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Research Article

Foraminiferal evidence of submarine sediment transport and deposition by backwash during the 2004 Indian Ocean tsunami

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Abstract Micropaleontological analysis of nearshore to offshore sediments recovered from the southwestern coast of Thailand was performed to clarify the submarine processes of sediment transport and deposition during the 2004 Indian Ocean tsunami. The distribution pattern of benthic foraminifers showed seaward migration after the tsunami event. Agglutinated foraminifers, which are characteristic of an intertidal brackish environment, were identified in the post-tsunami samples from foreshore to offshore zones. These suggest that sediments originally distributed in foreshore to nearshore zones were transported offshore due to the tsunami backwash. On the other hand, the distribution pattern of planktonic and benthic species living in offshore zones showed slight evidence of landward migration by the tsunami. This suggests that landward redistribution of sediments by the tsunami run-up did not occur in the offshore seafloor of the study area. Our results and a review of previous studies provide an interpretation of submarine sedimentation by tsunamis. It is possible that tsunami backwashes induce sediment flows that transport a large amount of coastal materials seaward. Thus, traces of paleotsunami backwashes can be identified in offshore sedimentary environments as the accumulation of allochthonous materials. This can be recognized as changes in benthic foraminiferal assemblages.

Key words: backwash, foraminifer, sediment flow, 2004 Indian Ocean tsunami, 2004 Sumatra–Andaman earthquake.

INTRODUCTION

Paleotsunami events can be recognized from tsunami deposits in sedimentary sequences. Although ancient writings are important sources of information on tsunamigenic disasters, they are restricted either geographically or temporally. However, according to the observations of modern tsunamis, seawater inundation by tsunamis is evident in coastal sedimentary environments, which therefore record the occurrence of tsunami catastrophes (e.g. Minoura & Nakaya 1991; Shi *et al.* 1995; Nanayama *et al.* 2000; Gelfenbaum & Jaffe 2003; Hori *et al.* 2007). Tsunami run-ups transport materials of marine origin onto the backshore, leaving them as evidence of seawater flooding. If these materials are preserved in undisturbed sedimentary sequences, they may record the invasion of tsunamis over geological time and allow us to uncover the history of tsunami events. A number of tsunami deposits have been found in coastal flats (e.g. Dawson *et al.* 1988; Minoura & Nakata 1994; Minoura *et al.* 2000; Pinegina & Bourgeois 2001; Cisternas *et al.* 2005) and intertidal lacustrine environments (e.g. Atwater & Moore 1992; Bondevik *et al.* 1997; Goff *et al.* 2000; Kelsey *et al.* 2005), and they provide valuable

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information on the ages, recurrence intervals, and magnitudes of paleotsunami events.

Tsunami deposits are thought to be less frequent in the geological record than expected from the recurrence interval of tsunami events (e.g. Dott 1996; Einsele *et al.* 1996; Dawson & Stewart 2007). Since coastal zones are exposed under the influence of permanent or frequent current reworking, coastal sedimentary environments are geologically unstable. For example, both the existence and location of intertidal pools are greatly influenced by various factors, including evaporation and riverine sediment input. Therefore, the existence and distribution of tsunami deposits in coastal zones are restricted.

Submarine sedimentary environments beyond storm wave bases, on the other hand, are considered to be comparatively stable, and traces of paleotsunamis may be preserved for a longer time. A number of tsunami deposits have been identified in sublittoral (Massari & d'Alessandro 2000; van den Bergh *et al.* 2003; Fujiwara & Kamataki 2007), bathyal (Bourgeois *et al.* 1988; Albertao & Martins 1996; Shiki and Yamazaki 1996; Hassler *et al.* 2000; Cantalamessa & Di Celma 2005), and abyssal settings (Kastens & Cita 1981; Takayama *et al.* 2000; Goto *et al.* 2008), and they have been associated with historical and geological events of great interest.

Criteria for identifying onshore paleotsunami deposits have been developed based on the modern instance of tsunami sedimentation. Likewise, studies on submarine sedimentation by recent tsunamis are important to establish criteria for identifying submarine paleotsunami deposits. However, as mentioned by Dawson and Stewart (2007), there are no reliable observational data available on the submarine process of sediment transport and deposition by tsunamis, although hydrodynamic characteristics of paleotsunamis, such as waveforms (Hassler *et al.* 2000; Fujiwara & Kamataki 2007), and wave heights and current velocities (Kastens & Cita 1981; Bourgeois *et al.* 1988; Albertao & Martins 1996), have been estimated on the basis of the sedimentological features of submarine tsunami deposits.

Analysis of allochthonous remains of organisms included within tsunami deposits provides valuable information on the source and transportation process of the deposit. Distribution of marine organisms is controlled by the surrounding environments such as water depth, salinity, and type of bottom sediments. Remains of bottom-dwelling organisms, such as seashells and tests of benthic foraminifera, can be particularly useful indicators of the source of tsunami deposits. Based on such paleontological evidence, the provenance of onshore deposits by modern tsunamis has been associated with a range of areas from beaches to shelf bottoms (Kon'no 1961; Minoura *et al.* 1997; Nanayama *et al.* 2000; Gelfenbaum & Jaffe 2003; Hawkes *et al.* 2007), which in one case corresponds to a water depth of up to 100 m (Nanayama & Shigeno 2006). This implies the hydraulics of tsunamis on shallow-water zones. The current velocity of tsunami run-up is sufficiently high in shelf areas to erode and entrain sea-bottom sediments. In addition, tsunamis likely damage the ecological environment of benthic communities. By analogy, it is possible that traces of tsunamis in submarine settings can be found as the accumulation of allochthonous materials, such as the remains of shallower or deeper dwelling organisms. Changes in the assemblages of benthic species may provide valuable information on the submarine processes of sediment transport and deposition by tsunamis. Moreover, this may increase our knowledge on the hydraulics of tsunamis in offshore regions.

In the context of improving our understanding of submarine tsunami sedimentation, we conducted a micropaleontological analysis of sediments dredged from the southwestern coast of Thailand. Changes in planktonic and benthic foraminiferal assemblages across the 2004 Indian Ocean tsunami and the recovery process of the affected benthic communities are investigated in the present study.

THE 2004 INDIAN OCEAN TSUNAMI

The December 2004 Sumatra–Andaman earthquake ($M_W = 9.1–9.3$; Lay *et al.* 2005) generated a giant tsunami and caused the worst tsunami disaster in recorded history. The epicenter of the earthquake was located off the northwestern coast of Sumatra Island (Lay *et al.* 2005; Stein & Okal 2005), where the Indian Plate slides underneath the Burma Plate. The shallow focal depth (~30 km) and the great length of the rupture zone (~1200 km) may be responsible for the significant size of, and the extensive damage caused by, the tsunami.

Tsunami height and damage were investigated immediately after the tsunami by international groups of tsunami researchers. Measured tsunami heights reached more than 30 m above sea level on the northwestern coast of Sumatra Island (Borrero 2005), and over 10 m on the southwestern coast of Thailand (Thanawood *et al.* 2006) and on the coast of Sri Lanka (Liu *et al.* 2005). The total number of victims and missing people due to the earthquake and tsunami was estimated to be around 230,000 (National Geophysical Data Center 2005).

Onshore depositions of sand layers (Hawkes *et al.* 2007; Hori *et al.* 2007; Umitsu *et al.* 2007; Choowong *et al.* 2008) and coral boulders (Goto *et al.* 2007) by the tsunami were found along the southwestern coast of Thailand. The tsunami deposits covered the coastal plain extensively where the tsunami waves were measured to be high. It is reported that the distribution of a tsunami deposit exceeded 1 km from the shoreline of Khao Lak (Hori *et al.* 2007). Based on the analysis of foraminiferal assemblages, the provenance of tsunami deposits was estimated from subtidal to shelf zones (Hawkes *et al.* 2007). On the coastal plain of Nam Khem, sediments along channels have been eroded severely by the tsunami backwashes, and this has resulted in changes in the coastal topography (Umitsu *et al.* 2007).

MATERIALS AND METHODS

Benthic foraminifers have been a major marine fauna throughout the Phanerozoic and have adapted to diverse habitats ranging from intertidal to deep-sea environments. Their ubiquitous occurrence and excellent adaptation to local conditions afford us advantages in reconstructing the paleoenvironments of strata that yield benthic foraminifer fossils. Focusing on these paleontological characteristics of foraminifers, we aimed to detect living and dead tests in near-surface sediments from the coastal zones of Krabi and Laem Pakarang (Fig. 1a). Tsunami heights were measured around 9 m on the coast of Laem Pakarang and around 6 m on Phi Phi Don (Research Group on 26 December 2004 Earthquake Tsunami Disaster of Indian Ocean 2005). We used a boxed corer (volume 500 cm^3) to collect near-surface sediments. Pre-tsunami sediment samples were collected from the Krabi region on 25 March 1998 (Tsukawaki *et al.* 1999). Post-tsunami samples were collected from the Krabi region on 22 April 2005 and from the Laem Pakarang region on 27 February 2006 (Fig. 1b,c). The water depths of the sampling points were measured instrumentally, and grain-size composition, contents and color of the sediments were visually described immediately after the sampling (Table 1). In summary, the pre-tsunami samples are composed of fine to medium-grained sand and mud with abundant calcareous fragments. The post-tsunami samples collected in April 2005 are composed of fine- to very coarse-grained sand. They contained mollusk shells and their fragments, plant debris, and gravel. The post-tsunami samples collected in February 2006 are composed of very fine- to very coarse-grained calcareous sand.

Sediment samples were rinsed through a 63-μm screen and the residues on the screen were dried in an oven for about one day. The processed samples were divided into aliquot parts by using a sample splitter. About 200 individual benthic foraminifers were picked from one aliquot. We collected all planktonic foraminifers from the same aliquot. Benthic and planktonic foraminifers were identified under a binocular microscope and then counted (Table 2). The pre-tsunami samples were not treated with chemicals to identify living shells within specimens because formalin was not available in the field. Seawater–formalin (5–8 % concentration, depending on the condition of sediment samples) was used for cell fixation of foraminifers from the post-tsunami samples. Foraminifers were stained with Rose Bengal during processing to differentiate living from dead foraminifers.

ASSEMBLAGE ANALYSIS OF FORAMINIFERS

Planktonic foraminifers generally avoid nearshore shallow-water environments (Boltovskoy & Wright 1976). This can be confirmed in our results of the foraminifers from Krabi and Laem Pakarang; planktonic species are more abundant in the sediments from deeper water sites (Table 2). It is noteworthy that they were detected from both pre- and post-tsunami sites where water depths were greater than 15 m. The assemblages in the pre-tsunami sediments are considered to reflect the original habitats of benthic species. The taxa, which have major occurrences from the 2005 samples, are divided into two groups. The first group includes *Ammobaculites villosus*, *Ammonia beccarii*, *Elphidium advena*, and *Rosalina vilardeboana*, and is considered as a nearshore species group because it also occurred in pre-tsunami samples. The other group consists of *Cribrostomoides jeffreysii*, *Amphistegina radiata*, and *Hanzawaia boueana*, which did not occur in pre-tsunami samples. *Cribrostomoides jeffreysii* does not indicate deep-sea environments because it has a test with no alveoli. It is not unusual that *A. radiata* occurred from 24 m water depth, because it lives below the fair-weather wave base (Murray 2006). *Hanzawaia boueana* is known as an inner shelf genus (Murray 2006). Results of the assemblage

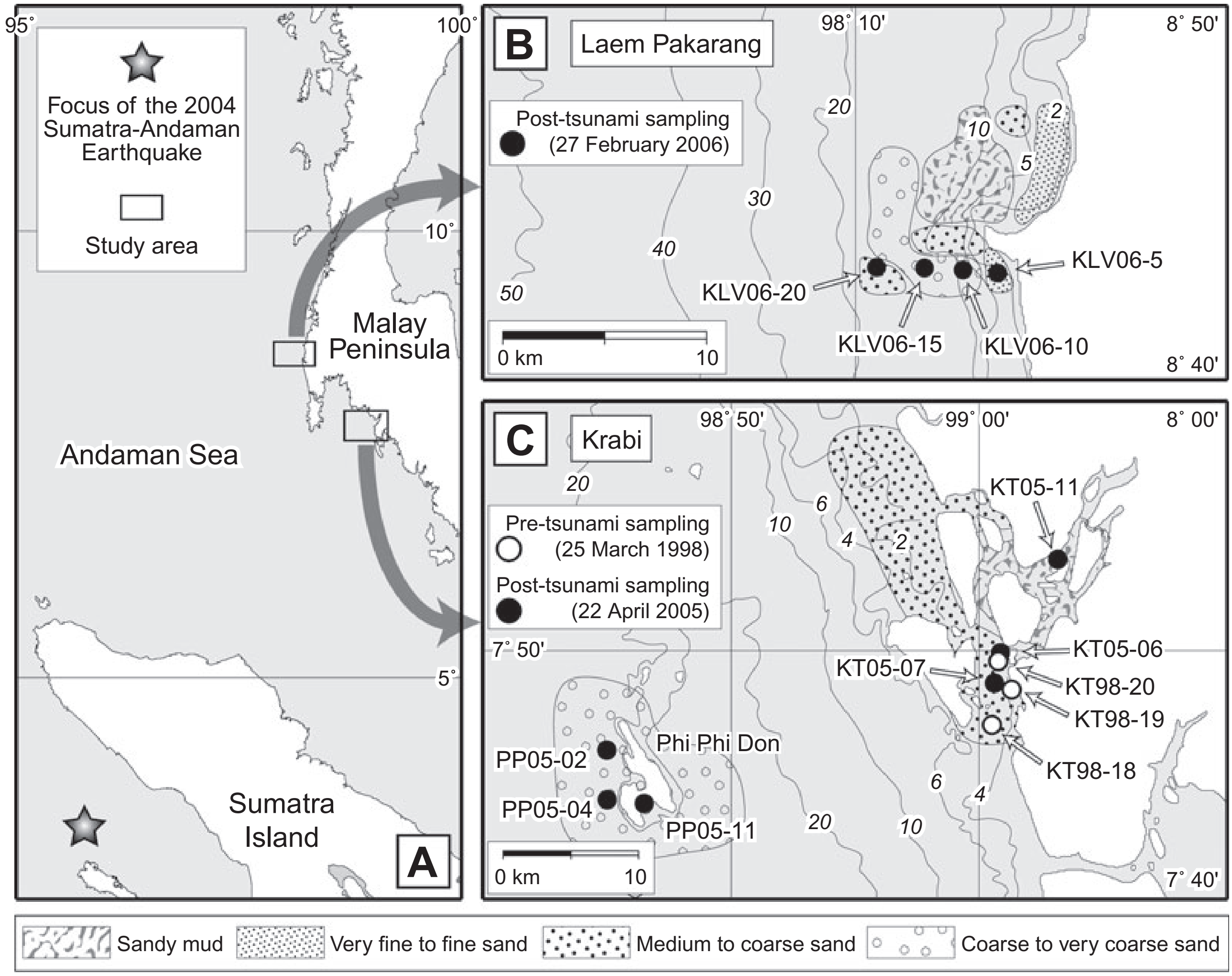

Fig. 1 (a) Location map of study area. Maps showing bathymetric contours (Hydrographic Department 1983), seafloor sedimentary facies, and sampling sites at (b) Laem Pakarang and (c) Krabi in Thailand. These maps were plotted using Generic Mapping Tool (GMT; Wessel & Smith 1998).

analysis show that the nearshore sediments collected on April 2005 do not include benthic foraminifers characteristically found offshore. Thus, neither group indicates transportation from an offshore area. These distributions of planktonic and benthic species suggest that landward redistribution of sediments did not occur in the offshore seafloor of the study area during the run-up to the 2004 Indian Ocean tsunami.

Agglutinated foraminifers are characteristic of an intertidal brackish environment and deep-sea bottom, and those living in the latter environment have a test with alveoli (Bandy 1960). Because the agglutinated foraminifers listed in Table 2 do not have such a test, it is considered that they lived in an intertidal brackish environment. They were identified in the post-tsunami samples from foreshore to offshore zones. The *Ammonia* group, which is common in marsh to subtidal areas with salinity 10–31 psu (Murray 2006), commonly occurred in the deepest sample in 2005, but rarely in the shallower samples (Table 2). This suggests that sediments originally distributed in foreshore to nearshore zones were transported offshore to water depths greater than 20 m due to the tsunami backwash.

To illustrate changes in the pre- and post-tsunami distributions of benthic foraminifers, we selected *A. villosus*, *A. beccarii*, *A. radiata*, *E. depressulum*, *H. boueana*, and *R. vilardevoana* as representative species (Fig. 2). This presentation clarifies the migrations of benthic species triggered by the tsunami backwash and the subsequent recovery of the original distribution patterns. The occurrence of some benthic foraminifers in intertidal zones is extrapolated in Figure 2, on the basis that agglutinated taxa and *Ammonia*–*Elphidium*–*Rosalina* groups are predominant in marsh and

Table 1 List of water depths, visually documented grain-size composition, and contents of sediment samples collected from Laem Pakarang and Krabi

Sample	Latitude (N)	Longitude (E)	Water depth (m)	Sediment
25 March 1998				
KT98-19	7°48′25.4″	99°01′19.3″	6.0	Calcareous fragment rich, dark gray, fine-grained sand
KT98-18	7°47′00.3″	99°00′31.2″	8.4	Calcareous fragment rich, yellowish brown, medium-grained sand
KT98-20	7°49′34.2″	99°00′46.6″	15.0	Granule- to pebble-gravels and shell fragment bearing, brown mud
22 April 2005				
KT05-11	7°53′41.2″	99°03′11.3″	5.3	Brownish gray, muddy fine- to medium-grained sand, brown surface, a little granule- to pebble-gravels, shell fragments and plant debris
KT05-07	7°48′42.2″	99°00′37.1″	9.2	Slightly greenish gray, medium- to coarse-grained sand, large shells and fragments, plant debris
PP05-11	7°43′51.3″	98°46′30.3″	13.1	Light gray, poorly sorted, fine- to very coarse-grained calcareous sand, surface slightly brownish
KT05-06	7°49′54.4″	99°00′52.2″	20.0	Dark grayish olive, muddy medium- to coarse-grained sand, brownish gray surface
PP05-02	7°46′00.1″	98°45′00.0″	24.0	Mollusk shell and shell fragment-rich, olive gray, poorly sorted, medium- to coarse-grained sand
PP05-04	7°43′59.8″	98°45′00.4″	30.0	Greenish gray to olive gray, well sorted, fine-grained sand with a few shell fragments
27 February 2006				
KL-V5	8°42′51.5″	98°13′50.0″	4.5	Bluish olive gray, very fine to fine, well sorted sand, a little organic matter on surface
KL-V10	8°42′56.2″	98°12′53.7″	9.3	Surface: calcareous rich, yellowish brown in color, poorly sorted coarse to very coarse sand. Lower: same but bluish gray
KL-V15	8°43′00.1″	98°11′51.9″	14.1	Surface: reddish/yellowish brown, poorly sorted, coarse to very coarse. calcareous sand. Lower: same but rather yellowish
KL-V20	8°43′00.6″	98°10′34.5″	20.5	Surface: reddish/yellowish gray, medium to coarse less calcareous sand. Lower: less reddish

intertidal lagoon environments, as suggested by Murray (2006). It is evident that *Ammobaculites*, *Ammonia*, *Elphidium*, and *Rosalina* were transported toward the deep environment, implying the influence of tsunami backwash. These shallow-sea species might have been extinct in deeper environments. Two years after the tsunami, *Ammonia* and *Rosalina* species adapted again to each bottom condition and recovered their original distribution pattern. This suggests that the bottom conditions have not changed significantly following the tsunami event. It is probable that these two species at least are quick to recover their original distribution patterns after outer perturbation (Fig. 2).

SUBMARINE SEDIMENT TRANSPORT BY TSUNAMI BACKWASH

Our analysis of the pre- and post-tsunami distributions of planktonic foraminifers indicates that the tsunami run-up did not cause sediment redistribution on the offshore seafloor of the study area (Table 2). The absence of benthic foraminifers, which are characteristic of the offshore environment in nearshore sediments shallower than 15 m, supports this interpretation. On the other hand, seaward migration of benthic foraminifers did take place after the tsunami (Fig. 2). The presence of plant debris in the post-tsunami samples exhibits seaward transportation of coastal sediments including terrestrial materials (Table 1). We suggest that sediments originally distributed in beach to nearshore zones were agitated during the tsunami run-up, and subsequently transported and deposited offshore by the tsunami backwash.

Submarine sedimentation induced by tsunami backwashes has long been investigated but is less understood due to the difficulties in observation of backwashes and resultant deposits (Dawson & Stewart 2007). Few recent studies have explored changes in sedimentological and paleontological features of sea-bottom sediments during tsunami events. In the case of the 2003 Tokachi-oki earthquake tsunami, erosion and changes in grain-size distribution and microfossil assemblages were recognized in the inner-shelf sediments of the eastern coast of Hokkaido, northern Japan (Noda *et al.*

Table 2 Count list of all planktonic and benthic foraminifers identified in sediment samples

Sampling date	25 March 1998			22 April 2005												27 February 2006						
Sample name	KT98-19	KT98-18	KT98-20	KT05-11		KT05-7		PP05-11		KT05-6		PP05-2			PP05-4	KLV06-5		KLV06-10		KLV06-15	KLV06-20	
Water depth (m)	6.0	8.4	15.0	5.3		9.2		13.1		20.0		24.0			30.0	4.5		9.3		14.1	20.5	
Mesh size (µm)	63–2000	63–2000	63–2000	>63		>63		>63		>63		>2000	63–2000		>63	>63		>63		>63	>63	
Living or dead†	T	T	T	L	D	L	D	L	D	L	D	D	L	D	D	L	D	L	D	D	L	D
Planktonic foraminifers																						
Globigerina cf. *bulloides* d'Orbigny															1							
Globigerina quinqueloba Natland														1	3							
Globigerina sp.														1	1							
Globigerinella sp.															2							
Globigerinoides ruber d'Orbigny																						1
Globigerinoides? sp.															1							
Globorotalia cf. *inflata* (d'Orbigny)														1								
Neogloboquadrina sp.											1									1		1
Neogloboquadrina? sp.															1							
Genus and species indeterminable indet.			1												9							
Benthic foraminifers																						
Agglutinated foraminifers																						
Agglutinella agglutinans (d'Orbigny)		1												2					2	1		
Agglutinella sp.															4				1			1
Agglutinella? sp.														1								
Ammobaculites villosus Saidova	23	5		5	43	1					2				1							
Ammobaculites sp. A	7		12																			
Ammobaculites sp.				1	2						1											
Ammobaculites? sp.	6		2		3																	
Ammodiscus intermedius Hoeglund		1	2											1								
Cribrostomoides jeffreysii (Williamson)				4	18					1												
Eggerella sp.															1							
Eggerella? sp.			1																			
Haplophragmoides sp.		3																				
Haplophragmoides? sp.	1																					
Paratrochaammina simplissima (Cushman & McCulloch)					1																	
Recurvoides sp.					1																	
Reophax sp.					1																	
Rhabdammina scabra Hoeglund												3										
Ruakinturia magdaliformis (Schwager)	9	2																				
Schlumbergerina alveoliniformis (Brady)																				2		
Spiroplectammina sp.		1																				
Spiroplectammina? sp.					1																	
Textularia cushmai Saidova																						1
Textularia cf. *foliacea* Heron-Allen and Earland															3							
Textularia cf. *lateralis* Lalicker																						1
Textularia subantarctica Vella																			1			
Textularia truncata Hoeglund														2								
Textularia sp. A																						1
Textularia spp.			1											2	4							
Textularia? sp.				1	1					1	1			2					1			
Thalmannanina sp.					2																	
Trochammina inflata (Montagu)					1					1												
Trochammina pacifica Cushman	3	4	2	1	2										1							
Trochammina cf. *pacifica* Cushman											1											
Trochammina sp. A				1	12																	
Trochammina sp. B			8																			
Trochammina spp.	3		8		9		1			1	4											
Genus et species indeterminated	2	3	3	3	10	2	3			2	6				1							
Calcareous foraminifers																						
Alveolinella guoyi (d'Orbigny)																			1	8		
Ammonia beccarii (Linnaeus)	26	21	43						1					2	12		2	1	2	1		2
Ammonia convexa (Collins)	5		2																			
Ammonia takanebensis (Ishizaki)	1	1																				
Ammonia spp.	10	8	34				2		6		3		1	3	5		3	1	3			
Ammonia? sp.	1	1												1	2				1			
Amphistegina radiata (Fichtel and Moll)														20			8		5	28		28
Amphistegina sp.																			2			
Amphistegina? sp.									1						2				1	5		
Anomalina? sp.			3								1				1		1					
Anomalinoides sp.	1																					
Aphelophragmina semilineata (Belford)	6		4												1							
Aphelophragmina sp.								1														
Amphistegmina? sp.									1													
Assilina ammonoides (Gronovis)									4			6		1					6	11		11
Assilina sp.																			1			
Assilina? sp.									7					1			1			5		1
Asterorotalia gaimardi (d'Orbigny)		8												1	6							
Asterorotalia? sp.	6		1																			
Astrononion? sp.																			1			
Bolivina compacta Sidebottom															2		1					
Bolivina cf. *glutinata* Egger															1							
Bolivina translucens (Phleger and Parker)																	1		1			
Bolivina vadescens Cushman															6							
Bolivina sp.																1			1	2		
Brizalina pseudopygmea (Cushman)									1						1							
Brizalina sp. A									2						12		3					
Brizalina sp. B																			1			

Table 2 *Continued*

Sampling date	25 March 1998			22 April 2005												27 February 2006						
Sample name	KT98-19	KT98-18	KT98-20	KT05-11		KT05-7		PP05-11		KT05-6		PP05-2			PP05-4	KLV06-5		KLV06-10		KLV06-15	KLV06-20	
Water depth (m)	6.0	8.4	15.0	5.3		9.2		13.1		20.0		24.0			30.0	4.5		9.3		14.1	20.5	
Mesh size (μm)	63–2000	63–2000	63–2000	>63		>63		>63		>63		>2000	63–2000		>63	>63		>63		>63	>63	
Living or dead†	T	T	T	L	D	L	D	L	D	L	D	D	L	D	D	L	D	L	D	D	L	D
Brizalina spp.									1								1					2
Buccella? sp.					1																	
Cassidulina reniforme Norvang														1	7							
Cellanthus craticulatus (Fichtel and Moll)	1	1							5					5	1		1		4	6		
Cheilochanus minutus Loeblich and Tappan	1																					
Cibicides lobatulus Walker and Jacob																						1
Cibicides sp.		1													15							1
Cibicides? sp.														1								
Cibicidoides sp.															1							
Cibicidoides? sp.	1																					
Cornuspira sp.																			2			
Cribroelphidium sp. A		2																				
Dendritina striata Hofker																						1
Dendritina? sp.																	1		4	12		1
Discorbia globospiralis Sellier de Civrieux		1																	1	2		
Discorbinella bertheloti (d'Orbigny)	1																					
Discorbinella? sp.															1							
Discorbinoides minogasiformis Ujiie																			1			
Elphidium advena (Cushman)	2	3					46							11								
Elphidium crispum (Linnaeus)														1								
Elphidium depressulum Cushman	14		3																			
Elphidium cf. *hyalocostatum* Todd		3																				
Elphidium indicum Cushman		2																				
Elphidium jenseni (Cushman)	3								4						3				1	1		2
Elphidium neosimplex McCulloch	28	13	2			2																
Elphidium simplex Cushman	21	3	1																			
Elphidium sp. A															1							
Elphidium sp. B																						
Elphidium sp. C							1															
Elphidium sp. D	3																					
Elphidium spp.	4	3	8				3		5		1			4	4		4		1	3		
Elphidium? sp.		3																				1
Eponides cribrorepundus (Asano and Uchio)							3										3			1		1
Fissurina marginata (Montagu)														1	1							
Gallitellia vivans (Cushman)															1							
Glabratella sp.															1							
Glabratella? sp.			1														1		1			
Gypsina vesicularis (Parker and Jones)																						1
Hanzawaia boueana (d'Orbigny)									1					5	21		4		3	3		10
Hanzawaia nipponica Asano	3																					
Hanzawaia sp.																						
Hanzawaia? sp.			2														2		2			1
Hauerina? sp.									1								1					
Heronallenia? sp.		1																				
Heterolepa subhaidingeri (Parr)														4								
Lachlanella parkeri (Brady)														1								
Lagena substriata Williamson															1							
Massilina? sp.															1							
Miliolinella sp.															1							
Miliolinella? sp.															1					2		
Mississippina? sp.			1																			
Murrayinella murrayi (Heron-Allen and Earland)	15	5	27				1															
Murrayinella sp.		1															1					
Nonion subturgidum (Cushman)	10														1							
Nonion sp.																				1		
Nonionoides grateloupi (d'Orbigny)															1							
Nummulites venosus (Fichtel and Moll)									6								1		1	2		3
Operculina heterosteginoides Hofker												1										
Orbitina sp.																				1		1
Parahauerinoides fragilissimus (Brady)																						1
Pararotalia calcariformata McCulloch		17																				
Pararotalia domantayi McCulloch																			7			
Pararotalia sp. A														2			1					
Pararotalia sp. B														1								
Pararotalia sp. C																			7			
Pararotalia sp.											1						2					
Pararotalia? sp.		21																				
Peneroplis arietina (Batch)																		1	4	1		1
Peneroplis pertusus (Forskal)																	1					
Planorbulina acervalis Brady																	1					
Poroeponides? sp.														1								
Pseudononion spp.	1														3							
Pseudononion? sp.		1																				
Pseudoparrella sp.															1							
Pseudoparrella? sp.														1								
Quinqueloculina crassicarinata Collins															1							
Quinqueloculina cf. *cavieriana* d'Orbigny		1																				
Quinqueloculina elongata Natland															1							
Quinqueloculina cf. *elongata* Natland	1																					

Table 2 *Continued*

Sampling date	25 March 1998			22 April 2005												27 February 2006						
Sample name	KT98-19	KT98-18	KT98-20	KT05-11		KT05-7		PP05-11		KT05-6		PP05-2			PP05-4	KLV06-5		KLV06-10		KLV06-15	KLV06-20	
Water depth (m)	6.0	8.4	15.0	5.3		9.2		13.1		20.0		24.0			30.0	4.5		9.3		14.1	20.5	
Mesh size (μm)	63–2000	63–2000	63–2000	>63		>63		>63		>63		>2000	63–2000		>63	>63		>63		>63	>63	
Living or dead†	T	T	T	L	D	L	D	L	D	L	D	D	L	D	D	L	D	L	D	D	L	D
Quinqueloculina incisa Vella														1			2		1			
Quinqueloculina latidentella Loeblich and Tappan																						2
Quinqueloculina philippinensis Cushman																			1			
Quinqueloculina seminulum (Linnaeus)															1							
Quinqueloculina sommeri Tinoco															3							
Quinqueloculina tropicalis Cushman															1							
Quinqueloculina undulata d'Orbigny																	1					
Quinqueloculina vulgaris d'Orbigny							1												2			
Quinqueloculina sp. A														9						4		1
Quinqueloculina sp. B														1								
Quinqueloculina sp. C															1							
Quinqueloculina sp. D		1																				
Quinqueloculina spp.		1												5	3		1		4	3	1	1
Quinqueloculina? sp.		1								1					1		2			1		
Rectobolivina cf. *biformis* (Brady)	1																					
Reussella sp. A															2							
Rosalina bradyi (d'Orbigny)	2	3													1							
Rosalina cosymbosella Loeblich and Tappan		5																				
Rosalina vilardevoana d'Orbigny		5	1										1	3	12		13		4			1
Rosalina sp. A																						1
Rosalina spp.	2	9	2						5					1			6		8	2	1	4
Rosalina? sp.			1											1	2							
Sagrina jugosa (Brady)									1					1			8					3
Sagrina sp.																			1			
Sagrina? sp.																				1		
Sagrinella spinosa (Zheng)															1							
Sagrinopsis fimbriata (Millett)	6	4																				
Spiroloculina subimpressa Parr														2								
Spiroloculina sp. A														1								
Spiroloculina sp.														1								
Spiroloculina? sp.														1								
Spirosigmoilina? sp.																	1					
Triloculina terguemiana (Brady)																			1			
Triloculina tricarinata d'Orbigny															1							
Triloculina trigonula (Lamarck)																						1
Triloculinella pseudooblonga (Zheng)																						1
Wiesnerella ujiiei Hatta																						1
Gen. et sp. indet.	1	6	14		1		1		20		3			9	16		5		12	7		11
Subtotal	231	176	190	16	109	5	62	1	72	7	25	10	2	117	197	1	84	3	104	117	2	103
Total	231	176	190	125		67		73		32		10	119		197	85		107		117	105	
P/T ratio‡ (%)	0.0	0.0	0.5	0.0		0.0		0.0		3.1		0.0	2.5		9.1	0.0		0.0		0.9	1.9	
A/BT ratio§ (%)	23.4	11.4	20.6	100	98	60	6.5	0.0	0.0	86	63	30	0.0	8.8	7.2	0.0	0.0	0.0	4.8	2.6	0.0	4.0

† D, dead; L, living; T, total.
‡ Relative abundance of planktonic foraminifers = ratio (%) of the number of tests of planktonic foraminifers to those of planktonic and benthic foraminifers.
§ Relative abundance of agglutinated benthic foraminifers = ratio % of the number of tests of agglutinated benthic foraminifers to those of benthic foraminifers.

2007). This can be associated with the influence of the tsunami backwash, although the overall trend of the changes is ambiguous. Gandhi *et al.* (2007) reported landward migration of the assemblages of benthic foraminifers after the 2004 Indian Ocean tsunami. Based on paleontological and sedimentological analysis, they suggested that the post-tsunami sediments on beach to nearshore zones of the Gulf of Mannar, southeastern coast of India, were brought from the inner-shelf region due to tsunamigenic activities. In addition, as mentioned above, some studies associated the provenances of onshore tsunami deposits with inner-shelf regions (e.g. Nanayama & Shigeno 2006; Hawkes *et al.* 2007). Although our results did not show offshore deposition of sediments originated in deeper water regions, this may not imply inconsistency with the results of other studies. It is probable that tsunami run-ups entrain offshore sediments and transport them landward, but do not necessarily leave detectable traces on the nearshore to offshore seafloor. In other words, deposition by tsunami run-ups is prominent in coastal lowlands; meanwhile, deposition by tsunami backwashes is evident in nearshore to offshore zones.

According to the onshore investigations on modern tsunamis, backwashes converge to topographic depressions such as channels (Kon'no 1961; Umitsu *et al.* 2007). This results in severe erosion of the ground surface and deposition of the reworked sediments (e.g. Nanayama & Shigeno 2006). Satellite imagery taken at the time of the 2004 Indian Ocean tsunami showed that the tsunami backwash transported a large amount of sediment seaward (images taken by the DigitalGlobe Quickbird satellite are available on http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=14400). The observations of the 1983

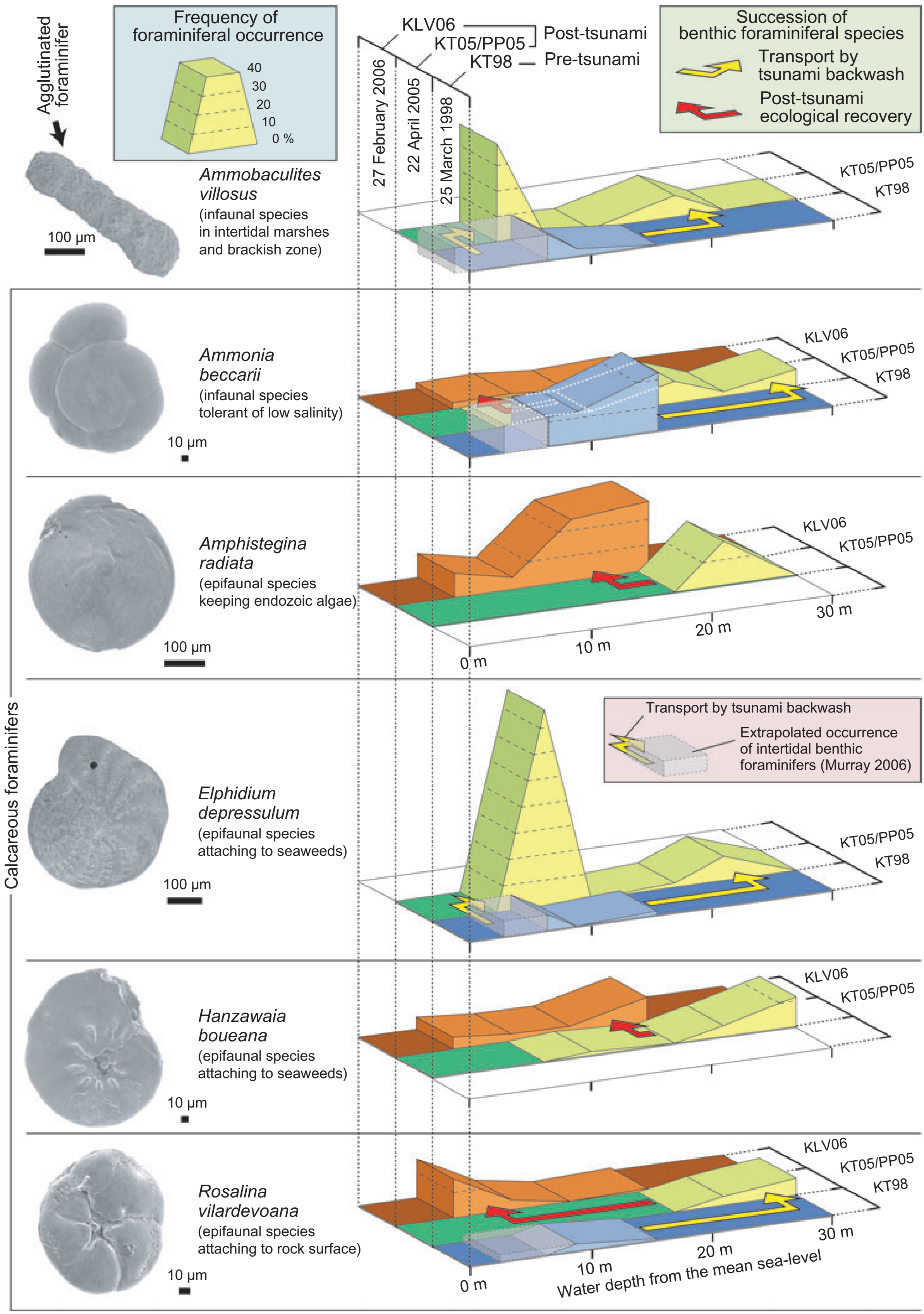

Fig. 2 Schematic diagram showing pre- and post-tsunami distributions of six representative benthic foraminifers, demonstrating backwash transport of foraminifers during the tsunami, and community recovery after the tsunami.

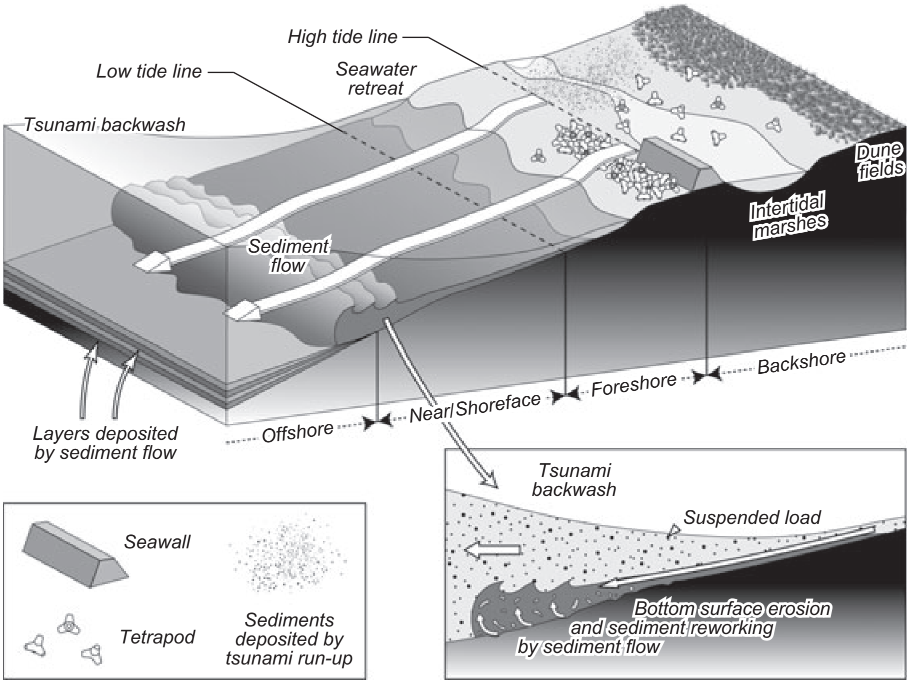

Fig. 3 Schematic diagram showing interpreted mode of sedimentation by tsunami backwash. Sediment load and speed of bottom currents from seawater retreat increase downslope to form sediment flow. The slope reduction at the base of the nearshore zone reduces the kinetic energy of the flow, and a layer of allochthonous sediments is deposited offshore.

Japan Sea earthquake tsunami by Minoura and Nakaya (1991) have shown that the tsunami backwash could dramatically move large volumes of material in suspension and by rolling. They noted that some of the human victims of the tsunami were carried out to sea by the backwash, together with terrigenous materials, and have never been found. These findings indicate that tsunami backwashes are extremely strong and can thus generate mass transport of materials over the seabed, and that allochthonous materials accumulate in nearshore to offshore zones.

Figure 3 illustrates our interpretation of sediment transport and deposition by tsunami backwashes. The retreating seawater caused by tsunami backwashes entrains movable material to form dense sediment flows in nearshore zones; these flow to the offshore zone, where the decrease in slope angle reduces the kinetic energy of the flow so that sediments, including allochthonous material, are deposited offshore. It is important to note that there may be traces of paleotsunami backwash in offshore sedimentary sequences. Since benthic communities affected by tsunami waves adapt again to the bottom conditions and recover their original distribution pattern one or two years after the tsunami, traces of tsunamis can be identified as abrupt changes in, and subsequent recovery of, benthic foraminiferal assemblages. The presence of allochthonous foraminiferal fossils allows estimation of the distance over which sediments have been transported by tsunami backwash, as long as information on the original habitat for the fossil species is available. The age of strata deposited by tsunamigenic sediment flow can be determined by Accelerator Mass Spectrometry (AMS) radiocarbon dating of the calcareous tests of foraminifers, and may be used to identify and date paleotsunamis.

CONCLUSIONS

Micropaleontological analysis of foraminifers in the sea-bottom sediments recovered from the southwestern coast of Thailand clarified submarine processes of sediment transport and deposition during the 2004 Indian Ocean tsunami. The distribution pattern of benthic foraminifers showed seaward migration after the tsunami event. Agglutinated foraminifers, which are characteristic of an intertidal brackish environment, were identified in the post-tsunami samples from foreshore to offshore zones. These findings suggest that sediments originally distributed in backshore to nearshore zones were transported offshore due to the tsunami backwash. The presence of plant debris in the post-tsunami sediment samples supports this interpretation. On the other hand, the distribution pattern of planktonic and benthic species living in offshore zones showed slight evidence of landward migration by the tsunami. This suggests that a large landward redistribution of sediments by the tsunami run-up did not occur in an offshore seafloor of the study area.

These results and a review of previous studies provide an interpretation of submarine processes of sediment transport and deposition by tsunamis. Tsunami run-ups entrain offshore sediments and transport them landward, but do not necessarily leave detectable traces on the nearshore to offshore seafloor; meanwhile, tsunami backwashes produce sediment flow that transport and deposit a large amount of coastal materials onto the offshore seafloor. Deposition by tsunami run-ups is prominent in coastal lowlands, and deposition by tsunami backwashes is evident in nearshore to offshore zones. We suggest that accumulation of allochthonous foraminifers can be preserved as traces of paleotsunami backwash in offshore sedimentary environments. They are detectable on the basis of micropaleontological analysis.

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