Taylor and McLennan 1985; Othman et al. 1989; Plank and Langmuir 1998). The marine sediment around Sri Lanka comprises Bay of Bengal Fan sediment as described by Crowley et al. 1998 (see also Pattan and Shane 1999; Roonwal et al. 1997). Marine sediments also contain varying amounts of biogenic carbonate and opal, and consequently levels of elements such as Ca and Sr may be very high (Plank and Langmuir 1998). Abundances of Cl, Br and total sulfur are also useful indicators of marine origin for sediments. In general, sulfur contents >0.3 wt % indicates marine conditions (Berner 1970, 1982).

Results and discussion

Water quality

Average values of physico-chemical properties of water overlying OM-rich tsunami sediments and OM-poor pre-tsunami sediments were calculated for zones L1 and L2 (Hikkaduwa) and L3 and L4 (Hambantota) (Figs. 1, 2). The surface undulation of the floors of both lagoons is very limited, and hence topography is almost flat.

The pH, turbidity, DO and ORP of Hikkaduwa lagoon water ranges from 7.3 to 7.7, 1 to 37 NTU, 0.7 to 6.9 mg/L and 66 to 300 mV, respectively. Values of salinity, conductivity, TDS and temperature show little variation, and average 2.32%, 3.56 mS/cm, 22 mg/L and 32°C, respectively. The pH of the lagoon is neutral, and meets the United States Environmental Protection Agency (USEPA) criteria (6.5–9.0) for fresh water aquatic life. However, both pH and turbidity increase slightly towards the bottom (Table 1). ORP values were positive in the surface waters in both L1 and L2, but became more negative with depth. ORP values in L1 are abnormally low below 40 cm, due to decomposition of OM. DO values were highest at the surface in both L1 and L2, and decrease slightly downward. DO values in the lagoon are below the USEPA and Canadian water quality guideline for early life stage (>6 mg/L) and other life stages (>5.5 mg/L) in warm ecosystems.

Hambantota lagoon water is characterized by pH, turbidity, DO and ORP values of 8.3–10.5, 2–60 NTU, 6.4–11.5 mg/L and 129–32 mV, respectively. Salinity, conductivity, TDS and temperature vary as in Hikkaduwa lagoon, but have lower average values of 1.18%, 2.04 mS/cm, 13 mg/L and 30°C, respectively. Turbidity and pH increase slightly toward the bottom of the lagoon, whereas ORP gradually decrease with depth in both L3 and L4 (Table 1). Average pH of Hambantota lagoon is above from the USEPA criteria (6.5–9.0) for fresh water aquatic life, because values at some sites slightly exceed the guideline. DO is generally above the USEPA recommended values for aquatic life stages.

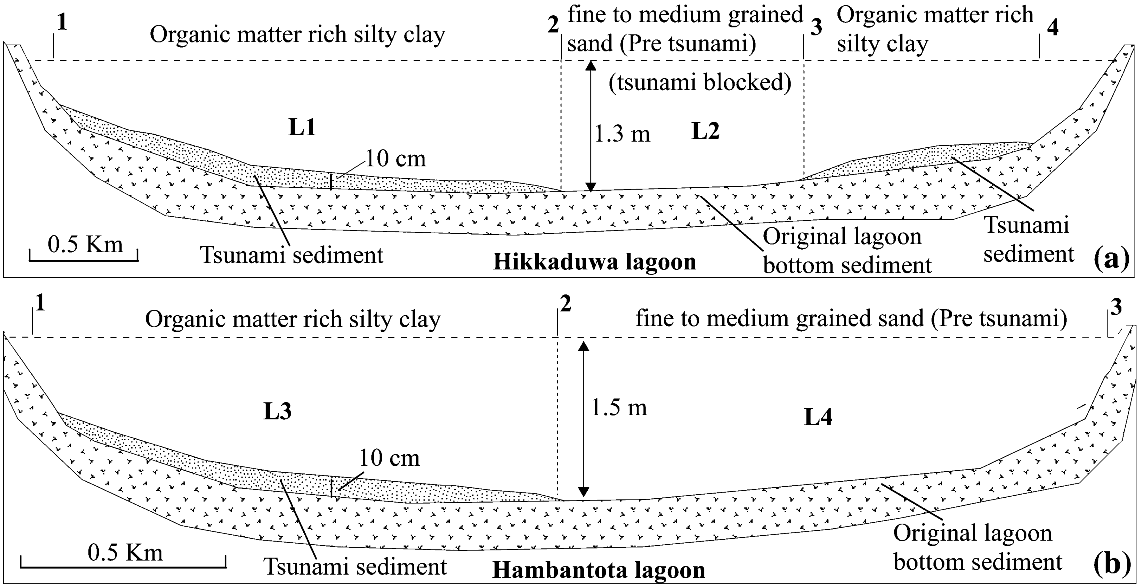

Fig. 2 Schematic cross-sections of Hikkaduwa and Hambantota lagoons

Table 1 Average physico-chemical properties of the water bodies in Hikkaduwa and Hambantota lagoons

Depth (m)	Temp (°C)	pH	EC (mS/cm)	Salinity (%)	DO (mg/L)	ORP (mV)	Turbidity (NTU)	TDS (mg/L)
Hikkaduwa								
L 1								
0	32	7.5	3.56	2.25	4.4	49	10	22
0.3	32	7.4	3.52	2.23	2.3	25	10	21
0.4	31	7.4	3.33	2.02	2.6	−289	15	20
0.7	31	7.5	3.43	2.18	0.7	−300	12	21
0.8	32	7.6	3.55	2.25	1.0	−230	16	24
1.1	32	7.6	3.53	2.25	1.2	−233	37	22
L 2								
0	33	7.5	3.58	2.27	5.5	66	9	22
0.1	33	7.5	3.57	2.27	4.3	12	4	22
0.4	33	7.3	3.75	3.25	6.8	20	3	23
0.7	33	7.7	3.72	2.37	6.9	12	3	23
1.2	32	7.7	3.58	2.27	2.7	−15	1	22
1.3	32	7.7	3.59	2.28	1.3	−70	6	22
Avg	32	7.5	3.56	2.32	3.3	−79	11	22
Min	31	7.3	3.33	2.02	0.7	−300	1	20
Max	33	7.7	3.75	3.25	6.9	66	37	24
Hambantota								
L 3								
0	29	9.0	1.71	1.01	7.3	29	20	11
0.3	30	9.6	2.06	1.22	9.9	20	6	12
0.5	31	9.4	2.70	1.19	11.5	12	20	12
0.6	31	10.5	2.13	1.29	10.7	8	16	13
1.1	32	10.0	2.19	1.28	9.8	11	24	13
1.2	30	9.9	2.05	1.24	11.4	−12	21	17
1.5	31	10.0	2.14	1.30	11.3	−32	60	13
L 4								
0	31	9.3	2.15	1.31	9.6	129	12	13
0.5	30	8.3	1.71	1.01	6.5	80	3	11
0.8	29	8.6	1.71	1.01	6.4	75	3	11
1.0	30	9.8	2.19	1.33	10.6	27	20	14
1.5	30	8.9	1.73	1.02	6.6	11	2	11
Avg	30	9.4	2.04	1.18	9.3	30	17	13
Min	29	8.3	1.71	1.01	6.4	−32	2	11
Max	32	10.5	2.70	1.33	11.5	129	60	17

Each value is the average of three measurements

L1 area with highly organic mud, *L2* area with sandy sediments, *L3* area with silt clays, *L4* area with sandy sediments

Textural characteristics of sediments

The tsunami sediment deposits in both lagoons are continuous, with thicknesses varying from a few centimeters to a few tens of centimeters. Thickness varies due to distance from the sea, undulation of the lagoon morphology, level of inundation, and wave strength. Landward fining of sediments was noted during field observation. In general, the sediments are overlaying by thin fine-grained gray silts and clays containing mafic minerals. These silts and clays may represent suspension fallout from the floodwaters.

Based on their textural characteristics, the sediments in Hikkaduwa lagoon can be divided into two categories (Fig. 2a). The central part of the lagoon predominantly consists of medium-grained sand deposits reflect the pre-tsunami sediments. The corners of the lagoon and an area infilled by the tsunami consist of black colored silts and clays. The amount of sand and volume of shell material

Table 2 Major oxide abundances and physico-chemical conditions of Hikkaduwa and Hambantota lagoon sediments

Sample ID	Remark	Lithology	pH	ORP (mV)	OM (wt%)	Major oxides (wt%)				
						TiO_2	Fe_2O_3	MnO	CaO	P_2O_5
Hikkaduwa										
HI 1	T	SC	7.0	−300	58	0.62	6.72	0.01	6.28	0.09
HI 2	T	SC	6.8	−347	63	0.24	4.60	0.01	8.84	0.12
HI 3	T	SC	6.9	−360	79	0.60	12.57	0.02	3.31	0.10
HI 4	T	SC	6.7	−320	78	0.47	11.52	0.01	4.27	0.14
HI 5	T	SC	6.8	−370	74	0.42	8.43	0.02	7.59	0.15
HI 6	T	SC	6.9	−364	80	0.60	12.99	0.03	3.22	0.10
HI 7	T	SC	6.7	−350	70	0.32	8.14	0.02	7.89	0.24
HI 8	T	SC	6.8	−330	66	0.48	6.31	0.01	7.72	0.16
HI 13	T	SC	6.9	−380	71	1.64	1.92	0.01	26.91	0.13
HI 14	T	SC	–	–	69	0.38	6.00	0.01	13.50	0.15
HI 15	T	SC	–	–	66	0.37	3.29		9.05	0.08
HI 16	T	SC	–	–	66	0.79	11.08	0.02	2.01	0.10
HI 17	T	SC	–	–	64	0.46	7.66	0.01	18.34	0.17
HI 18	T	SC	–	–	67	0.68	4.92	0.01	8.54	0.12
HI 19	T	SC	–	–	65	0.32	2.94		13.53	0.15
HI 20	T	SA	–	–	61	0.30	3.97		2.39	0.21
HI 23	T	SC	–	–	72	0.50	5.68	0.01	8.37	0.15
	T-Avg		6.8	−347	69	0.54	6.98	0.01	8.93	0.14
	Min		6.7	−380	58	0.24	1.92	0.01	2.01	0.08
	Max		7.0	−300	80	1.64	12.99	0.03	26.91	0.24
HI 9	Pt	SA	6.6	−340	33	0.24	0.76		10.95	0.07
HI 10	Pt	SA	6.7	−350	25	0.59	7.82	0.01	5.06	0.13
HI 11	Pt	SA	6.9	−365	30	1.54	1.59	0.01	8.24	0.08
HI 12	Pt	SC	6.8	−357	35	0.94	1.47	0.01	21.54	0.12
HI 21	Pt	SA	–	–	27	0.52	7.96	0.01	2.81	0.43
HI 22	Pt	SC	–	–	38	0.38	5.87	0.01	8.90	0.18
	Pt-Avg		6.8	−353	31	0.70	4.25	0.01	9.58	0.17
	Min		6.6	−365	25	0.24	0.76	0.01	2.81	0.07
	Max		6.9	−340	38	1.54	7.96	0.01	21.54	0.43
Hambantota										
HA 1	T	SC	7.8	−83	44	0.61	3.66	0.09	14.08	0.14
HA 3	T	SC	7.5	−297	50	0.72	10.12	0.20	7.02	0.18
HA 4	T	SC	7.7	−350	46	0.71	3.93	0.08	7.89	0.16
HA 5	T	SC	7.2	−300	49	0.63	7.51	0.18	6.32	0.19
HA 6	T	SA	7.9	−380	34	0.68	2.94	0.06	11.62	0.20
HA 7	T	SA	7.5	−266	39	0.81	2.86	0.06	7.31	0.18
HA 9	T	SA	–	–	35	0.52	3.05	0.04	9.08	0.18
HA 11	T	SC	–	–	40	0.61	2.98	0.04	6.33	0.16
HA 14	T	SA	–	–	38	0.52	3.05	0.04	9.08	0.18
HA 15	T	SA	–	–	42	0.81	2.86	0.06	7.31	0.18
	T-Avg		7.6	−279	42	0.66	4.30	0.09	8.60	0.18
	Min		7.2	−380	34	0.52	2.86	0.04	6.32	0.14
	Max		7.9	−83	50	0.81	10.12	0.20	14.08	0.20
HA 2	Pt	SC	7.4	−363	30	0.64	5.02	0.19	11.28	0.18
HA 8	Pt	SC	–	–	25	0.47	2.97	0.03	5.13	0.18
HA 10	Pt	SC	–	–	27	0.68	2.83	0.05	6.31	0.19

Table 2 continued

Sample ID	Remark	Lithology	pH	ORP (mV)	OM (wt%)	Major oxides (wt%)				
						TiO_2	Fe_2O_3	MnO	CaO	P_2O_5
HA 12	Pt	SC	–	–	26	0.68	2.83	0.05	6.31	0.19
HA 13	Pt	SC	–	–	20	0.68	2.83	0.05	6.31	0.19
	Pt-Avg		7.4	−363	26	0.63	3.30	0.07	7.07	0.19
	Min				20	0.47	2.83	0.03	5.13	0.18
	Max				30	0.68	5.02	0.19	11.28	0.19

T tsunami, *Pt* pre-tsunami, *OM* organic matter, *SC* silt and clay, *SA* sand

thus decreases from the middle of the lagoon towards the corners. Hambantota lagoon tsunami sediment deposits present clear contrast (Fig. 2b), with grain size decreasing with increasing distance from the sea. The lagoon floor near the coastline is covered by brown colored fine-grained sands containing copious shell material, and a lesser amount of organic matter. However, the proportion of OM-rich black colored silt and clay increases toward the center of the lagoon. According to the field observations pre-tsunami sediments in the lagoon consists of fine to medium-grained sandy muds.

Chemical characteristics of the sediments

The OM contents of Hikkaduwa tsunami sediments are characteristically greater (58–80 wt%; average 69 wt%) than in Hambantota lagoon equivalents (34–50 wt%, average 42 wt%). However, pre-tsunami sediment samples in both lagoons have lower values (Hikkaduwa 25–38 wt%; Hambantota 20–30 wt%, Table 2), with an overall average of 29 wt%. Because those sediments are predominantly reflect weathering component of the basement. The values of onsite physico-chemical measurements of the sediments are given in Table 2. The sediments are generally characterized by neutral pH (6.6–7.9) and negative ORP (−83 to −380 mV).

The analyzed samples are characterized by wide ranges of Fe_2O_3 (0.76–12.99 wt%) and CaO (2.01–26.91 wt%) contents. The tsunami sediments are differentiated by higher values of both oxides (Table 2). However, abundances of MnO, P_2O_5 and TiO_2 in the tsunami and pre-tsunami sediments do not differ greatly (Table 2). The tsunami sediments are relatively enriched in chalcophile elements (As, Pb, Zn and Cu), although contents are more variable (Table 3). Arsenic concentrations in Hikkaduwa lagoon sediments are consistently greater than in Hambantota, but Zn, Pb and Cu values are similar in both lagoons. Abundances of ferromagnesian elements (Ni, Cr, V and Sc) and large cations (Y, Nb, Zr, Th and Sr) also tend to be higher in tsunami sediments than in the pre-tsunami sediments (Table 3). In some tsunami sediments Sr concentrations are exceptionally high (>1,000 mg/kg), but the average value is very similar to that in the pre-tsunami samples.

Concentrations of Cl, Br, I and total sulfur (TS) are highly elevated in both lagoons, characteristically in the tsunami sediments. As for other elements, overall average abundances of Cl, Br, I and TS in Hikkaduwa lagoon (3.9 wt%, 74.5 mg/kg, 13.7 mg/kg, 4.4 wt%, respectively) are also greater than in Hambantota lagoon (1.7 wt%, 25.1 mg/kg, 17.8 mg/kg, 1.8 wt%).

Comparison with possible sources

Average contents of TiO_2, Fe_2O_3, and P_2O_5 in tsunami and pre-tsunami sediments in both lagoons are similar to those in average upper continental crust (Rudnick and Gao 2005) and the basement rocks in the area (Fig. 3a). MnO is strongly depleted in Hikkaduwa lagoon, whereas the average in Hambantota lagoon is comparable to UCC. CaO and Sr are slightly enriched in both lagoons relative to UCC. Arsenic is enriched in Hikkaduwa lagoon tsunami sediments, whereas in Hambantota lagoon it is slightly depleted (Fig. 3a). In both lagoons average contents of Pb, Zn, Cu, Ni, Cr and V are depleted relative to UCC, but follow similar patterns to the basement rocks (Fig. 5a). Yttrium is slightly depleted, in contrast to relative enrichment in the basement rocks. Average abundances of Nb and Zr are similar to UCC but are slightly depleted relative to the basement rocks. Thorium is slightly depleted in Hambantota lagoon sediments, but the Hikkaduwa average is similar to that of the basement rocks. Abundances of Cl, Br and I are strongly enriched, with values tenfold those of crustal values (Fig. 3a). Normalization of average values in the tsunami sediments against the pre-tsunami average (Fig. 3b) shows that Fe_2O_3, As, Pb, Zn, Cu, Ni, Cr, V, Sr, Y, Th, Sc and Br are enriched in the former, whereas Zr, TiO_2, P_2O_5, Nb and iodine are somewhat depleted. This suggests that the tsunami sediments reflect marine influence, and contain significant amounts of ferromagnesian heavy minerals rather than resistant heavy minerals such as zirconium, apatite and rutile.

Table 3 Trace element abundances in Hikkaduwa and Hambantota lagoon sediments

Sample ID	Remark	Lithology	Trace element (mg/kg)															(wt%)	
			As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	Br	I	Cl	TS
Hikkaduwa																			
HI 1	T	SC	9	13	41	6	10	78	84	306	11	15	271	16	8	49	16	2.0	4.0
HI 2	T	SC	9	12	29	5	5	75	39	392	7	4	123	10	8	49	19	3.2	3.4
HI 3	T	SC	15	17	80	9	21	104	139	175	18	12	235	20	7	89	7	5.1	4.7
HI 4	T	SC	12	17	79	11	14	65	103	319	13	11	168	16	5	115		7.8	7.6
HI 5	T	SC	11	15	67	9	12	61	75	394	12	11	178	14	9	117	10	7.3	5.5
HI 6	T	SC	17	17	88	10	23	106	136	169	19	12	208	21	7	103	10	5.6	4.6
HI 7	T	SC	12	21	88	14	12	53	66	486	11	7	89	13	10	158	4	9.4	6.0
HI 8	T	SC	9	16	59	8	11	62	64	425	9	11	184	14	8	73	22	3.9	4.7
HI 13	T	SC	8	14	38	5	0	64	133	1,290	8	43	920	31	19	14		1.7	1.7
HI 14	T	SC	11	12	44	7	6	52	60	884	11	9		12	12	65		3.4	5.1
HI 15	T	SC	7	10	25	4	5	58	28	335	6	9	202	11	9	31	20	1.6	2.9
HI 16	T	SA	15	17	83	9	25	117	147	105	19	19	404	24	8	71	13	2.9	4.0
HI 17	T	SC	16	14	50	8	8	68	79	1,189	15	11	206	19	17	84		1.5	4.7
HI 18	T	SC	9	12	31	6	7	80	68	370	9	16	273	14	7	28	15	0.6	4.6
HI 19	T	SC	10	10	16	6	5	68	44	512	6	7	119	10	11	43	16	3.1	3.5
HI 20	T	SA	8	16	23	8	18	45	54	144	8	8	143	8	2	170	13	7.3	5.5
HI 23	T	SC	12	13	35	7	12	53	68	467	10	12	175	13	9	79	6	3.3	5.6
	T-Avg		11	14	52	8	11	71	82	468	11	13	244	16	9	79	13	4.1	4.6
	Min		7	10	16	4	0	45	28	105	6	4	89	8	2	14	4	0.6	1.7
	Max		17	21	88	14	25	117	147	1,290	19	43	920	31	19	170	22	9.4	7.6
HI 9	Pt	SA	3	8	8	2	0	53	0	383	3	4	132	4	7	13	30	1.6	1.0
HI 10	Pt	SA	9	14	48	9	12	59	76	328	11	14	281	16	5	111	5	6.9	6.3
HI 11	Pt	SA	4	11	39	2	4	84	125	286	5	31	703	20	8	16	20	2.0	1.7
HI 12	Pt	SC	5	12	24	5	1	47	59	1,027	5	22	450	12	15	27	7	2.6	2.0
HI 21	Pt	SA	11	17	55	8	20	73	95	156	15	12	257	15	4	108	13	5.2	5.8
HI 22	Pt	SC	10	13	38	7	13	45	59	622	11	9	93	11	9	97		4.1	5.9
	Pt-Avg		7	13	35	6	8	60	69	467	8	15	319	13	8	62	15	3.7	3.8
	Min		3	8	8	2	0	45	0	156	3	4	93	4	4	13	5	1.6	1.0
	Max		11	17	55	9	20	84	125	1,027	15	31	703	20	15	111	30	6.9	6.3
Hambantota																			
HA 1	T	SC	3	13	51	10	10	64	71	603	18	11	156	8	20	16	8	0.8	5.2
HA 3	T	SC	5	20	151	26	33	90	167	592	31	12	57	7	25	37	18	1.2	1.1
HA 4	T	SC	4	16	63	10	14	79	91	408	16	11	243	6	17	13	20	0.8	0.8
HA 5	T	SC	5	19	107	25	32	81	127	467	23	12	115	5	19	51	13	2.8	0.9
HA 6	T	SA	3	14	59	8	10	86	75	661	13	10	98	4	15	14	24	0.6	0.7
HA 7	T	SA	2	15	47	6	7	87	80	347	13	12	305	6	13	7	18	0.4	0.3
HA 9	T	SA	3	13	38	6	8	79	65	556	11	8	112	4	10	40	20	3.3	2.8
HA 11	T	SC	4	14	39	7	10	66	46	312	11	9	195	6	12	18	16	1.6	3.0
HA 14	T	SA	3	13	38	6	8	79	65	556	11	8	112	4	10	40	20	3.3	2.8
HA 15	T	SA	2	15	47	6	7	87	80	347	13	12	305	6	13	7	18	0.4	0.3
	T-Avg		3	15	64	11	14	80	87	485	16	11	170	6	15	24	18	1.5	1.8
	Min		2	13	38	6	7	64	46	312	11	8	57	4	10	7	8	0.4	0.3
	Max		5	20	151	26	33	90	167	661	31	12	305	8	25	51	24	3.3	5.2
HA 2	Pt	SC	3	15	72	12	17	61	96	601	24	11	158	5	20	22	12	1.0	2.3
HA 8	Pt	SC	4	14	38	5	10	63	54	288	11	10	255	7	6	48	16	3.4	2.8
HA 10	Pt	SC	3	14	41	9	10	78	66	328	12	10	240	7	9	21	21	1.8	1.5

Table 3 continued

Sample ID	Remark	Lithology	Trace element (mg/kg)															(wt%)	
			As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	Br	I	Cl	TS
HA 12	Pt	SC	3	14	41	9	10	78	66	328	12	10	240	7	9	21	21	1.8	1.5
HA 13	Pt	SC	3	14	41	9	10	78	66	328	12	10	240	7	9	21	21	1.8	1.5
	Pt-Avg		3	14	47	9	11	72	70	375	14	10	227	7	11	27	18	2.0	1.9
	Min		3	14	38	5	10	61	54	288	11	10	158	5	6	21	12	1.0	1.5
	Max		4	15	72	12	17	78	96	601	24	11	255	7	20	48	21	3.4	2.8

TS total sulfur, *SC* silt and clay, *SA* sand

Inter-element relationships

As shown in Figs. 4 and 5, significant positive linear correlations exist between Fe_2O_3 and the trace metals, and between total sulfur and Cl, Br, Fe_2O_3 and As in Hikkaduwa lagoon tsunami sediments. Hambantota lagoon tsunami sediments show negative correlations between total sulfur with As and Fe_2O_3 may be due to mixing with non-marine beach sediments during the tsunami; positive linear correlations exist between Fe_2O_3 and the trace metals, and between total sulfur with Cl and Br. Fe_2O_3 is also positively correlated with Cl and Br and negatively correlated with iodine. Positive correlation between Cl and Br also occurs in the tsunami sediments (Hikkaduwa $R = 0.89$, $n = 17$; Hambantota $R = 0.88$, $n = 11$), and both elements are negatively correlated with iodine (Hikkaduwa Cl $R = -0.61$, Br $R = -0.60$, $n = 17$; Hambantota Cl $R = -0.50$, Br $R = -0.50$, $n = 11$). A strong positive correlation also exists between Sr and CaO in

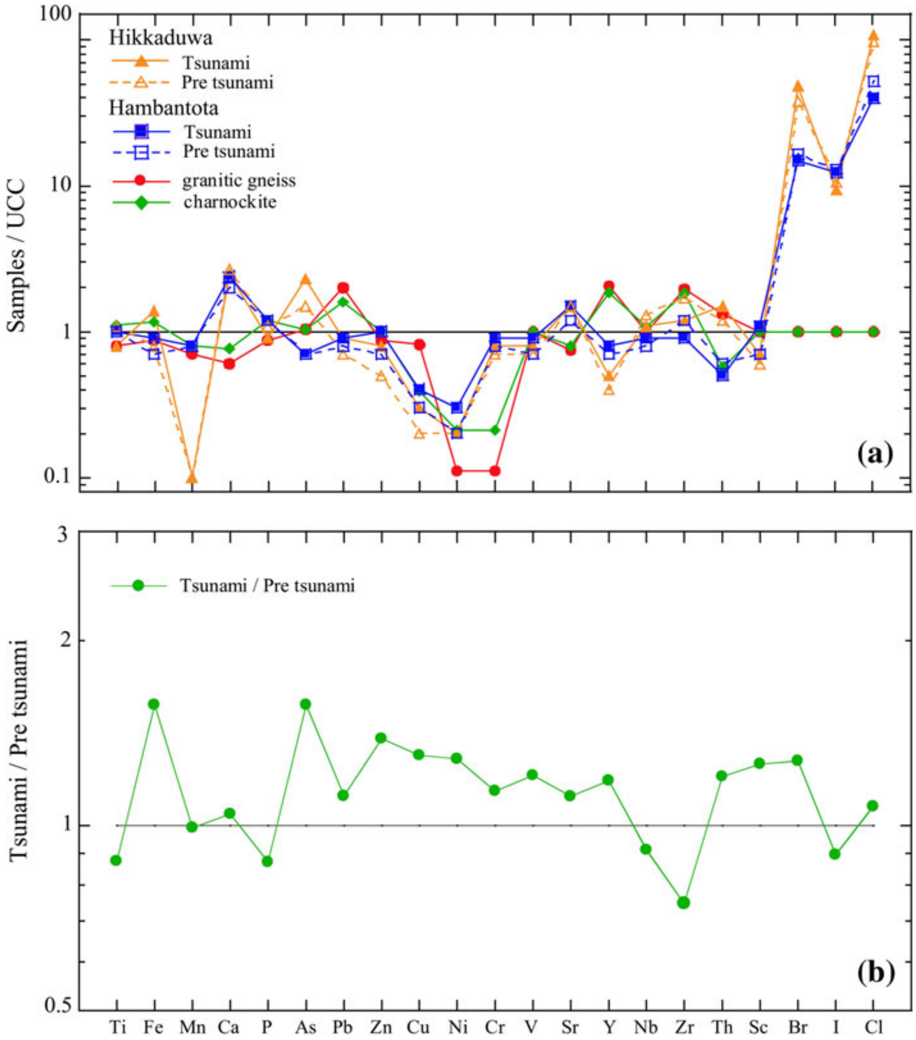

Fig. 3 Average bulk concentrations of major oxides and trace elements in the surface sediments from Hikkaduwa and Hambantota lagoons. **a** Normalized against average UCC composition (Rudnick and Gao 2005); data for local granitic gneiss and charnockite from Pohl and Emmermann (1991); **b** tsunami sediment average normalized against the pre-tsunami sediment average

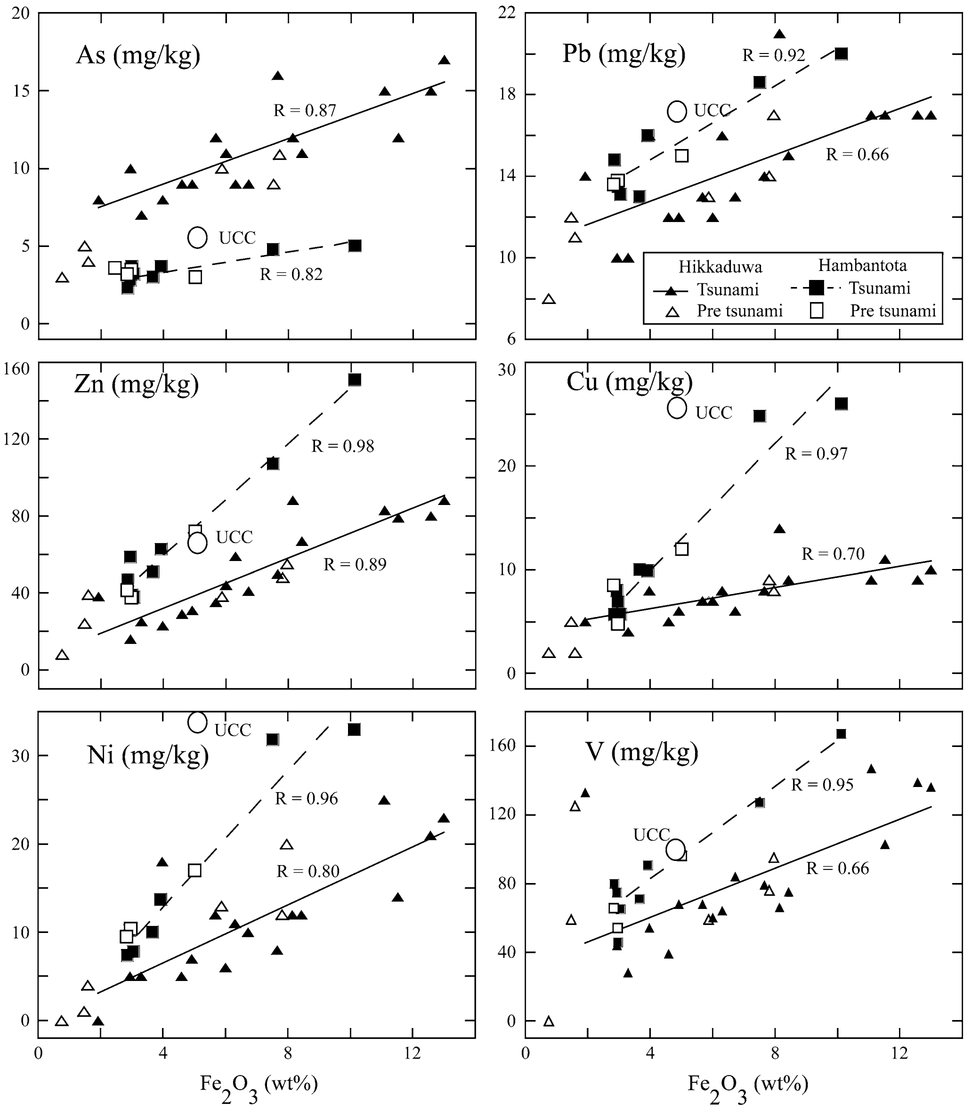

Fig. 4 Trace element (As, Pb, Zn, Cu, Ni and V)-Fe_2O_3 variation diagrams for Hikkaduwa and Hambantota sediments. Fitted regressions are for the tsunami sediments in each lagoon

the tsunami sediments (Hikkaduwa $R = 0.95$, $n = 17$; Hambantota $R = 0.68$, $n = 11$), and both are weakly or negatively correlated with all other elements.

Principal component analysis of the tsunami sediments is illustrated in Fig. 6. The analysis was done using correlation matrix which obtained from geochemical data. Component 1 accounts for 42% of the variance, and which reflects the carbonate phase (CaO and Sr). This component shows negative loading for all other elements except TiO_2, Nb, Zr, Th and Sc. This component suggested association of many shell fragments and heavy minerals with tsunami sediments. Principal component 2 accounts for 33% of the variance, and represents the association of Cl, Br, As, Th, Fe_2O_3 and total sulfur. Small positive loadings also occur for Ca and Zr.

Special features of the sediments

Enrichment of most of the elements (Fe_2O_3, Ca, As, Cl, Br and total sulfur) typically associated with marine sediments in the pre-tsunami samples. This is possibly due to original lagoon peat and bog soils formed during the Holocene marine transgressions, with subsequent changes arising from variation in salinity produced by evaporation of lagoon water due to high temperatures, coupled with mixing with in situ sediments (Dahanayake 1982; Dissanayake 1984; Katupotha and Fujiwara 1988).

Higher values of Cl and Br in many tsunami sediments compared to the pre-tsunami sediments suggest that the former may have experienced higher salinity conditions than those prevailing in normal lagoon environments. Positive correlations of these elements with total sulfur suggest that their source was seawater (Dellwig et al. 2002). This further implies that Cl and Br enrichment is an intrinsic signature of tsunami sediments, and hence these elements have used to study tsunami, palaeosalinity, and sea level changes (Szczuciński et al. 2005; López-Buendía et al. 1999; Chagué-Goff et al. 2002). However, iodine is depleted in the tsunami sediments relative to the pre-

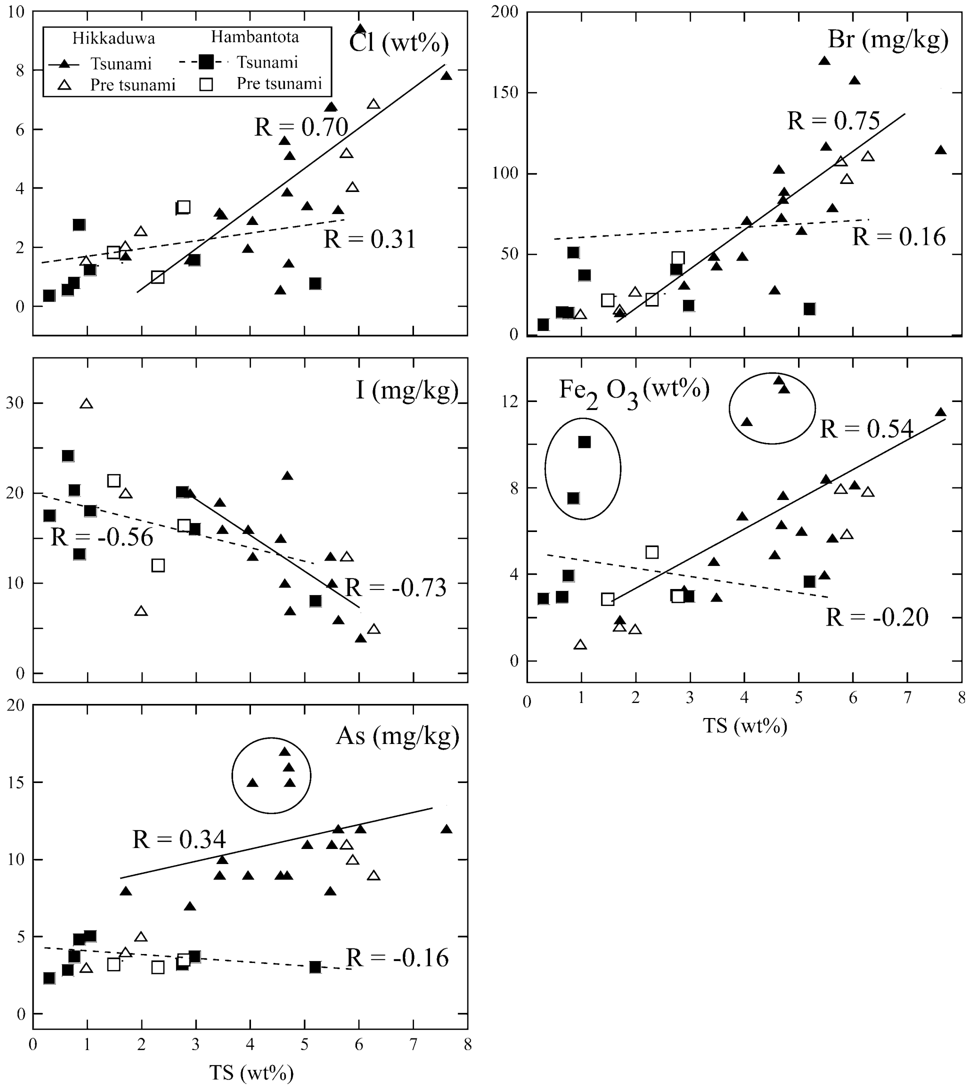

Fig. 5 Correlations between total sulfur (TS) and Cl, Br, iodine, Fe_2O_3 and arsenic. Regressions are for the tsunami data in each lagoon. *Circles* anomalous values

tsunami deposits, and shows negative correlation with sulfur (Figs. 3b, 5). Iodine is generally enriched in marine organic matter, and can be released to water during the mineralization of organic substances (Ullman and Aller 1985; Muramatsu et al. 2007).

CaO and Sr are major components of marine sediments, as they are usually associated with carbonate phases (Plank and Langmuir 1998), and consequently these parameters have been used to distinguish tsunami sediments (Szczuciński et al. 2005; López-Buendía et al. 1999; Nichol et al. 2007). High CaO and Sr values in the tsunami sediments in the present study suggest strong marine influence in the source (Tables 2, 3). Positive loadings for these elements in principal component 1 (Fig. 6) emphasize that CaO and Sr are dominant over the other elements. Biogenic carbonate is highly enriched in continental shelf areas, and thus the tsunami sediments indicate they predominantly originated from a shallow marine environment. Average Sr/Ca ratio (0.0054) is similar to the average levels seen in continental shelf areas (Guebuem et al. 1999; Müller 1966; Yan and Tang 2009).

Sulfur and Fe_2O_3 have been effectively utilized to study Holocene sea level changes and tsunami sediments in many parts of the world, because they are useful indicators that reflect brackish or marine environmental changes in coastal wetland sediments (Goff and Chagué-Goff 1999; Chagué-Goff et al. 2000, 2002). The pronounced enrichment of sulfur (Hikkaduwa 4.4 wt%, Hambantota 1.8 wt%) in this study is greater than the average level (0.3 wt%) in marine sediments (Berner 1970, 1982), suggesting that the sediments were deposited in marine conditions. The higher contents observed in tsunami sediments may be due to diffusion of sulfur into the sediments through reduction by sulfate bacteria under anoxic conditions developed by the abundant organic matter present. Sulfur also reacts with Fe_2O_3 in sediments and is fixed as FeS_2 (Berner 1970,

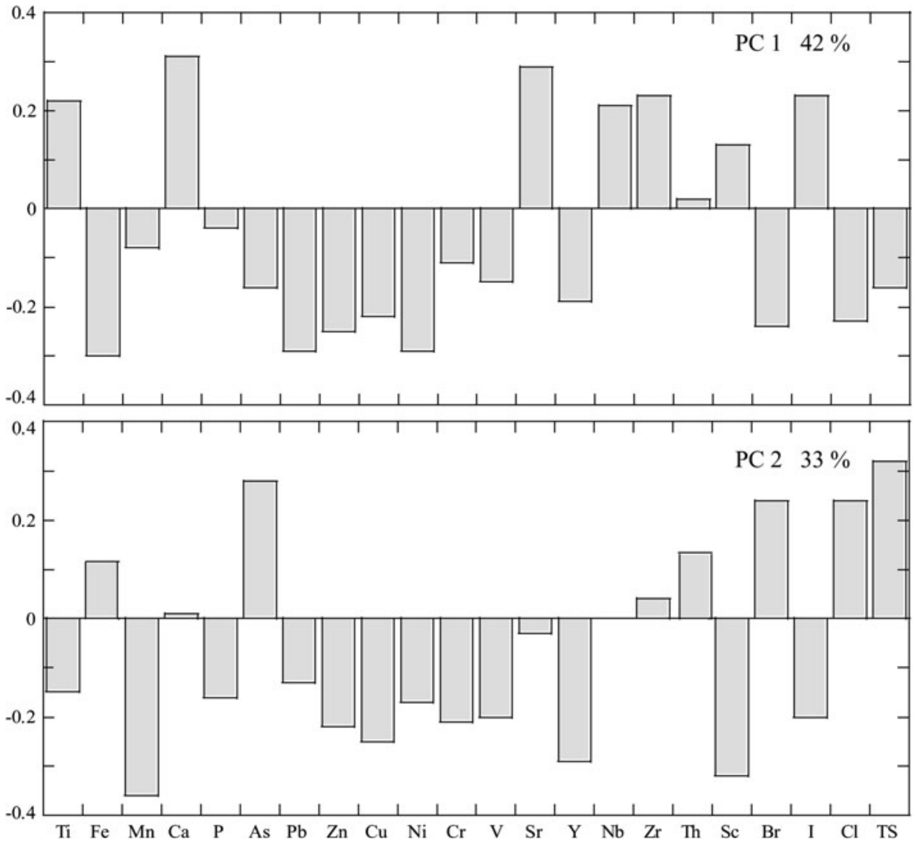

Fig. 6 Principal component analysis of the tsunami sediments to discriminate major components. Factors were determined by the Pearson's product-moment correlation matrix using Minitab 14 software

1982; Ishiga et al. 2000). The strong positive correlation between TS and Fe_2O_3 in Hikkaduwa lagoon (Fig. 5) thus suggest that the higher sulfur and Fe_2O_3 concentrations in the tsunami sediments are predominantly due to pyrite formation (Berner 1970). However, Hambantota lagoon shows negative correlation due to lower abundances of TS and Fe_2O_3 due to mixing of tsunami sediments with non-marine sediments during the tsunami.

Abundances of As, Pb, Zn, Cu and Ni in the tsunami sediments are high relative to the pre-tsunami deposits (Table 3; Fig. 3b). All these elements are closely associated with sulfur and have positive linear correlations with Fe_2O_3. This implies that they are also predominantly fixed as sulfides under anoxic conditions within the sediments (Ishiga et al. 2000; Bibi et al. 2006). The results of this study show that trace element correlations with Fe_2O_3 and/or sulfur are also useful chemical parameters for identifying tsunami deposits. However, arsenic is regarded as the most suitable indicator element for such studies due to enrichment in anoxic condition and seawater (Szczuciński et al. 2005; Chagué-Goff et al. 2002). High abundances of Pb, Zn, Cu and Ni seen in this study are also useful indicators, because these elements are relatively abundant in seawater and marine sediments (Dellwig et al. 2002).

Possible sources of the sediments

Tsunami sediments from Hikkaduwa lagoon show a scattered distribution on a Th–Sc–Zr/10 plot (Fig. 7a). The data lie toward to the Zr–Th edge and plot away from the value of sediments around the subduction zone (Plank and Langmuir 1998) in Sumatra where the tsunami waves originated (Fig. 7a). In contrast, Hambantota tsunami sediments show a flat-lying trend with variable Sc/Zr, trending differently from Hikkaduwa equivalents (Fig. 7a). However, some tsunami sediments also plot with the pre-tsunami samples, residual soils, marsh sediments, and basement rocks.

Hikkaduwa tsunami sediments have high Th/Sc and Zr/Sc ratios, plotting between the values typical of Phanerozoic granites, felsic volcanic rocks, and upper continental crust (Fig. 7b), thus indicating derivation from felsic source rocks. The variable Zr/Sc ratios and trend across the primary compositional trend reflects sorting and concentration of heavy minerals in both the tsunami and pre-tsunami sediments. Higher abundances of Sc in the Hambantota sediments suggest that their source was richer in mafic minerals (McLennan et al. 1993; Roser 2000), and may provide additional evidence for the association of such minerals in tsunamigenic sediments (Moore et al. 2007;

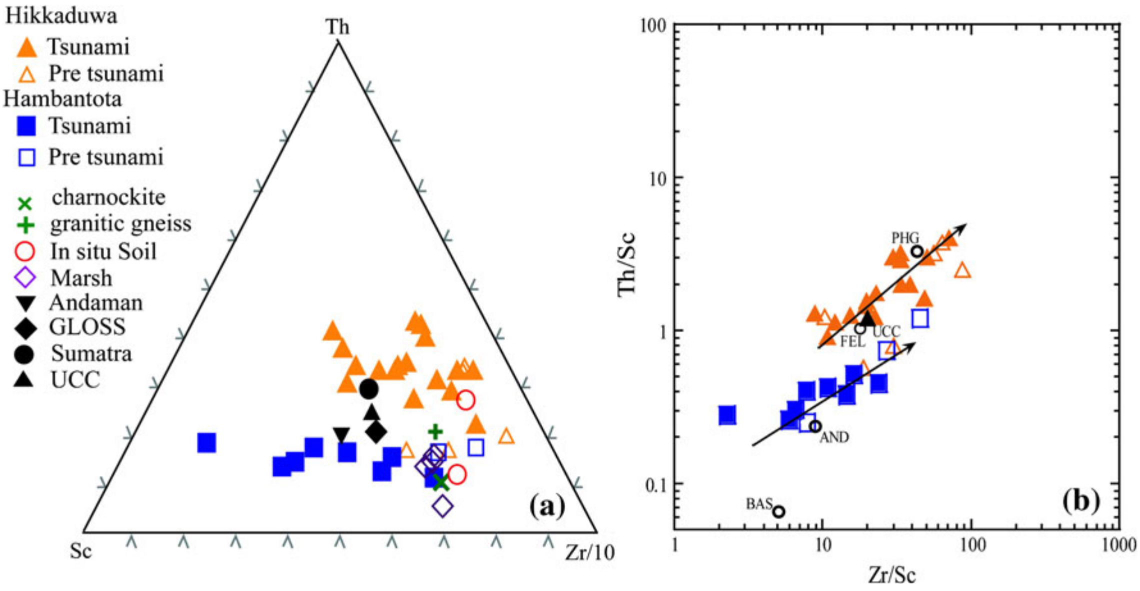

Fig. 7 **a** Th–Sc–Zr/10 plot (Bhatia and Crook 1986) for Hikkaduwa and Hambantota lagoon sediments and reference samples from soils and marsh lands (this study); charnockite and granitic gneiss (Pohl and Emmermann 1991); Andaman, Sumatra, and GLOSS sediment (Plank and Langmuir 1998), UCC (Rudnick and Gao 2005); **b** Th/Sc–Zr/Sc plot (McLennan et al. 1993; after Roser 2000). *Circles* igneous rock averages from Condie (1993); *PHG* phanerozoic granite; *FEL*, *AND*, *BAS* mesozoic-cenozoic felsic volcanic rock, andesite, and basalt, respectively

Morton et al. 2008). The Th/Sc–Zr/Sc plot also shows that Hambantota sediments are lie between andesite and felsic source at lower Th/Sc ratios, suggesting they have been derived from mafic mineral-rich charnockites (Fig. 7b). The scattered distribution of samples on the diagrams represents source change and sorting of the accumulated sediments in the shelf environment (Fig. 7a, b). In shallow marine environments, suspended sediments can be produced by earthquake vibration, and the wave velocity through the water column may bring such sediments to the coast (Weiss 2008; Zhang et al. 2009). The immobile element ratios in the pre-tsunami sediments are similar to those of local rocks, soils and marsh sediments. This implies that they are in situ sediments of local derivation (Fig. 7a).

Impacts on lagoon water

A clear contrast exists between the upper and the bottom waters of the lagoons in terms of ORP, DO, pH and turbidity, even at very shallow depths. Such variation can also exist laterally due to microbial mineralization of organic substances in bottom sediments (Markou et al. 2007) and may cause the prevailing anoxic conditions in the water overlying the organic matter-rich tsunami sediments (Table 1). Conditions that are more anoxic were observed in the bottom water of Hikkaduwa lagoon. The average pH of Hambantota lagoon water was 9.3. This may be coupled to phytoplankton photosynthesis, because the photosynthetic process consumes CO_2 (HCO_3–) and releases O_2 to the water, increasing DO (average 8.8 mg/l). However, Hikkaduwa lagoon lacks phytoplankton, thus lowering DO (3.5 mg/l). Production of carbonic acid due to decomposition of organic matter hence maintains the average pH around 7.6 (Lopes and Silva 2006). Moreover, the bottom water turbidity in water overlying organic matter-rich tsunami sediments in both lagoons is an intrinsic signature of microbial activities within the sediment (ThieBen et al. 2006). The salinity, conductivity and TDS of the lagoons show a brackish condition, although the values are much lower than those of seawater. In both lagoons, vertical variation of these parameters is insignificant (Table 1). This feature may be due to poor connection with the sea through narrow channels, or the particular morphological characteristics of each lagoon, which minimize seawater influence. The small tidal range around Sri Lanka may also be a contributing factor (Wijeratne and Rydberg 2007; Wijeratne and Pattiaratchi-web reference). Moreover, halogen compounds in sediments can create possible environmental effects, especially on the salinity of associated water bodies, because such compounds can freely dissolve in water due to their higher electronegativity and lesser redox sensitivity (Muramatsu et al. 2007; Killops and Killops 2005).

Physico-chemical measurements showed both the tsunami and pre-tsunami sediments had neutral pH and negative ORP. The negative ORP implies that the sediments were undergoing organic mineralization. In this process, oxygen in the system is reduced by sulfate-reducing and methane-producing bacteria, especially under negative ORP conditions at the surface of the sediments (5–20 cm depth) where highly active sulfate-reducing bacteria release H_2S to the lagoon water (Meyers et al. 1996; Killops and Killops 2005).

Role of tsunami waves on sedimentation

The higher organic matter contents of the tsunami sediments in both lagoons suggest that they were predominantly brought from a shallow marine environment, due to the high primary production in that zone (Killops and Killops 2005). The process of near-shore tsunami wave propagation may also contribute to more effective collection of organic matter from continental shelves rather than from slope or deep marine environments. Tsunami waves travel throughout the water column at equal velocity, but when they reach the continental slope deeper waves are obstructed and move upwards at lower velocity, while the velocity of the surface waves remains the same (Weiss 2008). Organic matter contents of Hikkaduwa lagoon tsunami sediments are relatively high. This may be due to stronger wave impact in the southwestern district than in the south, and variation of morphology of the continental shelf. A greater volume of OM-rich sediments may therefore have been transported from continental shelf and slope marine environments to Hikkaduwa lagoon (Weiss 2008). The lower abundances in Hambantota lagoon may have been controlled by lesser wave action, and hence greater contribution from shallow marine sediments and coastal sands.

Conclusions

Geochemical investigation of tsunami and pre-tsunami sediments reveal compositional contrasts. Tsunami sediments contain higher abundances of Cl, Br, As, Fe and total sulfur reflecting higher salinity and stronger marine influence. Higher values of Ca and Sr associated with OM-rich sediments are attributed to biogenic phases of shallow marine origin. Immobile element abundances and ratios indicate that the tsunami sediments were predominantly derived from a felsic source containing some mafic assemblages, further influenced by heavy mineral concentration and sorting. The compositional variations in the tsunami sediments according to the location are predominantly due to variation of wave strength, morphology of the continental shelf, and composition of local source rocks, reflected in the differing compositions in Hikkaduwa and Hambantota lagoons.

The physico-chemical properties of the lagoon waters suggest that there is significant influence from OM-rich tsunami sediments on oxidation–reduction potential of the bottom water, leading to the prevalence of strongly anoxic conditions and favorable conditions for mobility of redox-sensitive elements from the sediments to the lagoon water. This especially provides a favorable environment for anaerobic bacteria, promoting sulfate reduction and methane production.

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