

Effects of rainy season on mobilization of contaminants from tsunami deposits left in a coastal zone of Thailand by the 26 December 2004 tsunami

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Abstract Study on contamination of tsunami sediments deposited on 26 December 2004 conducted shortly after the tsunami in coastal zone of Thailand revealed elevated contents of salts in water-soluble and some heavy metals and arsenic in bioavailable fractions (Szczuciński et al. in *Env Geol* 49:321–331, 2005). Few months later rainy season started and effected in total rainfall of over 3,300 mm. This paper presents results of survey repeated 1 year after the tsunami. To assess the effects of rainy season on mobilization of previously determined potential contaminants, the same locations were sampled again and analysed with the same methods. The tsunami deposit layer was well preserved but in many locations the sediments were coarser than just after tsunami due to washing out of finer fractions. The water-soluble salts contents were strongly reduced after the rainy season. However, the concentrations of acid leachable heavy metals and metalloids were still elevated in comparison to reference sample from an area not impacted by tsunami. It is possible that the metals and metalloids are successively moved to more bioavailable fraction from forms which were more resistant to mobilization.

Keywords Tsunami deposits · Contamination · Bioavailable fraction · Coastal hazard · Thailand

Introduction

The large tsunami, which was generated by an earthquake on 26 December 2004, affected most of the countries around the Indian Ocean and was claimed to be one of the world's worst natural disasters in decades. Various aspects of its direct and indirect impacts were reported including medical, sociological, engineering, environmental and geological effects (e.g. Danielsen et al. 2005; Rigg et al. 2005; Ghobarah et al. 2006; Goff et al. 2006; Kench et al. 2006; Morgan et al. 2006; Mruthyunjaya Reddy et al. 2006; Satake et al. 2006; Babu et al. 2007). One of important consequences of the tsunami was deposition of sediment layer on the inundated coastal land areas. These sediments were reported to be rich in salts and other pollutants and buried the former soil horizon (UNEP 2005; Szczuciński et al. 2005, 2006; Boszke et al. 2006; Chaudhary et al. 2006). The tsunami deposits layer may present a long-term threat because accumulated salts and contaminants might be released to ground waters and plants in period of several years.

Thailand belongs to one of the most tsunami-affected countries where about 20,300 ha of land were covered by seawater (UNEP 2005). The tsunami reached in places more than 1.5 km inland (Bell et al. 2005; Siripong 2006; Szczuciński et al. 2006) and its maximum runup was about 15 m (Siripong 2006) but usually it was less than 10 m (Bell et al. 2005; Choi et al. 2006; Siripong 2006; Szczuciński et al. 2006; Thanawood et al. 2006; Tsuji et al. 2006). Most of the inundated area was blanket with

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a few to several tens of centimetres thick layer of tsunami sediments (Bishop et al. 2005; Szczuciński et al. 2005, 2006) with maximum values of more than 0.5 m. These sediments are composed mainly of silty sand and sand and in distance of 500 m and more from the shoreline they generally do not exceed thickness of 2 cm (Szczuciński et al. 2006). Shortly after the tsunami samples were collected from the tsunami deposits and also from soils not covered by the tsunami (Szczuciński et al. 2005). There was no rainfall between the tsunami and the sampling survey, so the chemical composition was not altered by washing. The analysis revealed that the tsunami deposits have elevated contents of salts (Na^+ , K^+ , Ca^{+2} , Mg^{+2} , Cl^- , SO_4^{-2}) in water-soluble fraction, heavy metals (Cd, Cu, Pb, Zn) in acid leachable fraction (assumed to be bioavailable), and arsenic in the exchangeable fraction in relation to the reference sample taken from soil of similar grain size composition but not covered by the tsunami (Szczuciński et al. 2005). For the same set of samples also mercury fractionation was performed (Boszke et al. 2006) and it was found that although the difference in the total mercury content are very small, the highly toxic organomercury fraction contribution is higher in the tsunami deposits. Several months after the tsunami rainy season started and total precipitation during that period reached more than 3,300 mm as measured at Phang Nga province meteorological station (Szczuciński et al. 2006). The same sampling locations as studied in 2005 were revisited one year after the tsunami and the tsunami deposits were found to be almost not altered in regard of thickness and spatial distribution (Szczuciński et al. 2006). This study repeats the same analysis as immediately after the tsunami (Szczuciński et al. 2005) to assess the effects of the rainy season on mobilization of contaminants from those deposits. Additionally analysis of arsenic in fractions of varying bioavailability were performed on samples from both: 2005 and 2006 field campaign.

The major objective of our study is to assess long-term impact of tsunami on coastal environment by analysis of effects of rainy season on mobilization of salts and bioavailable (acid leachable and exchangeable fractions) heavy metals and metalloids from tsunami deposits left on land. In the study also usefulness of salt content as a proxy of paleotsunami deposits recognition and preservation potential of the tsunami deposit layers will be discussed.

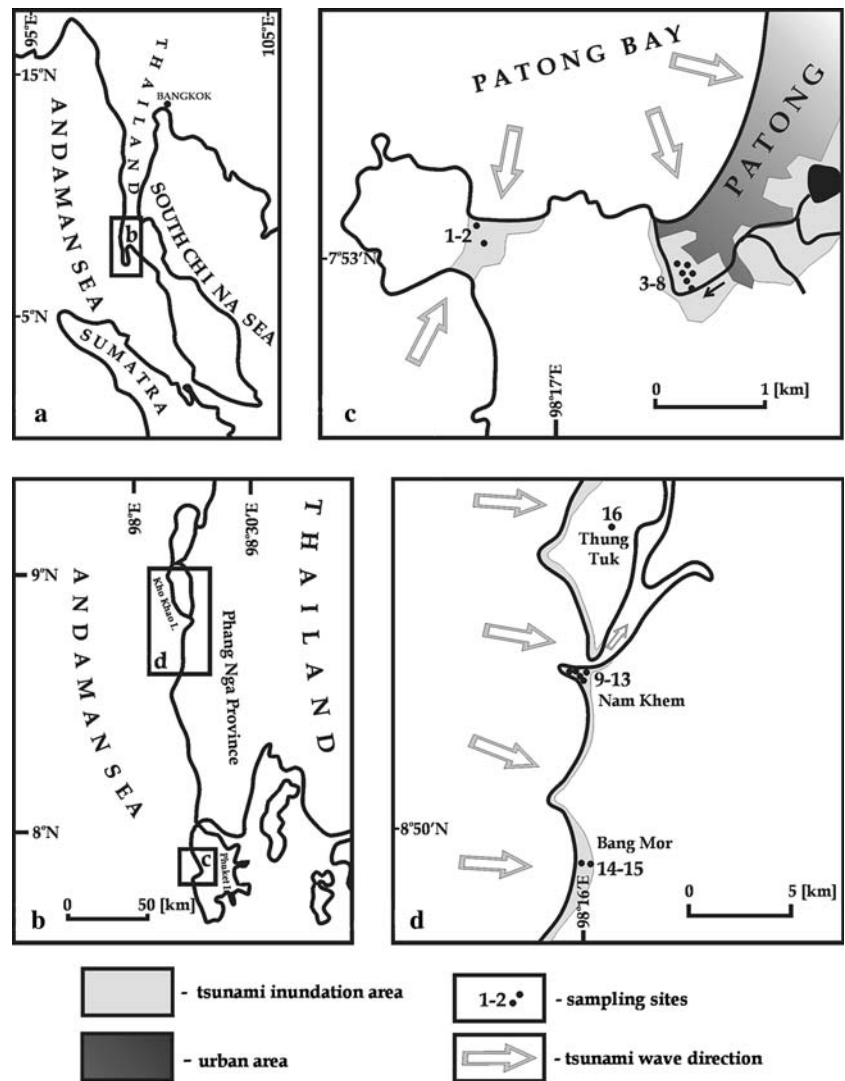
Material and analytical techniques

Samples were collected from the area flooded on the 26 December 2004 tsunami during field campaign

conducted in February 2006. In most cases, the sampling locations (Fig. 1 and Table 1) were identical with those from the previous survey (Szczuciński et al. 2005). Only in the cases where tsunami deposit layer was removed (usually due to cleaning actions) or if it was not possible to approach the former locations, the samples were collected from nearby region (see Table 1) covered with similar tsunami sediments and being in approximately the same distance from the shoreline. The entire tsunami sediments layer was sampled unless it was thicker than 5 cm. Otherwise only the uppermost few centimetres thick layer was collected. One additional sample (16) was taken for reference from an area out of reach of the tsunami wave. Samples were collected using plastic tools and packed into polyethylene bags. Collected samples were affected by UV irradiation (field lamp with antibacterial fluorescent light by Philips) in order to limit biological activity after the sampling. They were transported within 2 weeks to laboratories. They were divided into subsamples for sedimentological and chemical analysis.

To determine grain size distribution, the subsamples were dried and sieved into 13, 0.5-phi interval, grain size fractions ranging from gravel to mud. Salts contained in water-soluble fraction of the samples were determined by standard titration method (Greenberg et al. 1992). A water extract was obtained from 1 g of sample treated for 24 h with 100 ml of deionized water. In the prepared extracts: Na, K, Ca, Mg, Cl and SO_4 were measured. The accuracy of measurements was tested by ion balance. Heavy metals (Cd, Cr, Cu, Ni, Pb and Zn) were analysed from extracts obtained by 1-h extraction with 2 mol HCl in 80°C. In this way all the metals, which are potentially bioavailable were separated. The metals were measured with AAS spectrometer in flame mode. The limits of determination were 0.06, 0.22, 0.04, 0.05, 0.5 and 0.14 (mg kg^{-1}) for Cu, Pb, Cd, Zn, Ni and Cr, respectively. Metalloids: As, Se and Sb, were measured in solution extracted by phosphate buffer (concentration of PO_4 about 50 mmol l^{-1} and pH around 6.0) in 80°C for 1 h. Such an extraction is believed to release exchangeable fraction of the metalloids (Orero Iserte et al. 2004). For As determination in the samples analysed in this study and also for those collected in 2005 (the same as presented by Szczuciński et al. 2005) the acid extraction following the procedure of heavy metals bioavailable fraction analysis was additionally performed. Concentrations of metalloids were measured with HG AAS equipment (220FS spectrometer by SpectrAA) with hydride generation unit VGA-77 (Varian). The determination limits were 15 $\mu\text{g kg}^{-1}$

Fig. 1 Study area and sampling sites locations (after Szczuciński et al. 2005)



for all the determined metalloids and the uncertainty below 10%.

Sampling sites

Sampling sites were located in a range of settings representing variable morphology, degree of tsunami damages and pre-tsunami human impact (Fig. 1 and Table 1). Samples 1 and 2 were collected on a narrow isthmus on peninsula, which encompass the southern edge of Patong Bay. Both samples were taken from local small depressions/ponds. The location 2 was subjected to flashing by wastewater. Samples 3–8 were taken from a low-lying terrain, adjacent to a small river in the southern part of Patong city. In a village Nam Khem, which was largely damaged, samples 9–13 were collected. Samples 14 and 15 were collected in tsunami

inundated zone in a vicinity of Bang Mor village, and sample 16 was taken as a reference sample from area not inundated by the tsunami in a neighbourhood of Thung Tuk village.

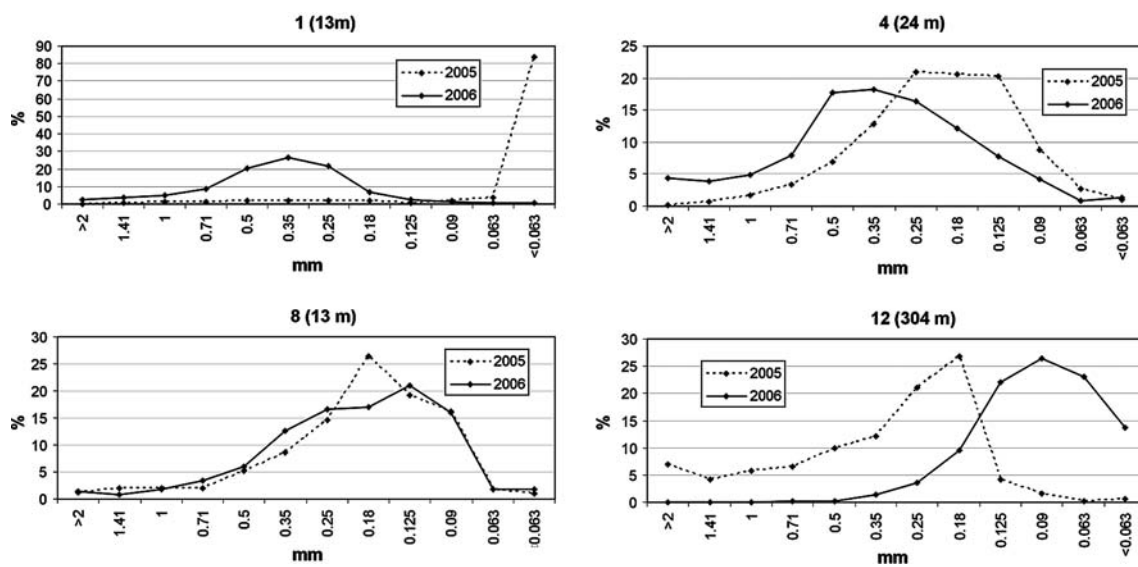
Results

Sediment characteristic

Tsunami deposits at the studied locations are in the form of few centimetres to few tens of centimetres thick, sheet of fine and medium sand. The layer usually resolves upward fining of grain size (in 1–3 sequences). They are generally poorly sorted (Fig. 2) and their mean grain size varies between coarse silt and coarse sand (Table 1). However, most of the samples are in the range of very coarse silt to medium sand. The

Table 1 Sampling locations including distance from the shoreline and calculated distance to the locations of sampling sites from the previous survey in 2005

Sample	Location	Latitude N	Longitude E	Distance from shoreline (m)	Distance to 2005 sampling location (according to GPS coordinates) (m)	Sediment mean grain size (according to method by Folk and Ward 1957)
1	Patong Bay	7°53.088′	98°16.443′	75	13	Medium sand
2	Patong Bay	7°53.014′	98°16.435′	315	17	Very coarse silt
3	Patong	7°52.924′	98°17.309′	430	108	Medium sand
4	Patong	7°52.910′	98°17.320′	480	24	Medium sand
5	Patong	7°52.887′	98°17.328′	520	11	Medium sand
6	Patong	7°52.864′	98°17.349′	545	41	Medium sand
7	Patong	7°52.953′	98°17.328′	390	96	Coarse sand
8	Patong	7°52.938′	98°17.336′	410	13	Fine sand
9	Nam Khem	8°51.470′	98°15.930′	60	19	Very fine sand
10	Nam Khem	8°51.417′	98°15.953′	100	325	Coarse silt
11	Nam Khem	8°51.405′	98°16.310′	570	40	Very coarse silt
12	Nam Khem	8°51.553′	98°15.940′	50	304	Very fine sand
13	Nam Khem	8°51.618′	98°16.527′	1,100	6	Very find sand
14	Bang Mor	8°49.973′	98°16.128′	300	72	Very find sand
15	Bang Mor	8°49.907′	98°16.271′	590	172	Very coarse silt
16	Thung Tuk	8°53.766′	98°16.694′	1,500	0	Medium sand

**Fig. 2** Examples of grain size distribution for four representative locations sampled in 2005 and in 2006. After the site sampling number, a GPS-based distances between coordinates of the locations in particular years are given (in *brackets*)

samples collected from river valley in Patong town area are generally coarser (medium and coarse sand) than the remaining.

Salts in water-soluble fraction of sediments

Concentrations of major ions determined in water-soluble fraction are reported in Table 2. For all the analyzed samples contents of K and Mg were higher in the tsunami deposits than in the reference sample (16). Except samples 2 (1,300 mg kg⁻¹) and 8 (180 mg kg⁻¹),

the K content is in range of 21–85 mg kg⁻¹. Also in regard to concentration of Mg in water-soluble fraction, the samples 2 and 8 are outstanding with values of 2,100 and 450 mg kg⁻¹, respectively. The range of Mg content for the rest of samples is from 5 to 250 mg kg⁻¹. In the case of Ca, only sample 6 (18 mg kg⁻¹) had lower concentrations than the reference one (56 mg kg⁻¹). Most of the samples had Ca content between 130 and 1,600 mg kg⁻¹. Maximum values are again in samples 2 and 8, 1,800 and 6,800 mg kg⁻¹, respectively. Contents of SO₄ were at the lowest level

Table 2 Contents of salts (K, Na, Ca, Mg, Cl, SO₄) leached with deionized water in mg kg⁻¹ of dry mass

Sample	K (mg kg ⁻¹)	Na (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)	Cl (mg kg ⁻¹)	SO ₄ (mg kg ⁻¹)
1	85	58	370	92	300	300
2	1,300	26,000	6,800	2,100	34,000	35,000
3	74	147	1,100	78	700	800
4	77	1,200	130	120	2,000	600
5	80	130	210	57	300	200
6	55	85	18	19	300	50
7	61	1,000	340	160	1,700	220
8	180	3,700	1,800	450	8,000	3,400
9	23	95	420	40	200	50
10	35	100	1,300	51	300	50
11	85	1,100	690	200	900	1,300
12	46	98	818	94	1,000	50
13	67	718	793	184	960	820
14	71	260	1,400	250	960	1,100
15	33	110	1,600	75	900	500
16	21	280	56	5	400	50

(50 mg kg⁻¹) in samples 6, 9, 10, 12 and 16 (the reference). Maximum values were measured in samples 2 (350,000) and 8 (3,400), and in the remaining samples they are in range of 200–1,300 mg kg⁻¹. Concentrations of Na and Cl were lower than in the reference samples in samples: 1, 3, 5, 6, 9, 10, 12 and 14 for Na and in 1, 5, 6, 9 and 10 for Cl, respectively. In the remaining samples concentrations of these ions were higher (in the sample 2 significantly higher) than in the reference sample. The ranges of measured values were for Na from 58 to 26,000 and for Cl from 300 to 3,4000 mg kg⁻¹. Among the analysed samples, three are particularly outstanding the sample 2, 8 and 6. The first two are characterized by several times higher values of the studied ions and the last by the lowest values.

Heavy metals in acid leachable fraction of sediments

Following elements were analysed among the heavy metals: Cd, Cr, Cu, Ni, Pb and Zn. The obtained results are listed in Table 3. The concentrations of these metals in acid leachable fraction of tsunami deposits were in almost all cases much higher than in the reference sample (16).

Concentrations of Cd in tsunami deposits is generally several times higher than in the reference sample (0.44 mg kg⁻¹), except sample 4, where very low value of Cd (0.07 mg kg⁻¹) was measured. The remaining samples have concentrations in range of 0.46–2.8 mg kg⁻¹, and only in sample 14 extraordinary high value of 13.3 mg kg⁻¹ was measured. Cr had higher concentrations in all the analyzed tsunami deposits samples than in the reference one (0.73 mg kg⁻¹) and are in the range of 0.89 mg kg⁻¹ for sample 7 to 8.6 mg kg⁻¹ for sample 2. The lowest concentration of Cu was

found in sample 4 (0.95 mg kg⁻¹) and in the reference sample (1.2 mg kg⁻¹). The highest concentrations are in samples 2, 7 and 14 (in the range 12–14 mg kg⁻¹). The remaining samples have concentrations between 1.4 and 3.5 mg kg⁻¹). Ni in tsunami deposits revealed higher concentrations than in the reference sample (<0.5 mg kg⁻¹). Its contents were in range of 0.69 (for sample 5) to 3.7 mg kg⁻¹ (for sample 8). Also in the case of Pb all the tsunami deposits had 2–13 times higher concentrations. They were in the range of 8.6 (for sample 4) to 62 mg kg⁻¹ (sample 2). In the case of Zn the values on tsunami deposits were 2–28 times higher than in the reference sample. They were in range of 3.6–45 mg kg⁻¹, in samples 4 and 13, respectively.

Concerning the spatial changes, the lowest values of the analysed metals were in the reference sample and in tsunami deposits from Patong town (samples 3–7) and in some samples from Nham Khem (9 and 11). The highest concentrations of all the metals were in samples 1, 2 (both from the area south of Patong Bay), 13 (Nham Khem) and 14 (Bang Mor). The differences between the highest and lowest measured concentrations were usually large—at least of an order of magnitude.

Metalloids in exchangeable fraction of sediments

Arsenic in exchangeable fraction is from 329 µg kg⁻¹ for the reference sample to 2,009 µg kg⁻¹ for sample 2. Values above 1,000 were note also in samples 11, 13 and 15—from Nham Khem and Bang Mor areas. Detected range of Sb concentrations in the studied samples was from 65 to 671 µg kg⁻¹. Maximum value was detected in sample 2. In samples 10,11 and 15 values of Sb were close to that in the reference sample and in

Table 3 Heavy metals in acid leachable sediment fraction

Sample	Cd (mg kg ⁻¹)	Cr (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Ni (mg kg ⁻¹)	Pb (mg kg ⁻¹)	Zn (mg kg ⁻¹)
1	0.93	2.6	3.4	2.9	24	13
2	2.8	8.6	12	1.8	62	42
3	0.46	2.0	2.9	3.0	19	10
4	0.07	1.1	0.95	2.4	8.6	3.6
5	0.54	1.5	1.5	0.69	12	7.4
6	0.53	3.0	3.4	1.1	13	5.4
7	0.90	0.89	14	0.71	21	32
8	0.95	2.6	3.0	3.7	18	7.0
9	0.94	2.5	2.1	0.86	12	8.1
10	1.5	5.1	1.8	1.1	14	6.8
11	2.0	4.9	2.2	0.86	20	6.6
12	1.3	4.7	2.1	0.91	18	6.8
13	2.7	3.2	3.5	0.93	24	45
14	13.3	7.7	13	1.3	49	18
15	1.4	5.9	1.4	1.4	9.7	6.0
16	0.44	0.73	1.2	<0.5	4.8	1.6

samples 12 and 14 were lower. In the case of selenium maximum value was detected again in sample 2 (160 $\mu\text{g kg}^{-1}$). The remaining samples had concentrations in the range of <15–90 $\mu\text{g kg}^{-1}$. For ten samples detected, Se contents were lower than in the reference sample (Table 4).

Arsenic in acid leachable fraction of sediments

Arsenic determined in acid leachable fraction was measured for samples collected from the same locations shortly after the tsunami—in February 2005 (details in Szczuciński et al. 2005) and in 2006. The results are presented in Table 5. In both sets, the values for reference sample (16) are much lower (670 and 594 $\mu\text{g kg}^{-1}$) than for tsunami deposits (690–6,169 $\mu\text{g kg}^{-1}$). In tsunami deposits samples collected in 2005, arsenic content was in the range of 770–1,680 $\mu\text{g kg}^{-1}$ for locations around Patong Bay (samples 1–8) and

between 2,570 and 3,655 $\mu\text{g kg}^{-1}$ for samples from Nham Khem and Bang Mor (9–15). This difference was also evident in samples collected in 2006. However, for most of the locations, the As concentrations increased even fourfold. Only in the case of sampling locations 1, 4 and 7 decrease was observed. The ranges of As concentrations in 2006 were 690–4,316 and 4,154–6,169 $\mu\text{g kg}^{-1}$ for samples from around Patong Bay and from Nham Khem and Bang Mor, respectively.

Interelement relationships

Table 6 presents the correlation matrix of the analysed elements in the studied sediments. Very high positive correlation (≥ 0.95) is between major ions in water-soluble fraction (Na, K, Ca, Mg, SO_4 , Cl). High cor-

Table 4 Metalloids in exchangeable fraction

Sample	As ($\mu\text{g kg}^{-1}$)	Sb ($\mu\text{g kg}^{-1}$)	Se ($\mu\text{g kg}^{-1}$)
1	529	106	22
2	2,009	671	160
3	765	158	90
4	646	169	<15
5	487	175	29
6	490	159	23
7	403	121	<15
8	807	323	48
9	730	222	30
10	791	108	<15
11	1,260	203	<15
12	556	65	<15
13	1,859	277	52
14	332	71	70
15	1,205	108	<15
16	329	104	33

Table 5 Arsenic concentrations in acid leachable fraction in samples collected in the 2005 and 2006 year

Sample	Year of sampling	
	2005 ($\mu\text{g kg}^{-1}$)	2006 ($\mu\text{g kg}^{-1}$)
1	1,680	998
2	935	4,316
3	865	1,815
4	1,645	1,636
5	900	1,285
6	1,035	1,496
7	770	690
8	1,165	1,814
9	3,175	n.a.
10	3,510	5,515
11	3,450	5,764
12	2,730	5,098
13	2,570	4,154
14	3,320	6,169
15	3,655	4,280
16	670	594

n.a. Not analysed

relations (≥ 0.60) were found also for in relations between them and between metalloids and water-soluble salts. Among the heavy metals statistically significant correlations were for Pb with all the studied elements except Ni and As, for Zn (except Cd, Cr and Ni). Also Cr was well correlated with other elements apart from Se, Sb, Cu, Ni and Zn. Cu revealed high correlation only to Cd and Pb. Ni was not correlated at statistically significant level to any of the studied elements.

Intersite relationships

Correlation indexes were also calculated for similarities in composition of samples from different locations. This analysis was performed for results presented in this paper—1 year after the tsunami, as well as, for results obtained for samples collected shortly after the tsunami and published previously by Szczuciński et al. (2005). The correlation matrices are presented in Table 7—for data from 2005, and in Table 8—based on the results presented in this paper. The correlations between the sampling sites in 2005 were very high (in most cases ≥ 0.95) and for all the analysed cases were statistically significant. The weakest correlation had sample 16 (the reference), however, it was still above 0.57. For the samples analysed in this paper, the intersite correlations were much weaker, although, still most of the correlation indexes were above 0.5. Statistically significant correlations were obtained for sample 15 in all the cases, and samples 5, 12, 13 in only correlation with sample 2 were below 0.5. The latter sample was positively correlated only with 6 other samples. The remaining of the samples had high correlations with 9–13 other sampling sites.

Discussion

Effect of rainy season on tsunami deposits

The tsunami deposits were generally well-preserved 1 year after the tsunami and after the rainy season. The thickness of the layer was the same as shortly after the tsunami, except places where man-made changes were done (cleaning, earth works etc.). Such a situation was documented for a wider area of the coastal zone of Thailand (Szczuciński et al. 2006). Among the studied sites only at the former locations 10 and 12 new constructions were built and the tsunami sediments were removed so the samples were collected from sites located nearby.

Comparison of grain size distributions of the sediments analysed in 2005 and in the present study shows four different scenarios (Fig. 2). Several samples are not altered in regard of grain size distribution (2, 8, 9, 13), in this group is also the reference sample (16). In the case of sample 1, the sediment sampled in present study was much coarser. It is the effect of large spatial changeability at that location, where due to uneven ground the characteristics of tsunami deposits change over short distances. Two samples (12 and 15) were slightly finer. The both locations were, however, sampled in distance of about 100 m from the 2005 locations. The most common situation is that the sediments collected in 2006 are slightly coarser. Such a change was found for a half of the studied the samples (3, 4, 5, 6, 7, 10, 11, 14). Most of them were collected at exactly the same locations as previously or very close to them. The sediment type changed there from fine sand to medium sand (Fig. 2). It was probably caused by

Table 6 Correlation coefficient matrix of the analysed elements and compounds

	Na	K	Ca	Mg	SO ₄	Cl	Se	As	Sb	Cd	Cr	Cu	Ni	Pb	Zn
Na	1.00	1.00	0.95	0.99	1.00	1.00	0.83	0.63	0.91	0.06	0.54	0.48	0.16	0.74	0.56
K		1.00	0.95	0.99	1.00	0.99	0.84	0.63	0.90	0.08	0.55	0.48	0.17	0.76	0.56
Ca			1.00	0.96	0.95	0.95	0.80	0.67	0.84	0.21	0.72	0.48	0.22	0.79	0.54
Mg				1.00	0.99	0.99	0.81	0.64	0.91	0.15	0.59	0.53	0.19	0.80	0.59
SO ₄					1.00	0.99	0.84	0.64	0.90	0.09	0.57	0.48	0.15	0.76	0.56
Cl						1.00	0.83	0.62	0.91	0.06	0.53	0.47	0.22	0.73	0.54
Se							1.00	0.60	0.85	-0.06	0.29	0.28	0.31	0.59	0.53
As								1.00	0.74	-0.03	0.50	0.09	0.07	0.45	0.64
Sb									1.00	-0.06	0.38	0.31	0.23	0.60	0.58
Cd										1.00	0.62	0.58	-0.10	0.64	0.26
Cr											1.00	0.41	-0.04	0.74	0.32
Cu												1.00	-0.06	0.78	0.67
Ni													1.00	0.13	-0.08
Pb														1.00	0.68
Zn															1.00

The bold indexes are significant at level of confidence $p < 0.05$. $N = 16$

Table 7 Correlation coefficient matrix of the sampling sites based on their chemical composition from 2005 (data after Szczuciński et al. 2005)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1.00	0.98	0.99	0.96	0.99	0.99	0.95	0.96	0.99	1.00	0.92	0.94	0.69	0.99	0.71	0.64
2		1.00	0.99	0.95	0.99	1.00	0.98	0.99	0.99	0.98	0.95	0.99	0.82	0.99	0.72	0.67
3			1.00	0.98	1.00	0.99	0.97	0.98	1.00	1.00	0.93	0.97	0.74	1.00	0.74	0.71
4				1.00	0.97	0.96	0.97	0.96	0.97	0.96	0.95	0.96	0.70	0.97	0.84	0.78
5					1.00	0.99	0.97	0.98	1.00	1.00	0.92	0.97	0.74	1.00	0.72	0.69
6						1.00	0.98	0.99	1.00	0.99	0.95	0.98	0.79	0.99	0.74	0.68
7							1.00	1.00	0.97	0.95	0.96	1.00	0.85	0.97	0.79	0.75
8								1.00	0.98	0.97	0.96	1.00	0.86	0.98	0.77	0.72
9									1.00	1.00	0.95	0.97	0.75	1.00	0.75	0.70
10										1.00	0.92	0.96	0.71	0.99	0.71	0.67
11											1.00	0.96	0.80	0.94	0.90	0.76
12												1.00	0.87	0.97	0.78	0.74
13													1.00	0.75	0.60	0.57
14														1.00	0.74	0.70
15															1.00	0.80
16																1.00

The bold indexes are significant at level of confidence $p < 0.05$. $N = 15$

Table 8 Correlation coefficient matrix of the sampling sites based on the chemical composition from 2006

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1.00	0.41	0.92	0.49	0.95	0.76	0.45	0.47	0.88	0.79	0.80	0.76	0.93	0.73	0.92	0.63
2		1.00	0.53	0.84	0.44	0.27	0.77	0.91	0.09	0.08	0.77	0.44	0.49	0.66	0.34	0.60
3			1.00	0.47	0.79	0.50	0.46	0.56	0.76	0.83	0.77	0.80	0.80	0.93	0.95	0.50
4				1.00	0.62	0.61	0.97	0.95	0.32	0.19	0.72	0.66	0.63	0.49	0.43	0.90
5					1.00	0.91	0.56	0.52	0.89	0.67	0.82	0.73	0.97	0.57	0.81	0.80
6						1.00	0.55	0.43	0.78	0.44	0.63	0.61	0.85	0.22	0.58	0.85
7							1.00	0.94	0.34	0.27	0.63	0.74	0.57	0.51	0.47	0.88
8								1.00	0.23	0.22	0.68	0.70	0.53	0.66	0.47	0.76
9									1.00	0.87	0.62	0.72	0.86	0.50	0.87	0.62
10										1.00	0.50	0.77	0.68	0.69	0.94	0.38
11											1.00	0.56	0.90	0.68	0.68	0.75
12												1.00	0.69	0.74	0.88	0.70
13													1.00	0.59	0.81	0.80
14														1.00	0.82	0.36
15															1.00	0.54
16																1.00

The bold indexes are significant at level of confidence $p < 0.05$. $N = 15$

washing of finer particles during heavy rains. The depletion in fine sediment fraction is not observed in finer deposits (silts). The washing in sands, which were poorly sorted (Szczuciński et al. 2005), could be facilitated by removing fine particles—not loaded by overlying grains, from spaces between larger grains forming the framework of the deposits.

Effect of rainy season on content of the contaminants

Water-soluble salts, acid leachable heavy metals and arsenic, and exchangeable metalloids were studied for the same locations shortly after the tsunami

(Szczuciński et al. 2005) and 1 year later—after the rainy season (this study—2006). Comparison of the obtained results is presented in Fig. 3.

The major changes are observed in contents of water-soluble salts. Generally their concentrations are much lower in 2006, except of samples 2 and 8. The observed decline in salt content is attributed to dissolution by freshwater during rainy season. Sample 2 is characterized by maximum values of all the studied elements (including heavy metals and metalloids). It was collected at a location impacted by wastewaters from anthropogenic activity, which is probably the reason for outstanding concentrations of contaminants. Although, generally the water-soluble salts are

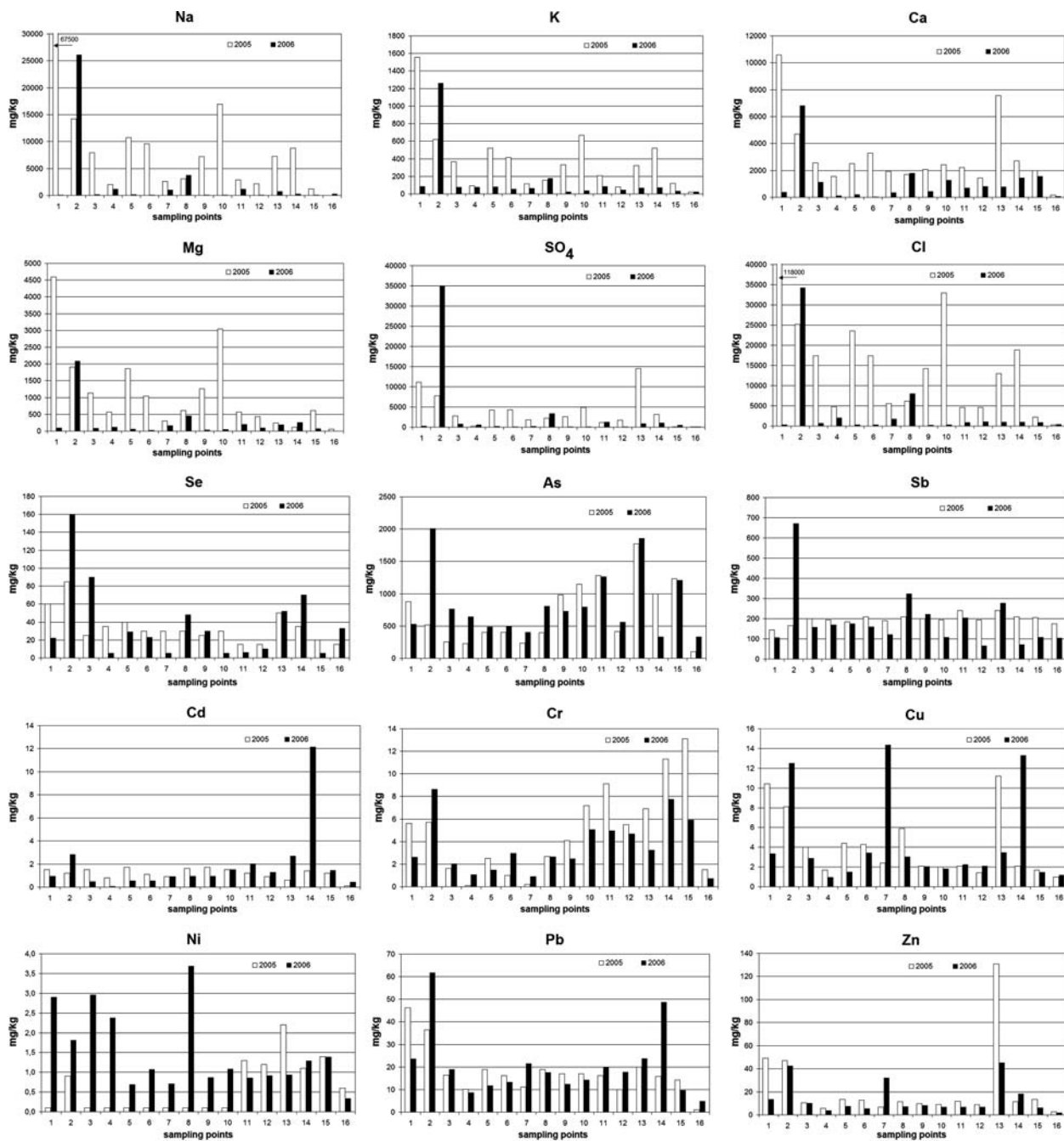


Fig. 3 Comparison of concentrations of the studied elements in water-soluble fraction (for Na, K, Cl, Mg, SO₄, Cl), exchangeable fraction (for Se, As, Sb) and acid leachable fraction (for Cd, Cr,

Cu, Ni, Pb and Zn) in tsunami deposits and reference sample shortly after the tsunami (2005) and after the rainy season (2006). The data from the 2005 are after Szczuciński et al. (2005)

removed from the tsunami deposits, it should be noted that after rainy season the concentrations are still higher than in the reference sample.

It is difficult to find general trend of changes when comparing heavy metals in acid leachable sediment fraction. For each element, some samples are enriched and some are depleted after rainy season. For Cd and Pb half of the samples noted decrease and half increase

in concentrations. Among the latter particularly elevated were values in sample 14.

Similar situation is in case of Cu, where reduction in its content was found in ten samples, and increased in six—particularly, in samples 7 and 14. Generally reduced concentrations of Cu and were measured for 2006; however, there were also some samples where content of these elements increased. The latter was

found in five and two samples for Cr and Zn, respectively. In the case of Ni, after the rainy season its content increased in eleven samples, and in eight of them the increase was significant. In the reference sample, the measured heavy metals contents before and after rainy season varied very little—much less than in most of the samples from tsunami deposits.

Similar trends to that observed in heavy metals were detected also in metalloids. Among them, samples: 12, 9 and 6 were depleted in Sb, Se and As, respectively. For the remaining samples the concentrations of the studied elements increased, particularly in sample 2. Also in the case of As in acid leachable fraction (Table 5) changes after rainy season were not uniform, however, for most of the samples the As content increased.

The presented comparisons of results for heavy metal and metalloids may be surprising, as one would expect decrease in concentrations of these mobile fractions after the rainy season. It is obvious that the mechanisms of mobilization of bioavailable fraction of heavy metal and metalloids are different from simple dilution of water-soluble salts. It is speculated that the removed easily mobilized fractions are recharged by continuously acting chemical weathering processes moving the discussed elements from less to more bioavailable fractions. Probably these processes are active on different stages of decompositions of minerals, as it is shown by a comparison of As in acid leachable (more resistant) and in exchangeable fractions—in both of them increase in concentrations was noted in most of samples. It suggests that both fractions were charged during the study period. In this way, the tsunami deposits may have long-term impact on higher amount of bioavailable potentially toxic elements in the environment. It could be of particular importance in case of elements, which are at elevated background values in this region—e.g. arsenic (Williams et al 1996; Zarcinas et al. 2004; Wattanasen et al. 2006). However, because regional background values are not defined for “bioavailable” fraction, it is not possible to perform more specific assessment. As shown by grain size data, several samples were depleted in finer fractions. However, it is not correlated to acid leachable or exchangeable element concentration changes.

In the 2005 correlation coefficients of analysed elements and compounds were relatively high (Szczuciński et al. 2005) but in the 2006 are even higher (Table 6). One of reasons may be removal of the most mobile water-soluble forms. On the other hand, the comparison of intersite correlations shows much higher values in 2005 (Table 7) than in 2006 (Table 8). It may be related to one major forming process in 2005 and

dominance of site-specific conditions during the further alterations as observed 1 year later.

Implications for paleotsunami study

Tsunami deposits preserved in geological record may be useful in assessment of a tsunami hazard of particular regions. For example, they may help to determine recurrence period and potential area of inundation (e.g. Nanayama et al. 2003; Dawson et al. 2004). In some cases, this record may be the only evidence that a region may be at risk from a tsunami. However, identification of paleotsunami deposits is quite complex and is still a subject of discussion (e.g. Nanayama et al. 2000; Pratt 2002; Nott 2003; Goff et al. 2001; Tuttle et al. 2004; Rhodes et al. 2006; Shanmugam 2006). Sediment geochemistry, particularly contents of Na, S, Cl, Ca, Mg, is often used as one of diagnostic features used in identification of paleotsunami and other catastrophic saltwater inundation (e.g. Minoura et al. 1994; Chagué-Goff and Goff 1999; Chagué-Goff et al. 2002; Goff et al. 2004). It is important indicative attribute if sediments deposited in lagoons or lakes are investigated. In the present study, a short assessment of reliability of some of these diagnostic features in the case of tsunami deposits left on land and subjected to washing due to rainfalls was analysed.

One of important features used in paleotsunami studies is grain size distribution, which helps to interpret wave hydrodynamic—for instance current velocity (e.g. Gelfenbaum and Jaffe 2003; Nanayama and Shigeno 2006). As shown by the above presented comparison of grain size distributions of tsunami sediments before and after the first rainy season, it is very likely that overall coarsening of tsunami deposits layer may occur in consequence of washing of finer particles. So it suggest that even material collected shortly after tsunami but not before heavy rains may be not fully representative for the tsunami sedimentary processes.

The next tool used in paleotsunami studies in sediment geochemistry. In particular contents of Na, S, Cl, Ca, Mg, is often used as one of diagnostic features. However, they were used only in the case of lagoon or lake sediments, where salt water may persist after the saltwater inundation event (e.g. tsunami). In some areas, like along large part of coastline in Thailand, such a sediment sinks are missing. Consequently, there is a need to explore sediments left on land. From the above-presented results, it is clear that the water-soluble compounds may be dissolved and probably will be completely removed after several rainy seasons. Some potential may be behind some trace metals (heavy metals and metalloids) as indicators of the marine

origin of sediments—at least on local scale, however, this aspect needs to be explored more in future.

Conclusions

The tsunami deposits left in coastal zone of Thailand were still preserved and had the same sediment thickness after rainy season. The most important alterations documented in this study include depletion of fine grain size fraction in poorly sorted tsunami laid sands and significant removal of water-soluble salts. The previously documented (Szczuciński et al. 2005) elevated concentrations of bioavailable heavy metals and arsenic are still sustained after one year. It is possible that this state will be sustained for longer period due to postulated steady recharge of bioavailable fraction from more resistant fractions. After rainy season the intersite correlations were much weaker proving that site specific conditions are important in further chemical changes of the tsunami deposits layer.

The results may have implication for studies of paleotsunami deposits on land. They must take into account post-depositional changes. In particular, washing out of fines and dissolution of salts.

The observed effects may be of significance not only for tsunami impacted coastal zones but also for other saltwater inundations leaving a layer of sediments, e.g. hurricanes (e.g. Turner et al. 2006).

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