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The impact on bottom sediments and ostracods in the Khlong Thom River mouth following the 2004 Indian Ocean tsunami

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Abstract. Fossil ostracods are a useful tool for identifying tsunamigenic sediments. However, the behavior of ostracod shells within the bottom tsunami sediments in Recent river mouths and estuaries is poorly understood. In this study, we analyzed bottom sediments and ostracod specimens taken from sites within the Khlong Thom River and sites adjacent to the Malacca Strait along the Malay Peninsula during three intervals—pre-tsunami, four months after the tsunami, and post-tsunami—to determine the impact of the 2004 Indian Ocean tsunami on the bottom sediments in the river mouths and estuaries. The broad distribution of the terrigenous plant material-bearing sediments in the Malacca Strait and the southern part of river mouth areas after the tsunami indicates that the sediments and the suspended materials deposited on bottoms were preserved for four months after the tsunami. However, no plant debris was recorded in the Malacca Strait, the southern part of the river mouth (RM), or junction areas between the river mouth and the estuary in 2008, suggesting that they had dispersed from the bottom during the three years and eight months after the tsunami. Of the bottom sediments taken four months after the tsunami, a few containing no plant debris were recorded in the northern and middle parts of RM, characterized by no ostracods or an abundance of adult and late juvenile instar specimens of *Keijella reticulata*. Based on these observations, we believe that small materials, such as plant debris and early juvenile instar ostracods, were transported from the bottom after the tsunami by the ordinary current. Previous investigations have captured changes in the abundance and density of meiofauna within a few days of a tsunami; therefore, the existence of some changes in ostracods that were able to recover during the four months may be considered, although there was no change in ostracod biofacies caused by the tsunami in the study area.

Key words: age population, Ostracoda, plant debris, river mouth, Thailand, tsunami

Introduction

Over the past 20 years, several large earthquakes have caused massively destructive tsunamis. Numerous studies have investigated the effects of these tsunamis on the sea bottom and onshore areas and the mechanisms of sediment transport and erosion following the occurrence of tsunamis. Most of these studies have examined onshore tsunami deposits (e.g. Sato *et al*., 1995; Shi *et al*., 1995; Dawson *et al*., 1996; Gandhi *et al.*, 2007; Hori *et al*., 2007; Narayana *et al*., 2007; Umitsu *et al*., 2007; Choowong *et al*., 2008; Jankaew *et al*., 2008). A number of studies have attempted to clarify the impact of tsunamis on the sea bottom in offshore and nearshore regions under the sea surface (e.g. Noda *et al*., 2007; Sugawara *et al*., 2009; Goto *et al*., 2011; Feldens *et al*., 2012). However, few studies have investigated bottom sediments in shallow seas and estuaries. The distribution of sediments in a small estuary changes within a short interval (Tsukawaki *et al*., 1999), causing difficulties in recognizing tsunami effects. Thus, much more evidence is required to clarify tsunami effects on the sea bottom and biota inhabiting there.

Small organisms, including meiofauna, have sometimes been used to investigate the effects of tsunami on the biota. For instance, diatoms and foraminifera within onshore tsunami deposits can reveal their origins (Nagendra *et al*., 2005; Hawkes *et al*., 2007; Sawai *et al*., 2009; Sugawara *et al*., 2009; Uchida *et al*., 2010). Ostracods can also be a powerful tool in the study of Recent tsunami-affected sediments (Ruiz *et al*., 2010; Tanaka *et al*., 2012b; Elakkiya *et al*., 2013). A number of studies of Quaternary sequences have also suggested that fossil ostracods can be used to identify tsunamigenic sediments in coastal freshwater lakes (Rhodes *et al*., 2006), salt marshes and brackish lagoons (Alvarez-Zarikian *et al*., 2008), estuaries (Luque *et al*., 2002; Ruiz *et al*., 2004, 2005), and inner bays (Irizuki *et al*., 1999; Fujiwara *et al*., 2000; Sasaki *et al*., 2007; Tanaka *et al*., 2012a). Despite the usefulness of ostracods as indicators of tsunami sediments, there have been few studies on the changes in Recent ostracod assemblages caused by the impact of tsunamis (Hussain *et al*., 2006). The aim of this study was to examine the bottom sedimentary features and ostracod assemblages before and after the 2004 Indian Ocean tsunami by using surface sediment collected from an estuary and a river mouth.

Study area

The study area is located at the mouth of the Khlong Thom River situated 25 km southeast of Krabi City on the western coast of Thailand (Figure 1) and is divided into four geographic areas: the Malacca Strait (MS), the river mouth (RM), the estuary (ET), and the juncture between the river mouth and the estuary (JC) (Tsukawaki *et al*., 1999) (Figure 2B). Mangroves extend into the RM, ET, and JC areas. The two largest estuaries, the Phela (width: 700 m) and the Thom (width: 1 km) join north of Lu Du Island. RM connects to MS by three rivers located to the north and south of Si Bo Ya Island and to the south of Pu Island. The tidal range at the study site is 2–3 m and the samples were collected at water depths between 1.3 and 27.8 m (Table 1). The bottom sediments were mainly composed of fine- to medium-grained sands and gravel was also present in samples taken around the islands and channel in the study area (Figure 3).

The western coast of the Malay Peninsula is one of the regions that was seriously damaged by the tsunami on December 26, 2004. Tsunami heights of 5–7 m were recorded on Phuket (Kotwicki and Szczuciński , 2006; Matsutomi *et al*., 2006; Tsuji *et al*., 2006; Grzelak *et al*., 2009) and Phi Phi Island, which is located approximately 30 km southwest of the study area (Matsutomi *et al*., 2006). Increases in sea level of up to 1.65 m following the tsunami were also recorded near Krabi (Tsuji *et al*., 2006). Tsunami inundation was also observed on the western coasts of Pu and Si Bo Ya islands. In particular, large numbers of buildings were destroyed by the tsunami on the western coast of Pu Island as recorded in photographs (http://www.pensfans.com/koputsu2.html) and on video (http://www.youtube.com/watch?v=k2t4BXWXvPE). Seagrass damage was also found on the sea bottom east of Pu Island (Figure 2).

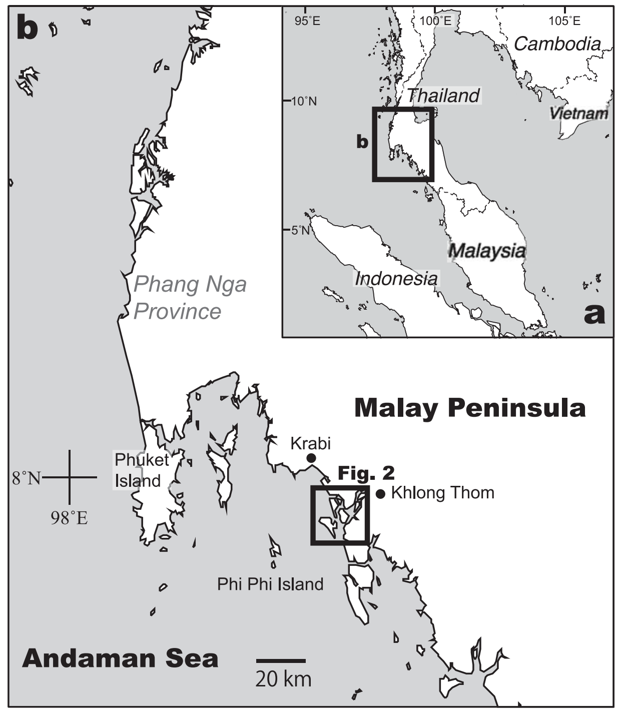

Figure 1. Maps showing the study area. Phuket and Phi Phi islands were severely damaged by the 2004 Indian Ocean tsunami.

Materials and methods

Thirty-five bottom-sediment samples were collected in the study area on February 25, 1999, September 7, 2003, April 21, 2005, and August 29–30, 2008. They comprised seven pre-tsunami samples (orange asterisks in Figure 2A; KT98-18–20 and KT03-01–04 in Table 1), 14 samples taken about four months after the tsunami (red squares in Figure 2A; KT05-01 and KT05-03–15 in Table 1), and 14 samples taken three years and eight months after the tsunami (blue open circles in Figure 2A; KT08-04, KT08-05, KT08-12, KT08-14–16, KT08-18, KT08-19, KT08-21, KT08-25, KT08-27, KT08-29, KT08-30, and KT08-32 in Table 1). In 1999 and 2005, the samples were collected in the dry season and in 2003 and 2008, the samples were collected in the rainy season. Approximately 12-cm-thick bottom-surface sediment was collected using a small gravity sampler (Daiki Rika Kogyo Co., Ltd), and for each sediment sample, a surface depth of 1–2 cm was checked for the presence of ostracods using a plastic spoon and fixed in 3–5% formalin-seawater. Water depth was concurrently measured by using a HANDEX-PS 7 portable digital sounder. The grain size, content, and color of the sediments were iden-

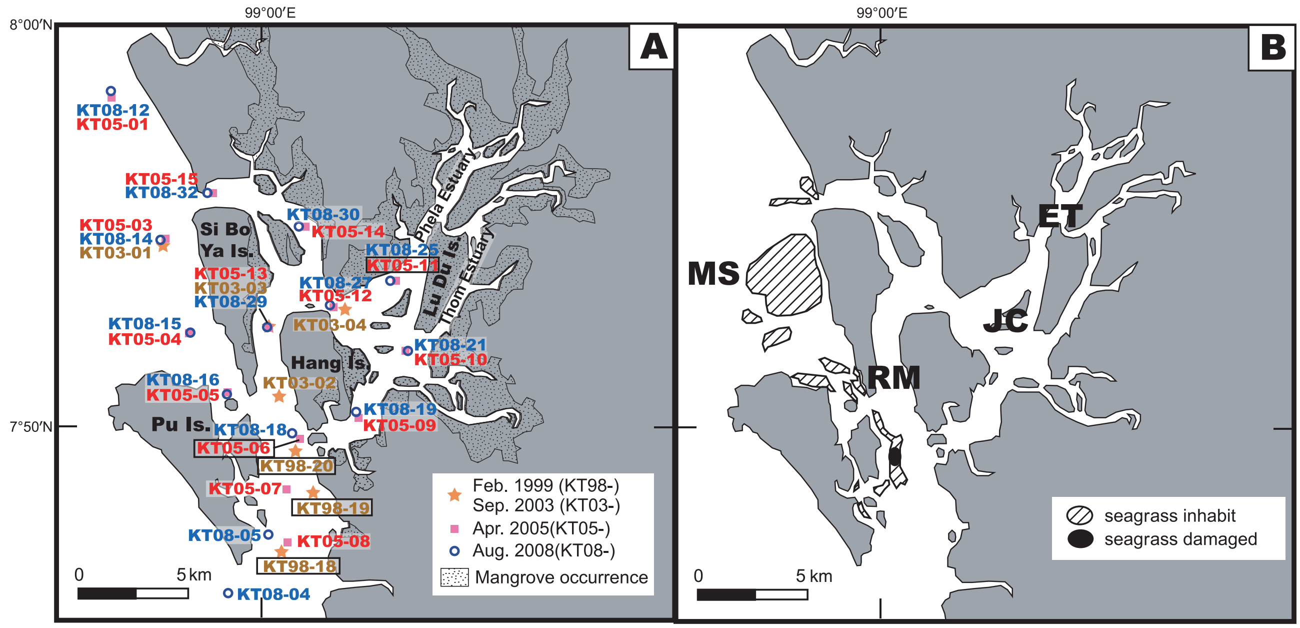

Figure 2. Maps showing the study area with the sampling points. **A**, the orange asterisks, red squares, and blue open circles indicate samples collected in the pre-tsunami period, four months after the tsunami, and three years and eight months after the tsunami, respectively. The samples in black squares were also examined by Sugawara *et al*. (2009). **B**, geographic setting, including the Malacca Strait (MS), river mouth (RM), junction area between river mouth and estuary (JC), and estuary (ET) in a modified version of the classification used by Tsukawaki *et al*. (1999) and the locations at which seagrass had flourished and was damaged (Department of Marine and Coastal Resources, Ministry of Natural Resources and Environment, 2005).

tified visually and recorded immediately on the boat (Table 1). The sediment samples were washed through a 63-µm sieve upon return to the laboratory. The residues were then dried and divided into appropriate groups, each of which contained more than 200 ostracod specimens. Ostracod shells >125 µm were identified using an optical binocular microscope. Left and right valves and carapaces were counted together as a single specimen. Ostracods with soft parts were counted as living specimens.

Sedimentary features

Information regarding the bottom sedimentary features gathered during December 1996 (rainy season) and August 1997 (dry season) from a previous study undertaken in the same area (Tsukawaki *et al*., 1999) was used to complement the pre-tsunami data. During the period between 1996 and 2003, numerous samples suggested that the sediment on the seafloor was composed of a variety of grain sizes caused by the complicated topography of the study area (Tsukawaki *et al*., 1999). Grain sizes in samples that were collected sporadically during 2005 and 2008 corresponded visually with those in samples collected in previous periods (Figure 3). Most of the grain size inconsistency between samples from the three periods, even those collected from very close areas, may be interpreted as being the result of the complicated topography.

However, the distribution of plant debris and deposition of muddy materials in JC was quite different between 2005 and other periods. Between 1996 and 2003, plant debris was contained in samples of RM and the eastern part of JC. In the rainy season, it was also observed in a specific area of MS. Plant debris was found in bottom sediments in all areas except the north and middle parts of RM, and the area covered with plant debris bearing sediments during 2005 was obviously wide (Figure 3). During the pre-tsunami interval and 2008, muddy sediment was recorded at the bottom of a quite small area. However, it was dominant in the middle part of RM and JC four months after the tsunami.

Ostracod analysis

Ostracod occurrence and dominant ostracods

In total, 96 species of ostracod belonging to 46 genera were identified from 31 sediment samples (Figure 4; Table 2). Ostracods were scarce in the eastern parts of JC

Table 1. Collection dates, water depths, visually documented grain sizes, and sediment contents of samples collected from the Khlong Thom River area.

Sample No.	Latitude (N)	Longitude (E)	Sampling date and time	Water depth (m)	Sediment
KT98-18	07°47'00.3"	99°00'31.2"	1999.02.25. 14:52	8.4	calcareous fragment rich yellowish brown medium-grained sand
KT98-19	07°48'25.4"	99°01'19.3"	1999.02.25. 15:15	6.0	calcareous fragment rich dark gray fine-grained sand
KT98-20	07°49'34.2"	99°00'46.6"	1999.02.25. 15:32	15.0	granule- to pebble-gravels and shell fragment bearing brown mud
KT03-01	07°54'51.0"	98°57'53.0"	2003.09.07. 09:15	2.7	calcareous fragment-bearing well sorted bluish brown-gray fine-grained sand, slightly muddy
KT03-02	07°51'15.0"	99°00'07.0"	2003.09.07. 10:10	7.7	gravel- and molluscan shell fragment-bearing poorly sorted medium- to coarse-grained sand
KT03-03	07°52'23.0"	99°00'12.0"	2003.09.07. 10:59	7.1	molluscan shell fragment-bearing gravelly brownish gray fine- to medium-grained sand
KT03-04	07°53'05.0"	99°01' 8.0"	2003.09.07. 11:40	6.1	gravel- and shell fragment-bearing well sorted gray medium-grained sand
KT05-01	07°57'58.2"	98°56'18.2"	2005.04.21. 7:52	3.1	greenish gray well-sorted very fine-grained sand with tiny shell fragments and plant debris, mud balls
KT05-03	07°54'35.3"	98°57'39.5"	2005.04.21. 8:35	3.4	greenish gray well-sorted very fine-grained sand with tiny shell fragments and plant debris. Many water plants on the surface.
KT05-04	07°52'23.2"	98°58'12.6"	2005.04.21. 9:00	4.9	greenish gray fine- to medium-grained sand, brownish gray soft surface, shell fragments and plant debris
KT05-05	07°50'54.7"	98°59'13.1"	2005.04.21. 9:23	1.3	greenish gray fine- to medium-grained sand, brownish gray soft muddy surface, coarse shell fragments and plant debris
KT05-06	07°49'54.4"	99°00'52.2"	2005.04.21. 9:44	20.0	dark grayish olive muddy medium- to coarse-grained sand, brownish gray surface
KT05-07	07°48'42.2"	99°00'37.1"	2005.04.21. 10:02	9.2	slightly greenish gray medium- to coarse-grained sand, large shells and fragments, plant debris
KT05-08	07°47'26.9"	99°00'38.0"	2005.04.21. 10:20	5.4	slightly greenish gray medium- to very coarse-grained sand, rich in large shells and fragments, rare plant debris
KT05-09	07°50'26.8"	99°02'20.1"	2005.04.21. 10:55	7.7	dark gray muddy fine- to medium-grained sand, shell fragments and shells, and large plant debris
KT05-10	07°51'58.5"	99°03'32.4"	2005.04.21. 11:19	4.3	dark olive colored muddy fine-grained sand, brownish and soft surface, a little shell fragments, much plant debris
KT05-11	07°53'41.2"	99°03'11.3"	2005.04.21. 11:59	5.3	brownish gray muddy fine- to medium-grained sand, brown surface, a little granule- to pebble-gravels, shell fragments and plant debris
KT05-12	07°53'01.5"	99°01'43.9"	2005.04.21. 12:14	11.8	olive gray muddy fine-grained sand with a little amount of granule-to pebble-gravels
KT05-13	07°52'31.9"	99°00'06.0"	2005.04.21. 12:34	8.5	fine- to very coarse-grained poorly sorted muddy sand with lateritic gravels and shell fragments, mud balls
KT05-14	07°54'55.9"	99°01'00.8"	2005.04.21. 13:04	7.4	shells and shell fragments-rich olive colored well sorted very fine-grained sand
KT05-15	07°55'48.5"	98°58'50.9"	2005.04.21. 13:22	11.8	shells and shell fragments-rich well sorted very fine- to fine-grained sand
KT08-04	07°46'09.5"	98°59'13.5"	2008.08.29. 9:52	9.8	shell fragment-rich pale olive brown fine- to medium-grained sand
KT08-05	07°47'44.4"	99°00'07.9"	2008.08.29. 10:20	4.0	granule-gravel and shell fragment bering fine- to coarse-grained yellow brown sand
KT08-12	07°58'14.6"	98°56'27.6"	2008.08.30. 8:05	2.8	shell fragment bearing olive gray fine-grained sand
KT08-14	07°54'34.8"	98°57'40.8"	2008.08.30. 8:45	3.4	shell fragment-bearing pale olive very fine- to fine-grained sand with fresh water plants
KT08-15	07°52'27.4"	98°58'22.3"	2008.08.30. 9:07	5.7	tiny shell fragment-bearing olive gray very fine- to fine-grained sand covered by brown layer
KT08-16	07°50'51.9"	98°59'13.7"	2008.08.30. 9:26	3.5	tiny shell fragment-bearing olive gray very fine- to fine-grained sand covered by brown layer
KT08-18	07°49'52.2"	99°00'50.7"	2008.08.30. 9:58	27.8	dark gray mud with surface layer
KT08-19	07°50'29.1"	99°02'20.6"	2008.08.30. 10:29	7.5	shell fragment-rich olive gray very fine- to fine-grained sand covered by brown layer
KT08-21	07°51'52.5"	99°03'32.4"	2008.08.30. 10:59	5.3	shell fragment- and gravel-bearing pale olive fine-grained sand covered by brown layer
KT08-25	07°53'36.5"	99°03'11.2"	2008.08.30. 12:20	7.7	shell fragment- and plant debris-rich pale brown fine-grained sand
KT08-27	07°53'02.7"	99°01'44.8"	2008.08.30. 12:48	12.6	tiny plant debris- and shell fragment-bearing pale brown fine-grained sand
KT08-29	07°52'29.3"	99°00'12.4"	2008.08.30. 13:21	5.9	shell fragment-rich, plant debris-bearing pale brown fine-grained sand
KT08-30	07°54'55.3"	99°00'59.4"	2008.08.30. 13:47	7.3	shell fragment-rich, plant debris and charcoal bearing pale brown fine-grained sand
KT08-32	07°55'45.5"	98°58'47.3"	2008.08.30. 14:15	8.3	shell fragment-rich, gravel and charcoal-bearing light brown fine-grained sand

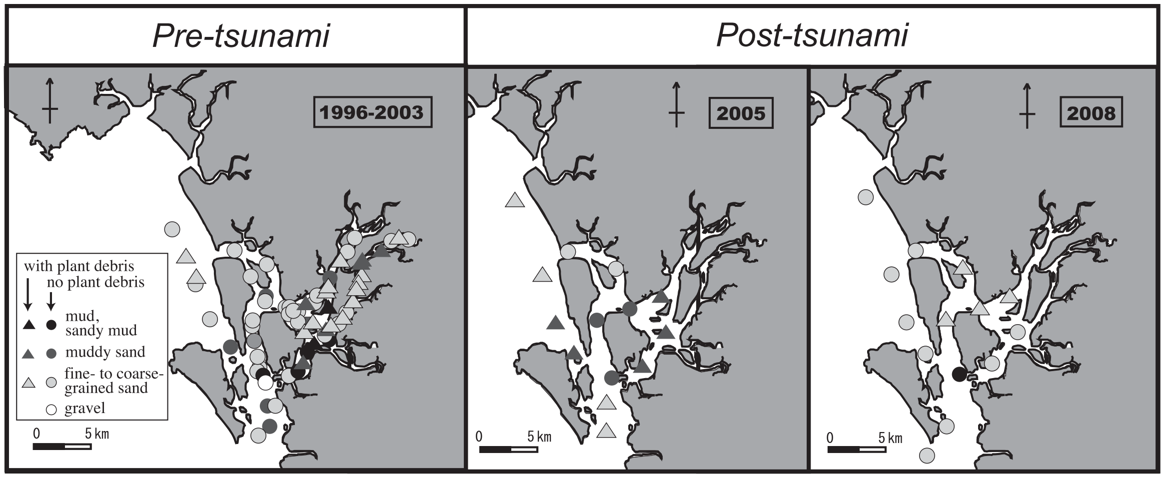

Figure 3. Pre-tsunami (1996–2003), four months after the tsunami (2005), and three years and eight months after the tsunami (2008) distributions of grain sizes in the study area. The 1996 and 1997 sedimentary descriptions are from Tsukawaki *et al*. (1999).

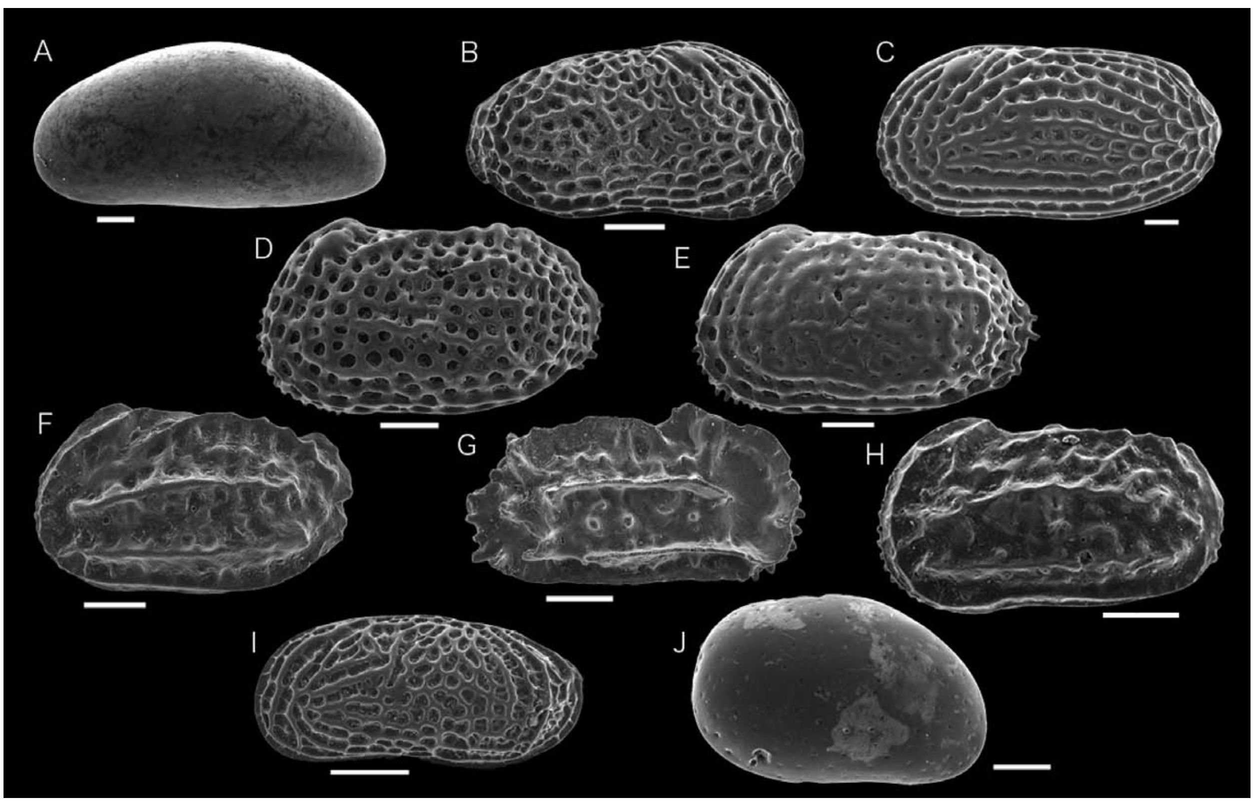

Figure 4. Scanning electron micrographs of the dominant ostracod species in the Khlong Thom River area, southwestern Thailand. Scale bars = 100 µm, RV = right valve, LV = left valve. **A**, *Argilloecia* sp. 1, lateral view of LV, adult, sample no. KT08-05; **B**, *Hemicytheridea ornata* Mostafawi, 1992, lateral view of RV, juvenile, sample no. KT98-19; **C**, *Keijella reticulata* Whatley and Zhao, 1988, lateral view of LV, adult, sample no. KT98-18; **D**, *Lankacythere multifora* Mostafawi, 1992, lateral view of LV, juvenile, sample no. KT98-19; **E**, *Lankacythere* sp. 3, lateral view of LV, adult, sample no. KT05-03; **F**, *Stigmatocythere* cf. *bona* Chen, 1982 in Hou *et al*. (1982), lateral view of LV, adult, sample no. KT08-15; **G**, *Stigmatocythere indica* (Jain, 1978), lateral view of RV, adult, sample no. KT98-19; **H**, *Stigmatocythere kingmai* Whatley and Zhao, 1988, lateral view of LV, adult, sample no. KT08-15; **I**, *Tanella gracilis* (Kingma, 1948), lateral view of LV, adult, sample no. KT98-19; **J**, *Xestoleberis* aff. *malaysiana* Zhao and Whatley, 1989, lateral view of RV, juvenile, sample no. KT08-05.

Table 2. Occurrences of ostracod species in samples taken from the Khlong Thom River area. Numbers in parentheses are of living ostracod specimens.

	KT98-18	KT98-19	KT98-20	KT03-01	KT03-02	KT03-03	KT03-04	KT05-01	KT05-03	KT05-04	KT05-05	KT05-07	KT05-08	KT05-09	KT05-13	KT05-14	KT05-15	KT08-04	KT08-05	KT08-12	KT08-14	KT08-15	KT08-16	KT08-18	KT08-19	KT08-21	KT08-25	KT08-27	KT08-29	KT08-30	KT08-32
Actinocythereis scutigera (Brady)	2	1					1			4		2	1				1	9	1		1	1						1			
Alocopocythere kendengensis Kingma		73		1																					5(1)			6			
Alocopocythere sp. 1	5				7																										
Alocopocythere sp. 2	1																														
Anchistrocheles sp.																		1													
Argilloecia sp. 1	17	8		6		2	1	5	15	40	1	6	19				3	24	46	5	18	13	16	1				3	4	2	2
Argilloecia sp. 2		4																													
Aurila sp. 1																		3													
Bradleya cf. *pitalia* (Hu)	1																														
Bythoceratina multiplex Whatley and Zhao										1																					
Callistocythere sp.		4																													
Caudites scopulicola jasonensis Hartmann	2	2	4		1(1)				11			1	4					3	2			1	3	1							
Cistacythereis sp. 1													1																		
Copytus posterosulcus Wang							3(1)											2				1		2(1)		2					
Cytherella incohata Zhao and Whatley																		1							3						
Cytherella sp. 1		4																				1									
Cytherelloidea excavata Mostafawi		5																9				15	7		3			2(1)	3	1	
Cytherelloidea leroyi Key			4				1		1			3		1				1	1					3						1	
Cytherelloidea malaccaensis Whatley and Zhao					5(1)								2		3																
Cytherura sp. 1			2																												
Hemicytheridea ornata Mostafawi	4	127	14	3					12	37	2	3							3	3		97		11	9	3		5	3		
Hemicytheridea reticulata Kingma		11			1	1	3(1)												1									4			
Hemicytheridea wangi Zhao and Whatley		27											1					1		2	2	13	2								1
Hemicytheridea sp. 1			1				1	4	1				1					23			1	20	4		1				1		
Hemicytheridea sp. 2																		5				8	8								
Hemikrithe peterseni Jain		1				2(2)																									
Keijia sp. 1												2																			
Keijella apta (Guan)																4															
Keijella karwarensis (Bhatia and Kumar)		9	2					1	1	3								21		2		14	3		3						
Keijella kloempritensis (Kingma)		4						1																				1			
Keijella multisulcus Whatley and Zhao																						11							4		
Keijella cf. *multisulcus* Whatley and Zhao																					3										
Keijella reticulata Whatley and Zhao	41	68	1	5	52(4)	31(2)		3	15	23		37	28		33	28	11	51	3	4	9	34	8	3	2			5(1)	32	8	14
Keijella sp. 1			6																												
Keijella sp. 2			2																					4							
Keijella sp. 3			6						1	5		1	1																		
Keijella spp.										3	1																				
Lankacythere elaborata Whatley and Zhao	4											3						5			1										
Lankacythere multifora Mostafawi	6	93	8	4	9	8		8	11	18		22	14	2	5	3	6	13	9	2	2	39	14	8	3		1	8	8	22	1
Lankacythere sp. 1		2	2														1					4									
Lankacythere sp. 2	1	2						4									5	2										4			
Lankacythere sp. 3	7	1						3	17(1)	6			5				4	1		6	11									1	5
Leguminocythereis elongatus Hu	12	23				4				3		1	9				1	4	8				3					1	4		1
Loxoconcha lilljeborgii (Brady)	2	4	10	1	5			3	7	8					2	1		10	5		2	3	4		1			2			
Loxoconcha paiki Whatley and Zhao	5	10			1			1	8	4	1(1)	6	6					18	10			15	8	5					2		
Loxoconcha cf. *tata* Hu						1						4						24				1								1	
Loxoconcha sp. 1		1																	1												
Loxoconcha sp. 2								1		1																					
Loxoconcha sp .3		7		1				3	6	3								4			3	31	1		1						
Loxoconcha sp. 4		1									3							2					7					1			

Table 2. *Continued.*

	KT98-18	KT98-19	KT98-20	KT03-01	KT03-02	KT03-03	KT03-04	KT05-01	KT05-03	KT05-04	KT05-05	KT05-07	KT05-08	KT05-09	KT05-13	KT05-14	KT05-15	KT08-04	KT08-05	KT08-12	KT08-14	KT08-15	KT08-16	KT08-18	KT08-19	KT08-21	KT08-25	KT08-27	KT08-29	KT08-30	KT08-32
Microceratina punctata Whatley and Zhao																		1													
Miocyprideis cf. *spinulosa* (Brady)	1	30						1	3	7	1	4	1				1	5	3			51	8	1	6			5		2	
Miocyprideis aff. *spinulosa* (Brady)																							2								
Mutilus australiensis Hartmann		8																3	1				1					2			
Mutilus cf. *variornatus* Hartmann		1																													
Neocytheretta murilineata Zhao and Whatley	2									2													2					4		1	
Neocytheretta spongiosa (Brady)				2		2		4	13	9		1	7			1		19		1	1	9			2				1	2	
Neocyprideis sp. 1		17	3		1					2								1				30	12	1	4				2		1
Neomonoceratina colombiformis Kingma		2							1	1								1				6		1							
Neomonoceratina delicata Ishizaki and Kato		1											1					1													
Neomonoceratina iniqua (Brady)		25	3					3												4		13	7	1	1						
Neomonoceratina sp. 1												1			1																
Neonesidea sp. 1	9	63			1	2			1	6		5	4		11	1		9					2	1	4			1	1	2	
Neonesidea sp. 2		1																	15				1					3			
Neosinocythere macropunctata Zhao and Whatley	34					2	1		1	3	3			1		2					1			1			1	1	1		
Neosinocythere sp. 1		12				2(1)		1	4													10								1	
Paijenborchellina sp. 1		3						2	1									1		1		6	1								
Paracypris sp.																		4											2		
Paracytherois sp. 1										1														2							
Paracytheroma ventrosinuosa Zhao and Whatley	7		1				4	3	1								3		1		3	1	6								
Paradoxostoma sp.																		2													
Parakrithella sp. 1												1																			
Perissocytheridea sp. 1	2	16	3	4	1			3	4	5	6		1				1	6	2	7	3	7	24	2				2			2
Polycope sp. 1																			2												
Pontocythere sp. 1	7	2		2		1				3			4		1			5				6								2	
Pontocythere sp. 2				5(5)																											
Propontocypris sp.		2																2					1								
Semicytherura sp. 1	1				1													4											1		
Semicytherura sp. 2																						9	3								
Sinocytheridea impressa (Brady)			1																												
Spinoceratina spinosa (Zhao and Whatley)		1																1													
Spinoceratina sp. 1										1		2										1									
Stigmatocythere cf. *bona* Chen		37		4				14	18(1)	8	2		1				3	7		5	4	37	13(1)	9				1			1
Stigmatocythere indica (Jain)		142	3						1			2				1	2			1					38(2)			12	5	5	
Stigmatocythere kingmai Whatley and Zhao		5	13		6(2)	3						10	5		4		4(2)	7	4			16	8	2					1	1	
Stigmatocythere sp. 1											1																				
Tanella gracilis (Kingma)	2	69	3	2	10(2)	3(1)	2	1	7	16	45	6			3		2(1)	35	5	3	2	42	4	1	6	1		1	5		
Triberina sp. 1		3																4	1												
Venericythere darwini (Brady)	5								1			17										4									
Venericythere papuensis (Brady)		35							1	2		3						6		1		28			1					2	1
Xestoleberis aff. *malaysiana* Zhao and Whatley	12	7	2	3				1	50	30			15					35	177	3	1	27	15	1				1	1		
Gen. et sp. Indet. 1	10	5			1	3			1	5			10			1	3	2													
Gen. et sp. Indet. 2																								1							
Gen. et sp. Indet. 3	1																														
Gen. et sp. Indet. 4		2																7	1												
unknown	1		1	1			1				1	1						1	1					2	1		1	1	1		
total specimens of ostracod	163	1022	94	45	102	65	15	72	215	259	67	147	141	3	64	40	52	409	302	51	64	628	193	69	95	6	2	77	82	55	29
total species of ostracod	27	51	22	16	15	14	9	23	28	32	12	26	23	2	10	8	16	50	23	17	16	38	31	23	20	3	2	25	20	17	10
total living species of ostracod	0	0	0	5	10	6	1	0	2	0	1	0	0	0	0	0	3	0	0	0	0	0	1	1	3	0	0	2	0	0	0
Proportion of living specimens (%)	0	0	0	11.1	9.8	9.2	6.7	0	0.9	0	1.5	0	0	0	0	0	5.8	0	0	0	0	0	0.5	1.4	3.2	0	0	2.6	0	0	0
Diversity	2.74	3.07	2.78	2.60	1.79	1.94		2.82	2.74	2.87	1.35	2.64	2.62		1.61	1.14	2.49	3.31	1.64	2.65	2.30	3.13	3.08	2.78	2.33			2.91	2.32	2.17	

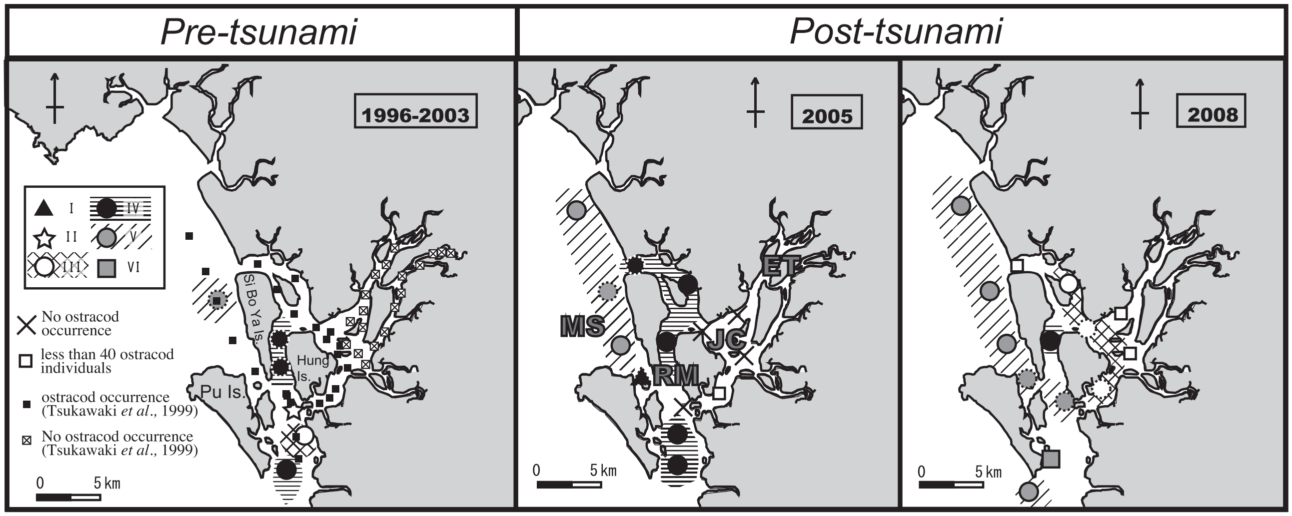

Figure 5. Schematic diagrams showing the distributions of biofacies during the pre-tsunami period (1996–2003), four months after the tsunami (2005), and three years and eight months after the tsunami (2008), and the ostracod occurrences in 1997 and 1998, as determined by Tsukawaki *et al*. (1999). Biofacies denoted by the dotted lines indicate samples containing living ostracod specimens. MS, RM, JC, and ET are the Malacca Strait, river mouth, junction area between river mouth and estuary, and estuary, respectively.

and ET throughout the study intervals (Figure 5). Two samples containing no ostracods were collected from RM and the western part of JC during 2005 (Figure 5). Living ostracod specimens accounted for less than 11.9% of all specimens, and a relative high proportion of living specimens was recognized during 2003 (Table 2).

Keijella reticulata was the most dominant species, whereas *Lankacythere multifora*, *Hemicytheridea ornata*, *Tanella gracilis*, *Argilloecia* sp. 1, *Xestoleberis* aff. *malaysiana*, and *Stigmatocythere* cf. *bona* were subdominant species (Figure 6). These dominant and subdominant species have been generally reported from the sand and muddy sand bottoms in the shallow sea of the Malay Peninsula (e.g. Whatley and Zhao, 1987, 1988; Zhao and Whatley, 1989; Mostafawi, 1992).

Q-mode cluster analysis

A Q-mode cluster analysis was applied to each of the 26 samples containing more than 40 individual ostracod specimens. Horn's (1966) overlap index was used as the similarity index, and clustering was carried out by using the unweighted pair group method with the arithmetic mean. The analysis was performed with the free software package Paleontological Statistics (PAST) provided by Hammer, 2013. Six biofacies (I–VI) were identified, with an overlap index of 0.55 (Figure 6).

Biofacies I is present only in sample KT05-05, taken from the southeastern part of the MS area in 2005 (Figure 5). *Tanella gracilis* accounted for approximately 60% of all ostracod specimens in this sample. Biofacies II comprised sample KT98-20, which was taken from the RM area and characterized by *H. ornata*, *Stigmatocythere kingmai*, and *L. multifora*. Biofacies III comprised four samples (KT98-19, KT08-19, KT08-27, and KT08-30) located at JC and RM sites. It was characterized by the predominance of *L. multifora*, *Stigmatocythere indica*, and *K. reticulata*. Between them, *L. multifora* and *S. indica* accounted for approximately 40% of the total specimens in samples KT08-30 and KT08-19. Biofacies IV comprised nine samples (KT98-18, KT03-02, KT03-03, KT05-07, KT05-08, KT05-13–15, and KT08-29), which were mainly distributed in the RM area located east of both Pu and Si Bo Ya islands. *Keijella reticulata* was the dominant species, while *L. multifora* and *Argilloecia* sp. 1 were commonly found in this biofacies. Biofacies V comprised 10 samples (KT03-01, KT05-01, KT05-03, KT05-04, KT08-04, KT08-12, KT08-14–16, and KT08-18). Except for KT08-04, all the samples were taken from MS sites. *Argilloecia* sp. 1, *S.* cf. *bona*, *X.* aff. *malaysiana*, *K. reticulata*, *T. gracilis*, and *L. multifora*, which inhabit shallow areas at depths of <30 m, were dominant. Biofacies VI comprised sample KT08-05 and was characterized by the dominance of *X.* aff. *malaysiana* and *Argilloecia* sp. 1. Sample KT08-05 was taken from a site located west of Pu Island and comprised fine- to very coarse-grained sands, with coarse sediments characterizing the samples taken in close proximity to Pu Island.

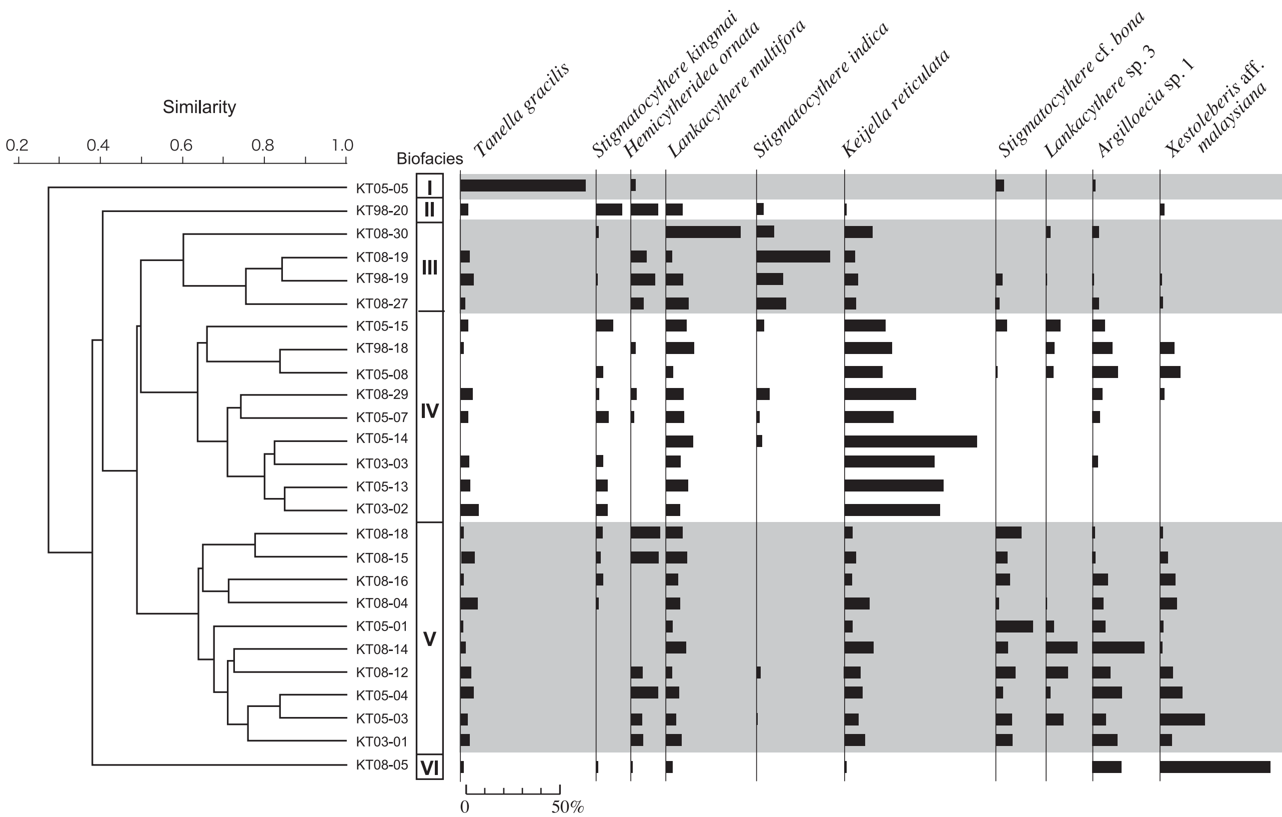

Figure 6. Dendrogram from a Q-mode cluster analysis of 26 samples and the relative abundances of the predominant ostracods in each biofacies.

Temporal changes in biofacies distributions from 1999 to 2008

Biofacies III, IV, and V predominantly covered specific areas (JC, RM, and MS, respectively) between 1999 and 2008 (Figure 5). Some changes were apparent in the coverage of each biofacies. For instance, a shift to biofacies IV (sample KT05-07) from biofacies III (sample KT98-19) was observed four months after the tsunami in an area of RM situated east of Pu Island, and also from biofacies IV (KT05-14) to biofacies III (KT08-30) in an area of RM northwest of Si Bo Ya Island in 2008.

Age structure of *Keijella reticulata*

Ostracods are crustaceans that grow over the course of several successive molts. The denotation A-1 indicates that a specimen has become an adult subsequent to molting. The age structures of ostracod populations can be used as a tool to determine whether ostracod assemblages are autochthonous or allochthonous (Van Harten, 1986; Whatley, 1988; Irizuki *et al*., 1999; Boomer and Eisenhauer, 2002; De Deckker, 2002). If the valves of early juveniles are sorted by a high-energy flow, larger valves, such as those of adult and A-1 specimens, become predominant. A further energy flow causes an absence of ostracods because whole valves are removed (Frenzel and Boomer, 2005). In the allochthonous assemblages generated by the deposition of transported valves, a high abundance of a particular growing stage, which depends on the energy intensity, is observed.

The age distribution of *Keijella reticulata*, which was identified as a dominant ostracod species in this study area, was investigated in 30 samples (Table 3). The valves of *K. reticulata* were occupied by an abundance of adult and A-1 specimens in samples KT05-01, KT05-13–15, and KT08-05, whereas the majority of the samples were mixtures of specimens from adults to the A-6 growth stage (Figure 7). In particular, from the samples in biofacies IV that were characterized by a high abundance of *K. reticulata*, samples KT05-13 and KT05-14 contained only specimens of the adult and A-1 growth stages of this species, despite being from the same localities as KT03-03 and KT08-29, and KT08-30, respectively.

Table 3. Population age structure of *Keijella reticulata* from the Khlong Thom River area. A, adult; A-1, specimen becoming adult after a molt.

	KT98-18	KT98-19	KT98-20	KT03-01	KT03-02	KT03-03	KT05-01	KT05-03	KT05-04	KT05-07	KT05-08	KT05-13	KT05-14	KT05-15	KT08-04	KT08-05	KT08-12	KT08-14	KT08-15	KT08-16	KT08-18	KT08-19	KT08-27	KT08-29	KT08-30
A	16	7		2	8	9	2	5	11	4	11	6	25	8	8	2		1	4	1		1		6	2
A-1	21	18		1	2	3	1	6	5	4	7	27	3	3	12		1	5	4	1			3	1	5
A-2	1	31		2	25	11		4	2	11	4				25		2	1	20	5			2	17	1
A-3	3	10	1		6	7			4	13	5				5		1	2	6	1	2	1		7	
A-4		1			7	1			1	5	1				1						1			1	
A-5		1			1											1									
A-6	3																								
Total number of specimens	41	68	1	5	52	31	3	15	23	37	28	33	28	11	51	3	4	9	34	8	3	2	5	32	8

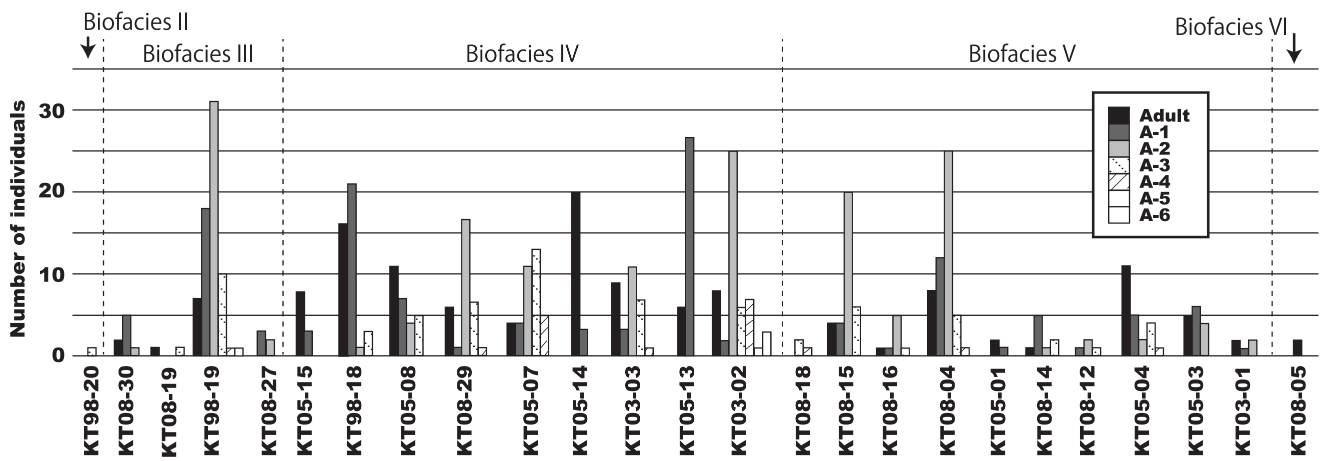

Figure 7. Graph showing the age structure of *Keijella reticulata* within each sample. A-1 indicates juveniles that have become adults subsequent to molting.

Discussion

In the pre-tsunami period, sediments bearing plant debris were recognized in JC and ET throughout the year and from a small part of MS in the rainy season (Figure 3). This indicates that plant debris derived from the land was usually trapped within sediments in ET and JC, and was not usually deposited in RM and MS during the dry season. We collected the 2005 samples at intervals at the end of the dry season, which extended from December 26, 2004. The monthly precipitation between December 2004 and April 2005 differed little from average years in Phang Nga Province, located 100 km northwest of the study area (Szczuciński, 2012). Furthermore, no flood deposits, composed of poorly sorted and coarse-grained sands, were present on the land or sea bottom in or surrounding the present study area. Thus, the occurrence of terrigenous plant materials dispersed over MS and the southern part of RM presumably reflected deposition caused by the tsunami.

In a small bay of Japan, tsunami deposits were composed of fine- to medium-grained sand and mud containing an amount of plant debris caused by suspension after the end of the tsunami currents (Fujiwara and Kamataki, 2008). The broad distribution of the plant debris in 2005 might be attributed to deposition as suspended materials. If this is the case, terrigenous plant materials would also be transported to the bottom of the northern and middle parts of RM after the impact of tsunami waves. Of the five samples containing no plant debris, two samples, collected from north and south of Hung Island, contained no ostracods. Moreover, high proportions of adult and A-1 molting stages of ostracod *K. reticulata* were recognized in the other three samples, suggesting the removal of early juvenile valves from bottom materials. Hence, the absence of plant materials in the middle and northern parts of RM may have been caused by their transport by the ordinary current after the tsunami, and not caused by tsunami impact. However, three of the samples containing no plant debris in 2005 were muddy sediments, which appears to contradict our interpretation (see above). Because of the combined topography, several types of bottom materials as well as their areas of deposition and erosion were found to shift at short intervals within the study area (Tsukawaki *et al*., 1999). Thus, the muddy sediments may be the result of a shift from deposition of sand to deposition of mud after the tsunami.

By contrast, the occurrence of plant debris in bottom sediments from MS and the southern part of RM suggested that some of the materials transported as a result of the tsunami were preserved for four months. Moreover, there were no plant debris-bearing sediments in MS and the southern part of RM during 2008, indicating that the major part of the tsunami sediment disappeared as a result of dispersal or was covered with overlying sediments during the three years and eight months after the tsunami. According to previous investigations into the density of benthic foraminifera, the areas where sediments are usually agitated by waves, such as the inner shelf, intertidal zone, and beach, showed little damage from the 2004 tsunami (Kotwicki and Szczuciński, 2006) or showed a quick recovery of the foraminiferal communities afterward (Kendall *et al.*, 2009). It can be assumed that this apparently slight tsunami damage to the foraminifera was the result of the dispersal of the tsunami sediments after the event. Other researchers have noted that the effects of tsunamis are poorly preserved in areas that are regularly disturbed by normal hydrodynamic processes (e.g. Irizuki *et al*., 1999); it is assumed therefore that the bottom materials were dispersed in MS and the southern part of RM in the study area during the three years and eight months after the tsunami.

Overall, the geographic areas marked by biofacies III, IV, and V did not change throughout the time periods studied (Figure 5). Even in samples taken from MS and the southern part of RM, no unusual changes were found in the ostracod biofacies and their distribution after the tsunami. Because channels develop within the estuary, quite different bottom environments can exist even in a small part of the study area (Tsukawaki *et al*., 1999) and a minor shift in biofacies identified in a small area between the three intervals can be attributed to the different local bottom settings, i.e., within or outside a channel. Moreover, there was no difference in the structures of mixed-age populations of *K. reticulata* between the three intervals. However, these facts do not necessarily prove that there were no effects of the tsunami on ostracods in the study area. In the short term, the abundance and diversity of the meiofauna, including ostracods, begin to vary within a few days and a few months after an event such as a tsunami (Altaff *et al*., 2005; Kotwicki and Szczuciński , 2006; Kendall *et al*., 2009; Lomovasky *et al*., 2011) and a hurricane (Park *et al*., 2009), or an iceberg (Lee *et al*., 2001), although several years are required for the communities to recover their status before the event occurred. For instance, at all locations during 2006, ostracods were lacking in the sand on beaches located on the west coast of Thailand damaged by the tsunami. However, the highest ostracod abundance was recorded at two of these three locations in 2008, although the sand was collected every year from 2005 (50 days after the tsunami) to 2009 (Grzelak *et al*., 2009). Thus, it is irrefutable that ostracod diversity and abundance could have changed up to the day of sampling (approximately four months) after the tsunami in the study area.

Two reports have considered the influence of the tsunami on the bottom sediments in the study area. The first study, carried out between December 30, 2004 and January 15, 2005, examined the tsunami damage to seagrass (Department of Marine and Coastal Resources, Ministry of Natural Resources and Environment, 2005). A survey was conducted in the area that included MS and RM and damage to seagrass was only found in a small area east of Pu Island (Figure 2). The seagrass had flourished in MS west of Si Bo Ya Island and no damage was observed there. This finding supports our result that there were only a few changes to ostracods. The second study dealt with the foraminiferal transfer caused by the tsunami and their migration back into the area (Sugawara *et al*., 2009). Here, samples collected before and after the tsunami were examined, including seven used in the present study (Figure 2). The conclusion was that foraminifers were transported by the tsunami backflow, and then migrated back to the location they had inhabited before the tsunami until 2006. Among the samples investigated by Sugawara *et al*. (2009), three (KT05-05, -07, and -11) were also examined in the present study in 2005. There was no evidence of sediment transportation by the tsunami backflow based on the ostracod data for 2005. This discrepancy may have arisen because the ostracod communities recovered more rapidly than the foraminifers, as found in the bottom after sediment dumping (Frenzel *et al*., 2009).

Conclusions

A study of the temporal and spatial changes in bottom sedimentary features and ostracods in the Malay Peninsula was undertaken to clarify the influence of a tsunami on bottom materials and ostracods in a river mouth and an estuary. We can draw the following conclusions.

1. The amount of plant debris-bearing sediments collected four months after the tsunami reflects transportation from land to the bottom in the Khlong Thom RM and adjacent area as a result of the tsunami. The terrigenous plant materials resulting from the tsunami were preserved four months after the tsunami; however, by three years and eight months after the tsunami, most of them had dispersed or were covered with sediments.

2. Samples taken from the middle and northern parts of RM four months after the tsunami contained no plant debris from the land. Neither did these samples contain ostracods or adult and/or late juvenile instar ostracod specimens in abundance. These findings allow us to infer that the ordinary current transported fine materials such as plant debris and early juvenile instar ostracod specimens from the middle and northern parts of RM after the tsunami.

3. The distribution of the biofacies, determined with Q-mode cluster analysis, showed that no assemblage changes occurred within the study area following the tsunami. Because ostracod diversity and abundance were expected to begin to vary within four months of the event, these findings can be interpreted as there being either no change caused by the tsunami or only a few changes, which were recovered within four months.

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