

Sediments deposited by the 2004 Indian Ocean Tsunami along the Malaysia–Thailand Peninsula

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Abstract

Stratigraphy, grain size distribution and foraminiferal assemblages of pre-tsunami and tsunami sediment from the Indian Ocean Tsunami at five sites along the Malaysia–Thailand Peninsula were analyzed to gain information on tsunami sediment source and deposition style. Between three and five stratigraphic units were identified at each site and contained between one and three fining upward sequences reflecting waning flow or pre-backwash deposition. Coarser sand layers reflecting uprush high-energy flow separated the fining upward sequences, with the exception of one site (Sungai Burong), which contained a coarsening upward sequence. All contacts between the pre-tsunami and tsunami sediment were sharp or erosional. Medium and coarse sand dominated all of the tsunami sediment deposits and often contained shell fragments. Foraminiferal assemblages were able to differentiate pre-tsunami sediment from tsunami sediment where no lithological or grain size distribution change was evident. Between two and four foraminiferal zones were identified at each of the five sites and provided estimates of sediment source and wave characteristics. © 2007 Elsevier B.V. All rights reserved.

Keywords: Malaysia; Thailand; tsunami; grain size; foraminifera

1. Introduction

On December 26th 2004 an M 9.3 earthquake deformed the ocean floor 160 km off the northwest coast of the Indonesian Island of Sumatra, displacing the overlying water and generating the Indian Ocean Tsunami

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(Fig. 1). The earthquake was the result of complex slip, where the Indo-Australian Plate was being thrust under the Sunda Plate (Ammon et al., 2005; Battacharjee, 2005; Borrero, 2005; Lay et al., 2005; Moore et al., 2005; Stone and Kerr, 2005; Titov et al., 2005; Yeh et al., 2005; ASCE, 2005; Thanawood et al., 2006). The earthquake ruptured 1300 km along the northwest–southeast trending Sunda Trench, propagating from the epicenter north at a rate of ~ 2.8 km/s for a duration of 8 min (Ammon et al., 2005; Ishii et al., 2005). The amount of fault slip was greatest off Sumatra and the Nicobar Islands and decreased as it propagated to the north (Ammon et al., 2005; Ishii et al., 2005; Okal and Stein, 2005). The 2004 Sumatra–Andaman rupture is the longest ever recorded in terms of duration and extent, and is second only to the great 1960 Chile earthquake in slip area (Ammon et al., 2005; Ishii et al., 2005). The tsunami devastated nearby areas such as Sumatra where waves reached heights of 34 m (Tsuji and Sumatra International Tsunami Survey Team, 2005). The tsunami was registered around the world by many tide gauges (Gower, 2005).

Evaluating the foraminiferal assemblages in pre-tsunami and tsunami sediment from modern tsunami

deposits may provide additional techniques to either support existing lithostratigraphic characteristics or importantly, distinguish tsunami sediment from other sediments where lithostratigraphic characteristics are inadequate. Furthermore, these findings may be applicable to identify and characterize paleo-tsunami deposits in the geologic record. Thus, in this paper, we used lithostratigraphic (grain size distribution and loss on ignition) and foraminiferal analyses to characterize pre-tsunami and tsunami sediment from the Indian Ocean Tsunami along the Malaysia–Thailand Peninsula to provide information on tsunami sediment source and deposition style.

Tsunami deposits have been identified using characteristics such as inland inundation, sand–mud couplets, fining upward sequences and boulder deposits (e.g., Clague and Bobrowsky, 1994; Dawson, 1994, 1996; Nelson et al., 1996; Dawson, 1999; Dawson and Shi, 2000; Nanayama et al., 2000; Goff et al., 2001; Moore, 2001; Goff et al., 2004; Tuttle et al., 2004; Atwater et al., 2005; Liu et al., 2005; Moore et al., 2005; Williams et al., 2005). Preliminary identification is often based on anomalous sand deposits in an environment where such a deposit was unusual, such as coastal lakes and marshes



Fig. 1. Location of five sites studied along the Malaysia–Thailand Peninsula. Thailand sites are: Khuk Khak Beach, Khao Lak; Tonsai village, Phi Phi Don; and Somewhere Else Resort, Ko Lanta Yai. Malaysia sites are: Kuala Teriang, Langkawi Island; and Sungai Burong, Penang Island.

(e.g., Atwater, 1987; Atwater and Hemphill-Haley, 1997; Atwater et al., 1995; Reinhard and Bourgeois, 1994; Nelson et al., 1996; Shennan et al., 1999). The literature is heavily focused on multi-proxy sedimentary and stratigraphic evidence (e.g., Dawson et al., 1996; Nanayama et al., 2000; Goff et al., 2001; Moore, 2001; Smith et al., 2004; Moore et al., 2005; Liu et al., 2005). These techniques are utilized to discount other processes such as storm surges and sea level change (e.g., Nelson et al., 1996; Atwater et al., 2005).

In addition, tsunami deposits have been identified by microfossil analyses where species show abrupt marked changes in assemblages that may include offshore taxa. Most studies have used diatoms (e.g., Hemphill-Haley, 1995, 1996; Williams and Hutchinson, 2000; Nanayama et al., 2003; Sawai et al., 2004; Williams et al., 2005; Kelsey et al., 2005). In contrast, the study of tsunami-deposited foraminifera is in its infancy and the potential value of such a technique in further defining tsunami sediment characteristics is yet to be realized (e.g., Dawson et al., 1995; Dawson, 1996; Dawson and Shi, 2000; Hawkes et al., 2005). Dawson and Shi (2000) indicated

that the presence of deep-water offshore foraminifera within sediment layers in western Crete was the result of landward deposition by a tsunami. Nanayama and Shigeno (2006) interpreted the offshore foraminifera found within one of four sediment layers deposited by the 1993 Hokkaido tsunami as indicative of deposition by the largest incoming wave. Dawson et al. (1995) concluded that the abundance of juvenile benthic foraminifera near the top of a tsunami deposit from the AD 1755 Lisbon earthquake might have reflected water sorting, sediment winnowing, or test buoyancy during deposition. Alternatively, McMurtry et al. (2004) attributed large, robust, reef-dwelling foraminifera in sediment at Kohala, on the large island of Hawaii, to high-energy deposition by a giant tsunami. The presence of abundant broken microfossil tests has been suggested to indicate high-energy deposition indicative of a tsunami origin (e.g., Murray, 1993; Dawson, 1996).

2. Regional setting

Sites were selected based on satellite images and aerial maps, local scientists' knowledge of the areas and

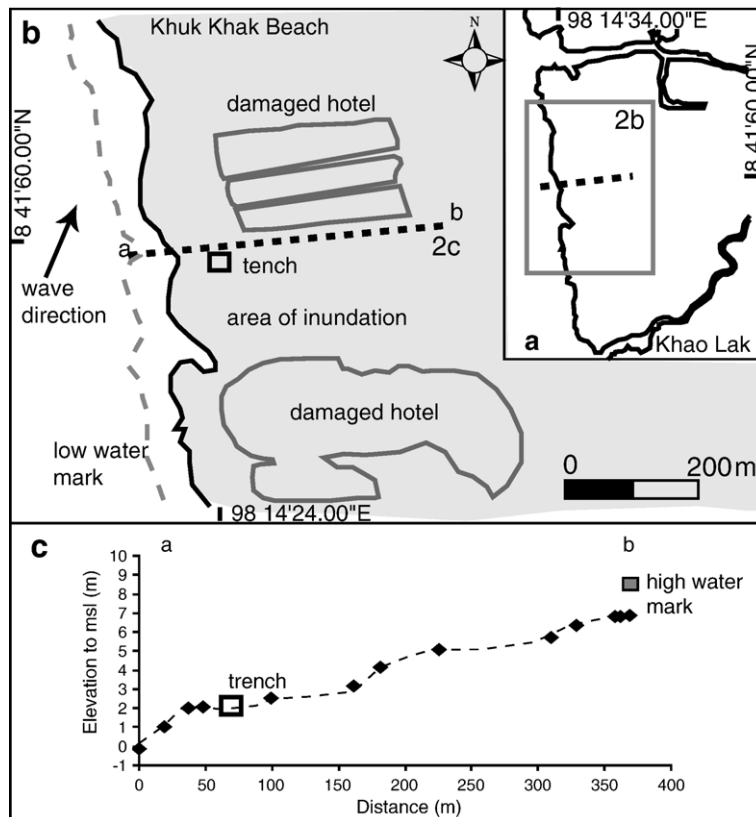


Fig. 2. (a) General location map of Khao Lak, Thailand. (b) Map of Khuk Khak Beach showing the location of the leveled transect. (c) A cross section a–b from subtidal to supratidal with respect to elevation above mean sea level. Trench location and maximum flow depth noted.

preliminary site reconnaissance. We selected five sites to fulfill three criteria: Indian Ocean Tsunami sediment was present; minimal site cleanup and reconstruction had been initiated; and eyewitness accounts were available. The study sites extend from north to south along the Malaysia–Thailand Peninsula (Fig. 1). The Thailand sites, Khuk Khak Beach, Khao Lak ($8^{\circ} 38' 49''\text{N}$, $98^{\circ} 14' 44''\text{E}$), Tonsai village, Phi Phi Don ($7^{\circ} 44' 36''\text{N}$, $99^{\circ} 46' 19''\text{E}$) and Somewhere Else Resort, Koh Lanta Yai ($7^{\circ} 36' 58''\text{N}$, $99^{\circ} 01' 45''\text{E}$), consist of beaches lying between rocky limestone headlands (Buranakul et al., 2005; Rigg et al., 2005). The transect at Khuk Khak Beach ran 369 m from the low water mark up to ~ 7 m above mean sea level (msl) across a sandy subtidal to a terrestrial supratidal environment. The trench was located 65 m along the transect at 2 m above msl (Fig. 2). The transect at Tonsai village ran 464 m from ~ 0.20 m below msl to ~ 4 m above msl across a sandy subtitle to supratidal zone. The trench was located 281 m along the transect at 3.65 m above msl (Fig. 3). At Somewhere Else Resort the transect ran 51 m from ~ 0.10 m below msl to ~ 3 m above msl across a sandy

subtidal to supratidal zone. The trench was located 47 m along the transect at 3.2 m above msl (Fig. 4).

The Malaysian sites, Kuala Teriang, Langkawi ($6^{\circ} 21' 39''\text{N}$, $99^{\circ} 42' 47''\text{E}$) and Sungai Burong, Penang ($5^{\circ} 20' 15''\text{N}$, $100^{\circ} 11' 44''\text{E}$; Fig. 2), included narrow, steep beaches with wide intertidal zones. The Kuala Teriang transect ran 16 m from ~ 0.10 m to ~ 3 m above msl across a silty intertidal zone across a rock revetment. The trench was located 7 m along the transect at ~ 2 m above msl (Fig. 5). The Sungai Burong transect ran from 0.5 m to ~ 3 m above msl across a silty intertidal zone to a brackish mangrove area. The trench was located at 44 m along transect at ~ 3 m above msl (Fig. 6).

3. Methods

3.1. Run up and flow depth

We measured the local topography, tsunami run up and flow depth along five transects from sub- to supra-tidal environments at five sites along the Malaysia–Thailand

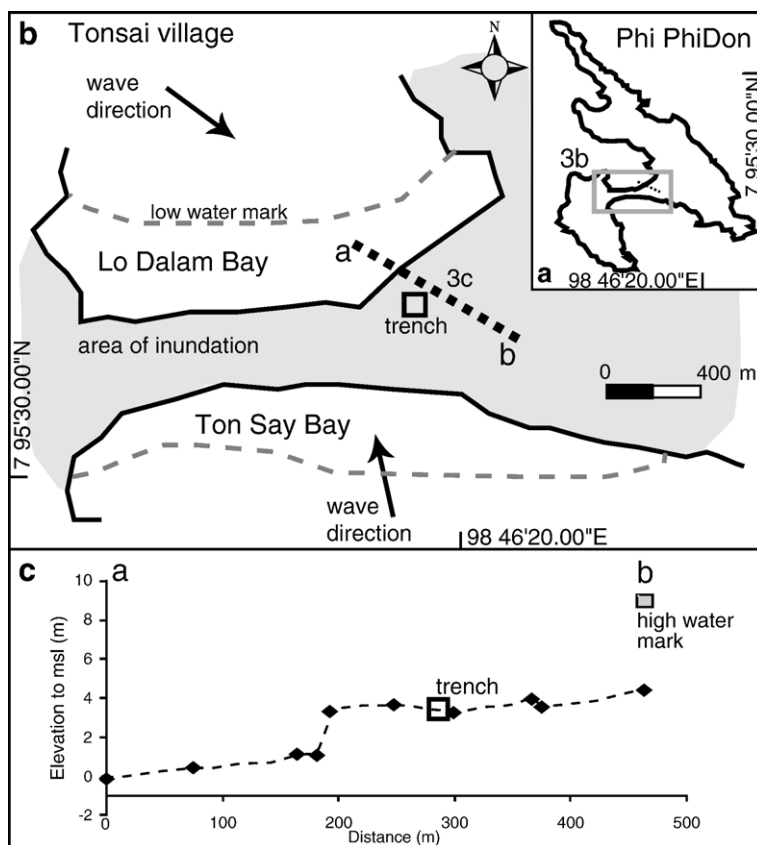


Fig. 3. (a) General location map of Phi Phi Don, Thailand. (b) Map of Tonsai village showing the location of the leveled transect. (c) A cross section a–b from subtidal to supratidal with respect to elevation above mean sea level. Trench location and maximum flow depth noted.

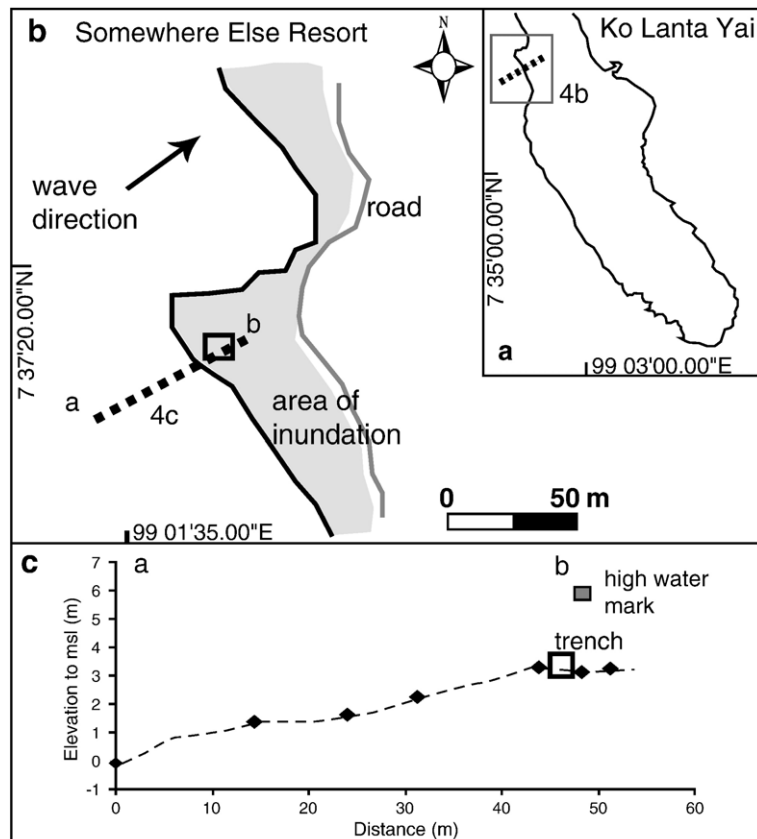


Fig. 4. (a) General location map of Ko Lanta Yai, Thailand. (b) Map of the Somewhere Else Resort area showing the location of the leveled transect. (c) A cross section a–b from subtidal to supratidal with respect to elevation above mean sea level. Trench location and maximum flow depth noted.

Peninsula (Figs. 2–6; IOC, 1998; Tsunami Technical Review Committee, 2002; Lynett et al., 2003; Schiermeier, 2005). We determined the height of minimum flow depth by watermarks defined by a thin film of mud and organic debris on trees and electricity poles using a Leica SR530 GPS system. The interpretation of watermarks on buildings is less straightforward (IOC, 1998). Detailed determination of watermark heights both outside and inside a single house directly in the path of the tsunami at Sungai Burong revealed a 1 m difference in elevation between the watermarks preserved on the outside wall of the house facing perpendicular to the direction of tsunami approach (1.55 m) compared to watermarks on the inside back wall of the house. Watermarks on the outside walls parallel to the direction of flow provide the most reliable estimates of minimum flow depth. As a result of this complication, the orientation of all walls was noted and used for the determination of water depth from preserved watermarks. We also mapped local features using a Trimble Geoxplorer XT. All measurements were fixed by GPS to a horizontal accuracy of ± 5 m. All elevation measurements are accurate to ± 0.15 m (Bird et al., 2007).

3.2. Stratigraphy and sampling

Through reconnaissance trenching and stratigraphic analyses, we selected the five trench locations. These trenches had the deepest deposit of 2004 tsunami sediment and were at an elevation unaffected by high tide along a leveled transect perpendicular to the coast (Figs. 2–6). It should be noted that we chose to study one trench at each site and that the stratigraphy, grain size and microfossil characteristics recorded may vary over metres to hundreds of metres and therefore may not be applicable within or between sites. We photographed and stratigraphically described the sediment profiles at all locations using a combination of USDA Soil Stratigraphic Nomenclature (NRCS, 1996) and Tröels-Smith nomenclature (1955). At the two Malaysian sites, Kuala Teriang and Sungai Burong, we used a 1 cm vertical sampling interval. At the three Thailand sites, Khuk Khak Beach, Tonsai village and Somewhere Else Resort, we took samples from each stratigraphic unit identified in the field. The differences in sampling regime were due to

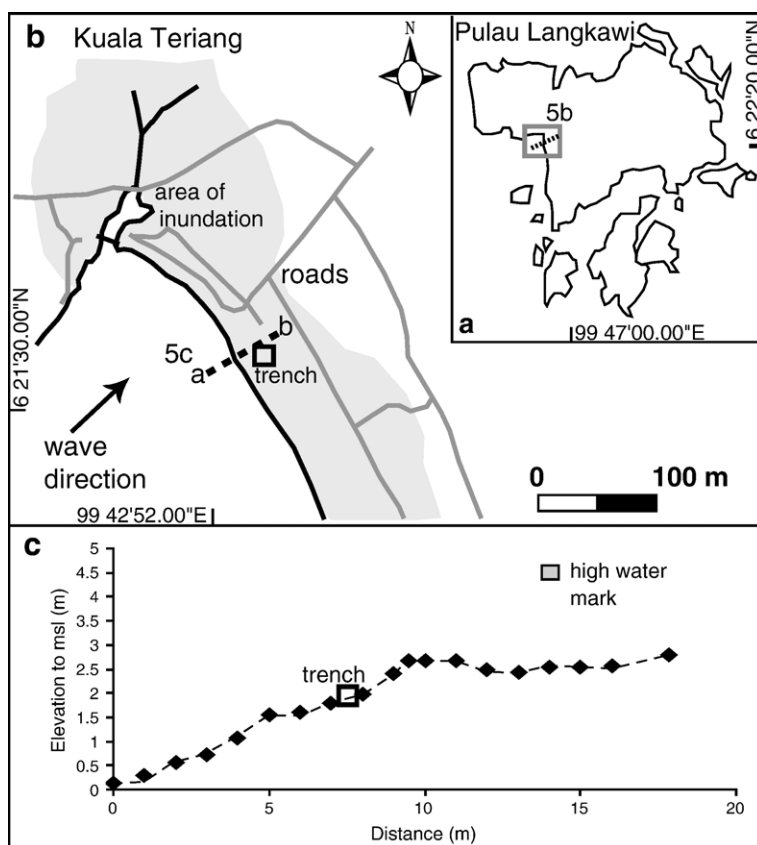


Fig. 5. (a) General location map of Pulau Langkawi, Malaysia. (b) Map of Kuala Teriang showing the location of the leveled transect. (c) A cross section a–b from intertidal to supratidal with respect to elevation above mean sea level. Trench location and maximum flow depth noted.

problems with non-cohesive sediment deposits. A 5 cm³ sample was taken for grain size distribution and loss on ignition tests, and 5 cm³ sample for foraminifera studies.

3.3. Grain size analyses

Grain size distribution was determined using a Beckman Coulter laser particle size analyzer (Beckman Coulter, 1999) following the sediment preparation procedures of Barrett and Brooker (1989) and Goff et al. (2004). Grain sizes were based on the Wentworth scale (1922). Organic content of the sediments was determined by loss on ignition (LOI) following the procedures of Ball (1964), Bondevik et al. (2003) and Heiri et al. (2001).

3.4. Foraminiferal analyses

Foraminiferal analyses followed the standard methods (e.g., Scott and Hermelin, 1993; de Rijk, 1995; Scott

et al., 2001; Horton and Edwards, 2006). Where possible we counted up to 300 specimens of foraminifera in the 63–500 µm size fraction in a liquid medium (e.g., Murray, 1979, 1993; Buzas, 1990). Minimum counts were never less than 50 individuals per 5 cm³ sample. We measured specimen test diameters with a graticule (<100 µm=small, <200 µm=medium and >200 µm=large). We also noted whether tests were broken, etched, or infilled but we found no relationship to lithology or foraminiferal assemblages. Foraminifera were identified using Frerichs (1970), Millett (1970), Whittaker and Hogkinson (1979), Jones (1994), Loeblich and Tappan (1994), Hayward et al. (1997), Hayward et al. (1999), and taxonomy was confirmed with reference to the Cushman Collection of Foraminifera, National Museum of Natural History, Smithsonian Institute (Plates I and II).

Stratigraphically constrained Euclidean distance cluster analysis was employed to detect, describe and classify patterns within the pre-tsunami and tsunami samples from the five Malaysia–Thailand foraminiferal

data sets. We also assessed species diversity using the Fisher's alpha diversity index, defined implicitly by the formula,

$$S = a * \ln(1 + n/a)$$

where, S is number of taxa, n is number of individuals and a is the Fisher's alpha (Fisher et al., 1943).

4. The tsunami

At Khuk Khak beach, Khao Lak (Fig. 2), eyewitnesses described the first wave coming ashore at 10:30 am (local time). Interviewees only described this initial wave. The run up penetration of the tsunami was between 1000 m and 2000 m (Fig. 2). Flow depth was 8.6 m above msl at 369 m inland.

At Tonsai village, Phi Phi Don (Fig. 3), eyewitnesses claimed the first wave came ashore from the south at

10:35 am (local time) but was not destructive. At 10:37 am (local time), a second wave arriving from the north combined with backwash from the first wave, created the most destructive wave. The sea rapidly retreated 200 m at 10:30 am (local time) just 5 min before the first wave came ashore. Run up was 464 m southwest from the Lo Dalam Bay side and the flow depth was 9 m above msl (Fig. 3).

At Somewhere Else Resort, Koh Lanta (Fig. 4), no time line of tsunami wave arrivals is available but eyewitnesses recalled that the first wave was 4 m to 5 m in height. Run up reached 52 m with a flow depth of 5.9 m above msl (Fig. 4).

At Kuala Teriang, Langkawi (Fig. 5), the first tsunami wave arrived at 12:27 pm (local time) and was sustained for 2 min. The second tsunami wave reached the harbor at 12:55 pm (local time). A final tsunami wave reached the harbor entrance at 14:07 pm (Bird et al., 2007). Tsunami run up reached 250 m inland and flow depth up to 4.3 m above msl (Fig. 5).

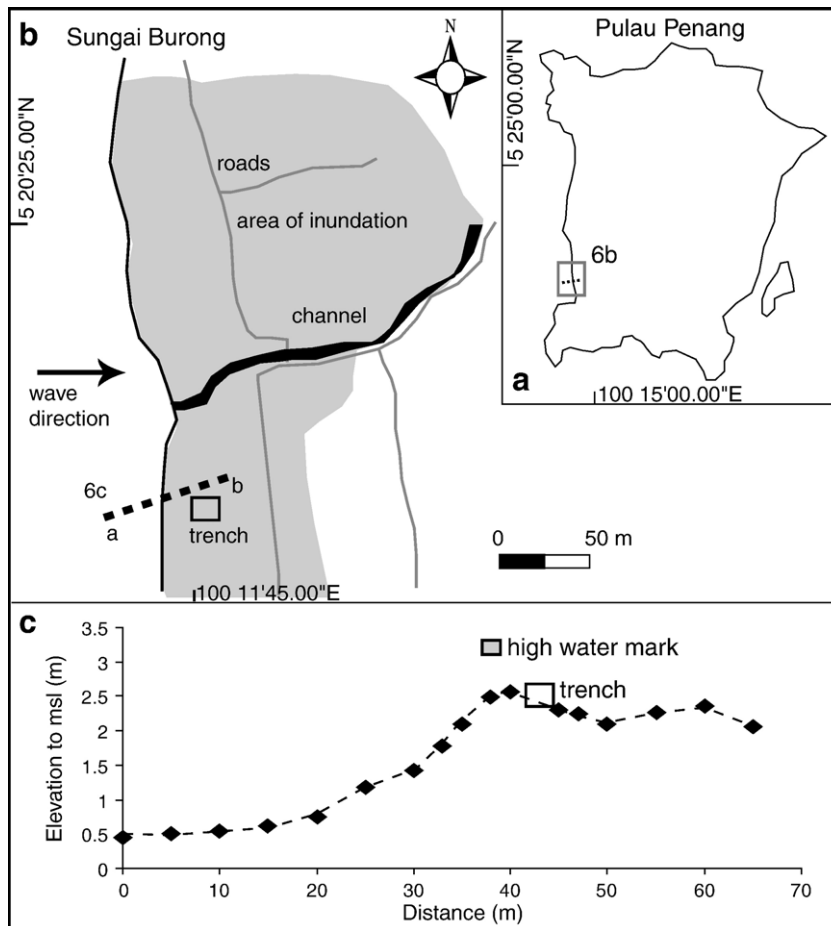


Fig. 6. (a) General location map of Pulau Penang, Malaysia. (b) Map of Sungai Burong showing the location of the leveled transect. (c) A cross section a–b from intertidal to supratidal with respect to elevation above mean sea level. Trench location and maximum flow depth noted.

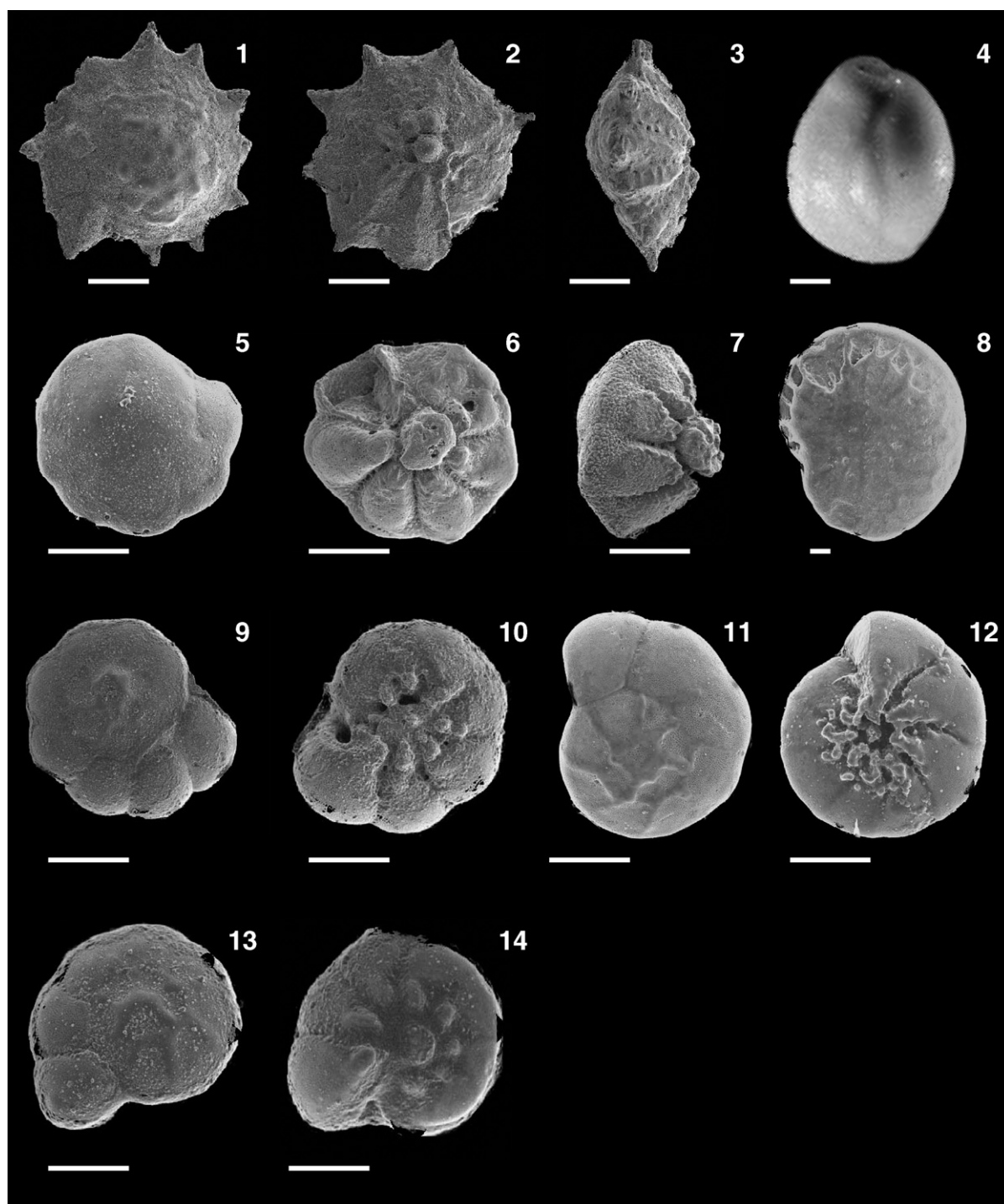


Plate I. All white lines are equal to 100 μm , scale reflects average size of specimens in this study. 1. *Pararotalia stellata* ventral view. 2. *Pararotalia stellata* dorsal view. 3. *Pararotalia stellata* side view. 4. *Quinqueloculina seminula* side view. 5. *Ammonia parkinsonia* ventral view. 6. *Ammonia parkinsonia* dorsal view. 7. *Ammonia parkinsonia* side view. 8. *Amphistegina gibbosa* side view. 9. *Ammonia* spp. A ventral view. 10. *Ammonia* spp. A dorsal view. 11. *Ammonia* spp. B ventral view. 12. *Ammonia* spp. B dorsal view. 13. *Ammonia* spp. C ventral view. 14. *Ammonia* spp. C dorsal view.

At Sungai Burong, Penang (Fig. 6), no time line of tsunami wave arrivals is available. The tsunami run up penetrated 1.5 km inland. Flow depth reached up to 3.2 m above msl within 40 m of the coastline. Incoming water rushed up through the creek channel and breached the paved levees (2.8 and 3.0 m above msl) up to 700 m upstream (Fig. 6).

5. Grain size distribution and foraminiferal analysis

5.1. Khuk Khak beach, Khao Lak

Samples were taken from an 18 cm deep trench with pre-tsunami sediment (unit 1) dominated by coarse to very coarse sand with organics from 18 cm to 15 cm and medium to coarse brown tsunami sand from 15 cm to 0 cm (Fig. 7). The contact between the pre-tsunami and tsunami sediment was abrupt and erosive with the underlying soil mat ripped and pulled back in a landward direction. Stratigraphical units 2, 3 and 4 all contained fining upward sequences of brown sand; the fining upward sequence in unit 3 partially eroded the top of unit 2. Loss on ignition showed little variation but was lowest at 0.6% between 15 cm and 10.5 cm and highest at 1.3% between 8 cm and 4 cm.

Three foraminiferal zones were identified within the 18 cm trench (Fig. 7). Zone KKI (18 cm to 15 cm) was the pre-tsunami sediment and contained no foraminifera. Zone KKII (15 cm to 10.5 cm) consisted of similar relative abundances (c. 25%) of *Elphidium craticulatum*, *Pararotalia stellata* and *Quinqueloculina seminulum*. Zone KKIII (10.5 cm to 0 cm) was in the upper tsunami sediment and was dominated by *Cibicides refulgens*, *Q. seminulum* and *Elphidium* spp. in decreasing order. Fisher's alpha diversity index showed the highest diversity between 10 cm and 8 cm in Zone KKII. The total number of foraminifera in the tsunami sediment ranged from 250 to 1750 individuals per 5 cm³ with the highest numbers occurring in Zone KKIII. Foraminiferal tests showed a consistent size fractioning throughout the tsunami sediment with 60% medium (100–200 µm), 25–30% small (<100 µm) and 15–10% large (>200 µm) test size.

5.2. Tonsai village, Koh Phi Phi

Samples were collected from a 20 cm deep trench with pre-tsunami sediment consisting of 5 cm of weathered brown medium sand overlain by 6 cm of darker brown organic soil from 20 cm to 11 cm. A medium to fine brown tsunami sand was found from 11 cm to 0 cm (Fig. 8). We distinguished three stratigraphic units

containing two fining upward sequences. The contact between the pre-tsunami and tsunami sediment was sharp and undulating. Unit 2 and 3 each contain a fining upward sequence; the basal section of unit 2 also contains small black organic rip-up clasts. Loss on ignition was lowest in the first fining upward sequence at 0.2% between 6 cm and 3 cm and highest in the pre-tsunami soil horizon at 5.2% from 14.5 cm to 11 cm.

Two foraminiferal zones were identified within the 20 cm trench (Fig. 8). Zone PPI (20 cm to 11 cm) of pre-tsunami sediment was dominated by *Amphistegia gibbosa* (40–60%), *Elphidium excavatum clavatum* (up to 40%) and *Ammonia* spp. (up to 40%). Zone PPII (11 cm to 0 cm) consisted of tsunami sediment dominated by *P. stellata* (25–50%) and *Ammonia* spp. (15–35%). Fisher's alpha diversity index showed the highest diversity between 11 cm and 6 cm in Zone PPII. The total number of foraminifera was low within the pre-tsunami sediment (<50 individuals per 5 cm³), whereas the tsunami sediments total numbers were higher (~1000 individuals per 5 cm³). The upper-most sample from 2 cm to 0 cm contained 3940 individuals per 5 cm³. The dominant foraminiferal test size throughout the 20 cm deposit was between 70% and 100% medium (100 to 200 µm). Large test size (>200 µm) appeared at the onset of the tsunami sediment and ranged between 20% and 30% with the highest percentage at 6 cm to 3 cm.

5.3. Somewhere Else Resort, Koh Lanta

Samples were taken from a 33 cm deep trench with a pre-tsunami coarse and medium soil horizon between 33 cm and 30 cm and fine to very coarse brown tsunami sand from 30 cm to 0 cm (Fig. 9). We distinguished five stratigraphic units containing three fining upward sequences. Shell fragments were present throughout the tsunami sediment. The contact between the pre-tsunami soil and tsunami sediment was sharp. Units 2, 3 and 4 each contain a fining upward sequence. Within unit 2, from 24 cm to 22 cm, small 1.5 cm-high asymmetrical current ripples were draped with a fine organic debris layer 0.5 cm thick. The deposition of unit 4 and 5 each eroded the top of the underlying unit. Loss on ignition showed little variation throughout the tsunami sediment (2.3 and 2.9%) whereas the pre-tsunami sediment reached a high of 4.2%.

Four foraminiferal zones were identified within the 33 cm trench (Fig. 9). Zone SEI (33 cm to 30 cm) within the pre-tsunami sediment was dominated by *E. craticulatum* (60%) and *A. gibbosa* (40%). Zone SEII (30 cm to 22 cm) was dominated by *E. craticulatum*

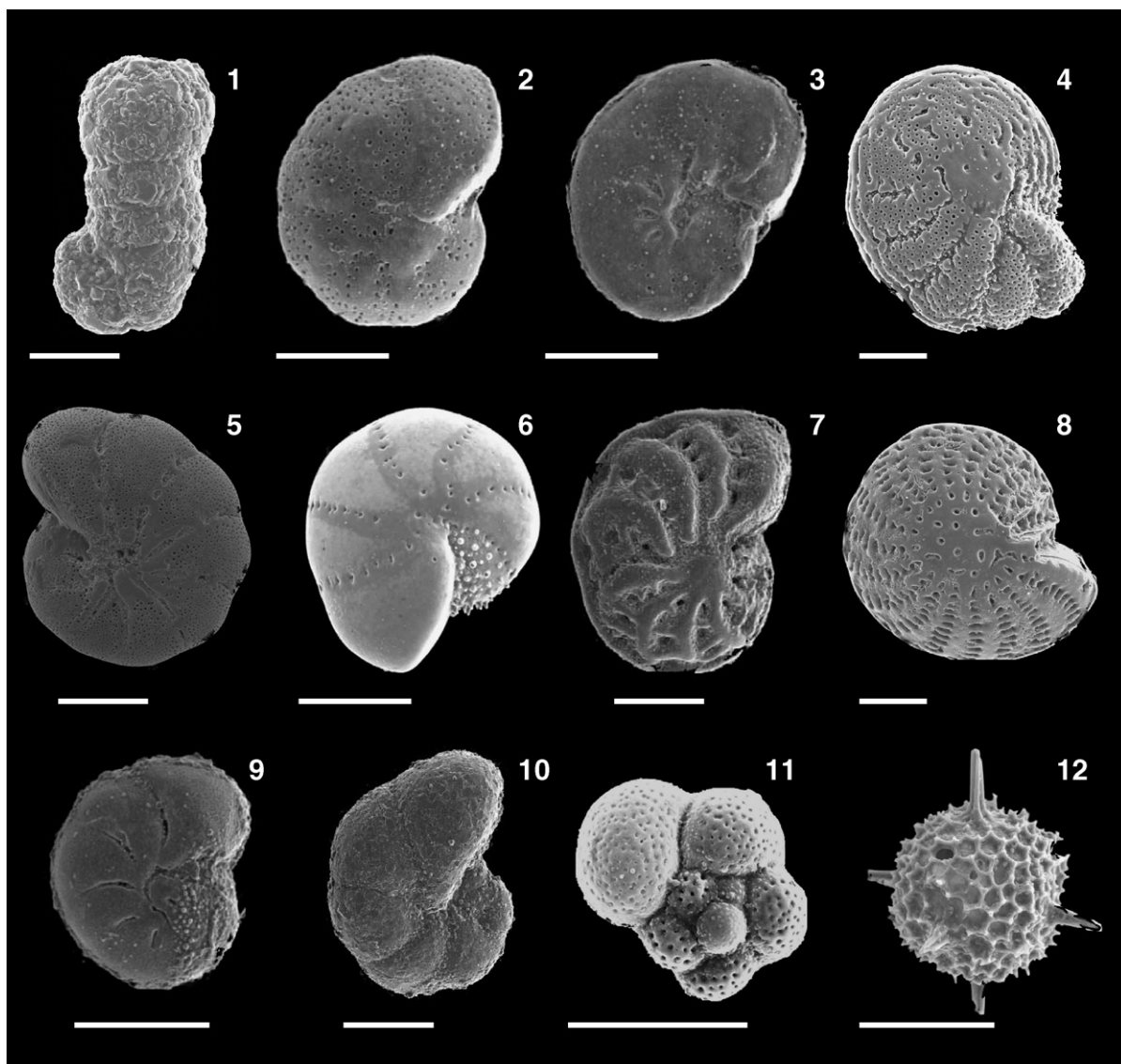


Plate II. All white lines are equal to 100 μm , scale reflects average size of specimens in this study. 1. *Ammobaculites exiguus* side view. 2. *Cibicides refulgens* dorsal view. 3. *Cibicides refulgens* ventral view. 4. *Elphidium hispidulum* side view. 5. *Elphidium excavatum clavatum* side view. 6. *Elphidium norvengi* side view. 7. *Elphidium advenum botaniense* side view. 8. *Elphidium craticulatum* side view. 9. *Elphidium* sp. side view. 10. *Haplophragmoides manilaensis* side view. 11. juvenile planktonic sp. dorsal view. 12. radiolarian sp.

(45–60%), *P. stellata* (25–50%) and *A. gibbosa* (5–15%). Zone SEIII was (22 cm to 10 cm) dominated by *P. stellata* (30–60%) and *E. craticulatum* (15–25%) and *Ammonia parkinsonia* (10–25%) and *A. gibbosa* (5–15%). Zone SEIV (10 cm to 0 cm) within the upper tsunami sediment was dominated by *A. parkinsonia* (35–50%) and *E. craticulatum* (20–30%). Fisher's alpha diversity index showed an increase in diversity within Zone SEIII between 16 cm and 13 cm. The total number of individuals per 5 cm^3 sample varied from 50 to 500 individuals with the lowest in the pre-tsunami sediment (SEI) and

highest within Zone SEIII between 22 cm and 20 cm. Test size was dominated by medium sized test (100–200 μm) with two exceptions where large tests dominated (27 cm to 25 cm and from 20 cm to 13 cm).

5.4. Kuala Teriang, Langkawi

Samples were taken from a 26 cm deep trench with pre-tsunami dark grey silt from 26 to 23 cm and coarse, medium and fine brown tsunami sand from 23 cm to 0 cm (Fig. 10). We distinguished three stratigraphic

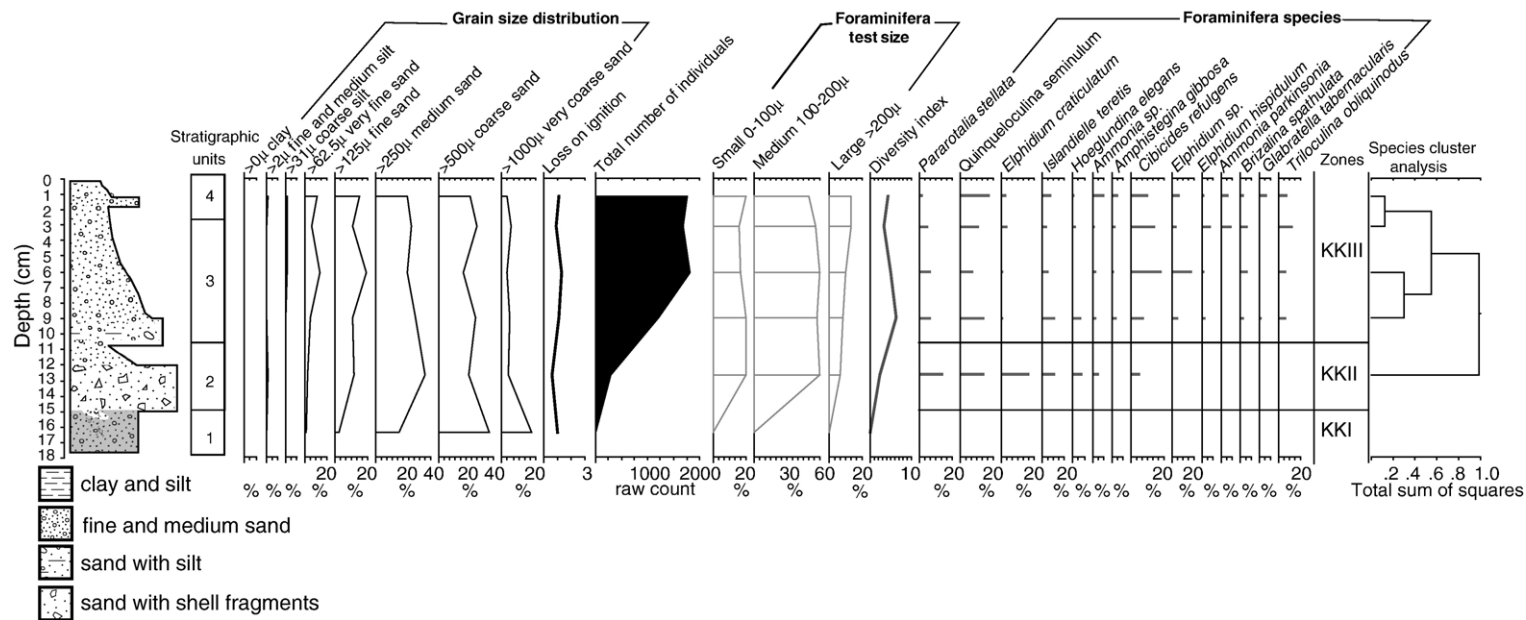


Fig. 7. Grain size distribution and foraminiferal analysis of Khuk Khak Beach, Khao Lak. Schematic stratigraphic column, grain size analysis, loss on ignition, total number of individuals per 5 cm³, foraminifera test size (small < 100 μm, medium 100–200 μm, large > 200 μm), foraminiferal species, Fisher's alpha diversity index and species cluster analysis are shown. All x-axes are in percentage except the total number of individuals per 5 cm³ and diversity increases from left to right.

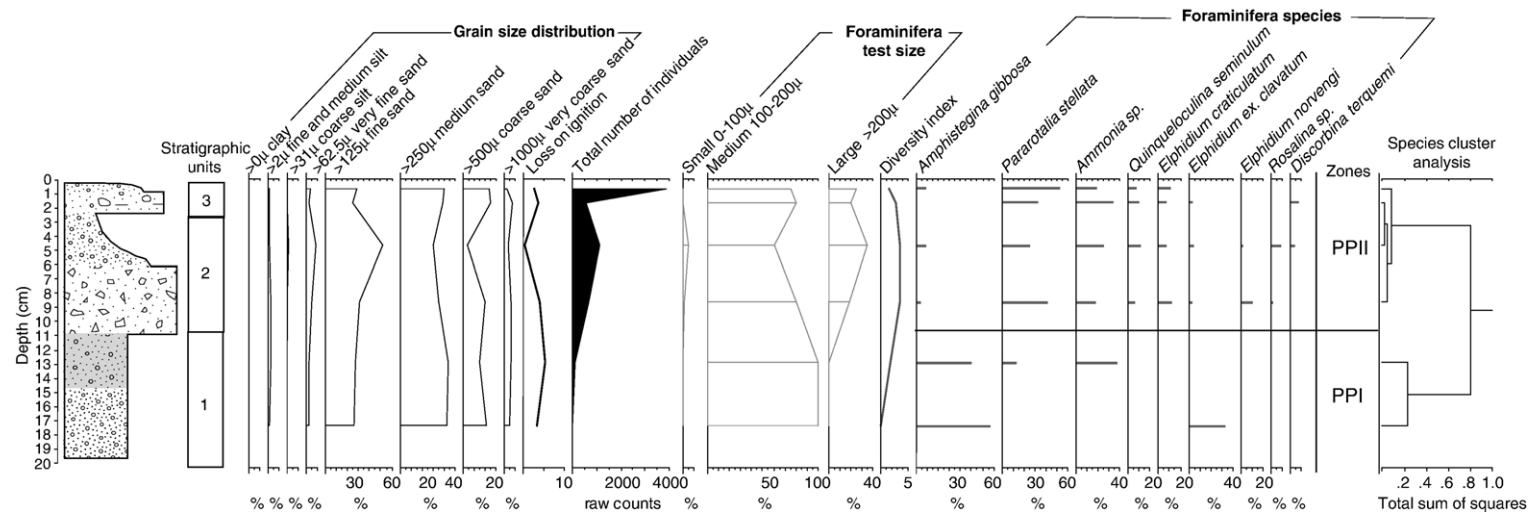


Fig. 8. Grain size distribution and foraminiferal analysis of Tonsai village, Phi Phi Don. Schematic stratigraphic column, grain size analysis, loss on ignition, total number of individuals per 5 cm³, foraminifera test size (small < 100 μ m, medium 100–200 μ m, large > 200 μ m), foraminiferal species, Fisher's alpha diversity index and species cluster analysis are shown. All x-axes are in percentage except the total number of individuals per 5 cm³ and diversity increases from left to right.

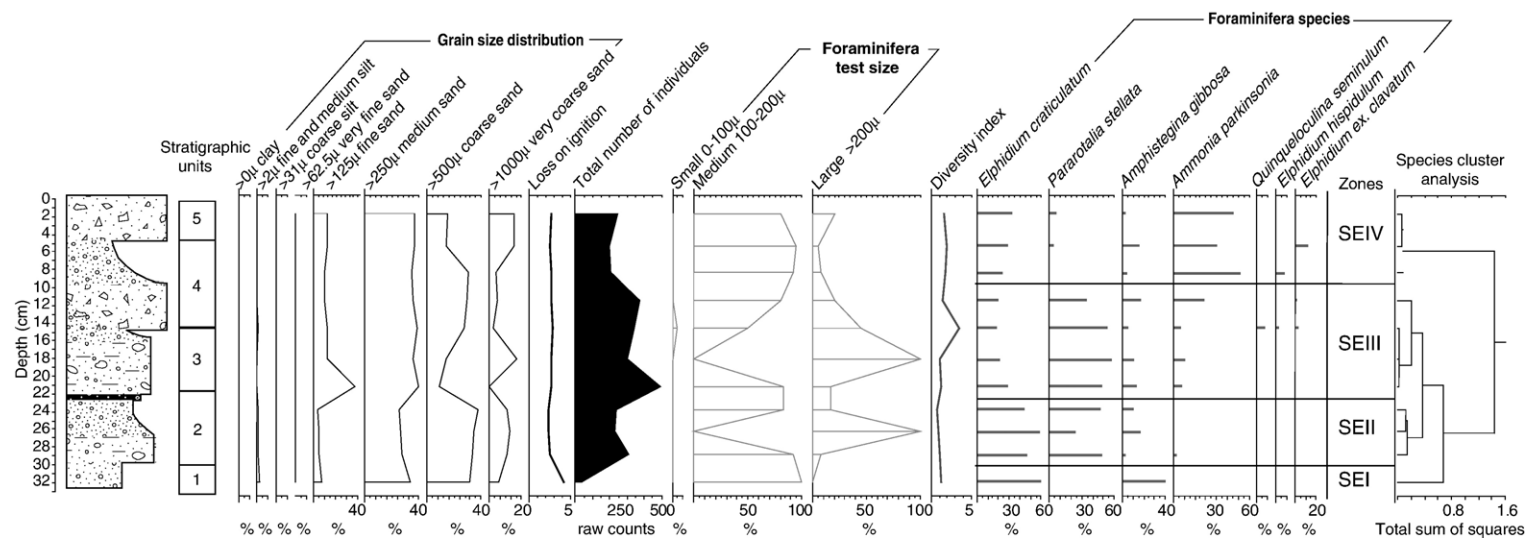


Fig. 9. Grain size distribution and foraminiferal analysis of Somewhere Else Resort, Ko Lanta Yai. Schematic stratigraphic column, grain size analysis, loss on ignition, total number of individuals per 5 cm³, foraminifera test size (small=<100 μm, medium=100–200 μm, large=>200 μm), foraminiferal species, Fisher's alpha diversity index and species cluster analysis are shown. All x-axes are in percentage except the total number of individuals per 5 cm³ and diversity increases from left to right.

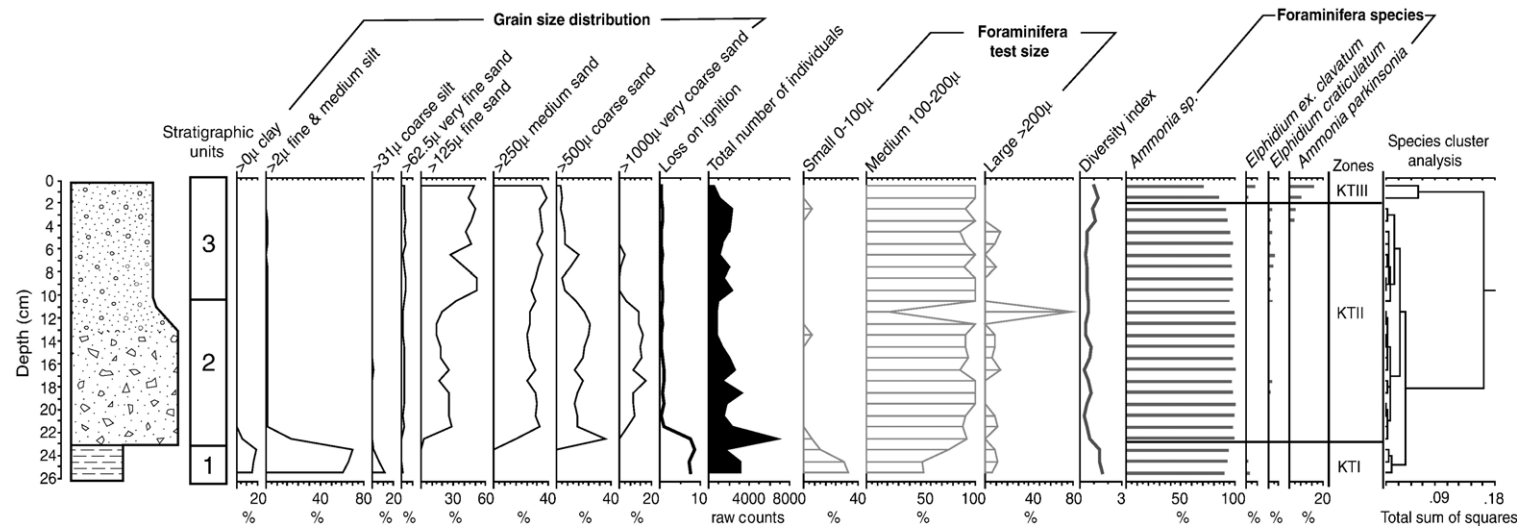


Fig. 10. Grain size distribution and foraminiferal analysis of Kuala Teriang, Pulau Langkawi. Schematic stratigraphic column, grain size analysis, loss on ignition, total number of individuals per 5 cm³, foraminifera test size (small = <100 μ m, medium = 100–200 μ m, large = >200 μ m), foraminiferal species, Fisher's alpha diversity index and species cluster analysis are shown. All x-axes are in percentage except the total number of individuals per 5 cm³ and diversity increases from left to right.

units containing one fining upward sequence. The contact between the pre-tsunami and tsunami sediment was sharp. Unit 2 contained shell fragments and fines upward into unit 3. Loss on ignition was between 7.3% and 8.7% from 26 cm to 22 cm in the pre-tsunami sediment and first tsunami sample. From 22 cm to 0 cm, loss on ignition ranged between 0.4% and 1.1%.

Three foraminiferal zones were identified within the 26 cm trench (Fig. 10). Zone KTI (26 cm to 23 cm) within the pre-tsunami sediment was dominated by *Ammonia* spp. (>90%) with a small percentage of *E. excavatum clavatum* (<10%). Zone KTII (23 cm to 4 cm) was dominated by *Ammonia* spp. (>92%) with a small percentage of *E. craticulatum* (<8%). Zone KKIII (4 cm to 0 cm) within the upper tsunami was dominated by *Ammonia* spp. (>70%) with small percentages of *A. parkinsonia* and *E. excavatum clavatum*. Fisher's alpha diversity index showed higher diversity in Zone KTI and KTII where values ranged from 0.9 to 1.6. The total number of individuals per 5 cm³ exceeded 1000 individuals with the exception of 1 cm to 0 cm. The highest number of total individuals (6840 individuals per 5 cm³) occurred at the interface between pre- and tsunami sediment between 23 cm and 22 cm. The foraminiferal test size was medium (90 to 100%) with the exception of the pre-tsunami sediment (26 cm to 23 cm), which contained 20 to 40% small-sized tests, and a layer of anomalously large tests (80%) within the tsunami sediment at 11 cm.

5.5. Sungai Burong, Penang

Samples were taken from a 20 cm deep trench with pre-tsunami light grey silt between 20 cm and 15 cm and dark brown medium and coarse tsunami sand from 15 cm to 0 cm (Fig. 11). We distinguished three stratigraphic units containing one coarsening upward sequence. The contact between pre-tsunami and tsunami sediment was sharp. Unit 2 coarsened and lightened upward into unit 3. Loss on ignition in the pre-tsunami sediment ranged between 6.2% and 9.4% while the overlying tsunami sediment was composed of between 0.4% and 2.7% with the exception of the sample at 5 cm to 4 cm, which contained 4.3%.

Three foraminiferal zones were identified within the 20 cm trench (Fig. 11). Zone SBI (20 cm to 14 cm) within pre-tsunami sediment was dominated by *Ammonia* spp. (20–60%), *Elphidium hispidula* (13–20%) and juvenile planktonic spp. (10–25%). Zone SBII (14 cm to 5 cm) within the tsunami sediment was dominated by *Ammonia* spp. (65–85%) with notable contributions from *Ammobaculites exiguus*, *Haplo-*

phragmoides wilberti, and *Q. seminulum*. Zone SBIII (5 cm to 0 cm) in the upper tsunami sediment was also dominated by *Ammonia* spp. (80–95%) with minor contributions of other taxa. Fisher's alpha diversity index showed that the diversity gradually decreased from 2.3 at 18 cm to 0.6 at 1 cm. Total number of individuals/5 cm³ sample varied from 50 to 1750 individuals. The highest concentrations occurred between the pre-tsunami sediment and tsunami sediment (18 cm to 6 cm) and the lowest concentration between 1 cm and 0 cm. The test size was small (c. 70%) in the pre-tsunami sediment while the overlying tsunami sediment contained (>85%) large sized tests.

6. Discussion

6.1. Run up and flow depth

In Thailand, at Khuk Khak Beach we measured between 1000 m and 2000 m of run up and flow depth of 8.7 m at 370 m inland (Table 1). Similarly, Matsutomi et al. (2005) measured 6–11 m of flow depth in Khao Lak and Thanawood et al., 2006 found flow depths of 8–12 m and run up of 1 km inland. On Phi Phi Don at Tonsai village, we measured a flow depth of 9.2 m at 464 m run up, higher than measurements made by Matsutomi et al. (2005) who found between 5–6 m of flow depth on Phi Phi Don. Near Somewhere Else Resort on Ko Lanta Yai, we measured a flow depth of 6.3 m at 52 m run up. In Malaysia, on Pulau Langkawi at Kuala Teriang, we measured run up to be 250 m and 1000 m at Sungai Burong, Pulau Penang. Yalciner et al. (2005) measured 70–100 m of run up along the southwest coast of Penang, although they also noted that run up was much more extensive up river channels. The flow depth at Kuala Teriang, Pulau Langkawi, was 4.3 m and 2.4 m at Sungai Burong, Pulau Penang. Similarly, Yalciner et al. (2005) found flow depth in western Langkawi to be 4.2 m and in southwestern Penang to be between 2.2–3.0 m. However, run up and flow depth depends on numerous variables such as wave height and speed, distance traveled and local coastal topography and bathymetry.

6.2. Stratigraphy and sedimentology

Khuk Khak Beach, Tonsai village and Somewhere Else Resort contained between two and three fining upward sequences separated by medium to coarse sand layers (Table 1). Pulsing of coarse sand and gravel between these sequences may be related to wave uprush, while fining up sequences could reflect

a pre-backwash stage involving decreased energy deposition, or sediment winnowing because of normally graded sand units (e.g., Dawson et al., 1996; Dawson and Shi, 2000). Similarly, Gelfenbaum and Jaffe (2003) inferred that normal grading with thicker and coarser bases reflected turbulent flow where grain size distribution decreased as the turbulence waned potentially preserving each wave arrival. However, due to the complexity of tsunami deposition, successive waves may result in the partial or complete erosion of the sediment deposited by a previous wave (e.g., Dawson and Shi, 2000). Furthermore, the patterns and processes of tsunami deposition are additionally convoluted (in addition to differences in bathymetry, coastal topography and tsunami wave approach) by episodes of backwash flow, following maximum landward inundation, which may cause backwash erosion and sediment re-deposition (e.g., Dawson and Shi, 2000; Gelfenbaum and Jaffe, 2003). Therefore, there does not

necessarily appear to be a one-to-one relationship between the number of waves and the number of fining upward sequences (e.g., Gelfenbaum and Jaffe, 2003). This is supported by the observations of the tsunami wave arrivals and the grain size distribution we gathered (Table 1). At Tonsai village and Somewhere Else Resort the number of waves matched the number of fining upward sequences. However, at the Khuk Khak Beach, Kuala Teriang and Sungai Burong there was no agreement between the number of waves and fining upward sequences.

At both Kuala Teriang and Sungai Burong massive sand units occurred within the tsunami sediments, separated by a fining upward and coarsening upward sequence, respectively (Table 1). Grain size at Kuala Teriang fined upwards (23 cm to 0 cm) and may indicate a decrease in wave energy common to sediment deposited during tsunami backwash flow, periods between tsunami waves, or, alternatively, the grain size distribution of a subsequent wave (e.g., Dawson et al., 1995, 1996;

Table 1
Summary of tsunami sediment characteristics

Sites (N–S)	Number of waves	Run-up	Water height	Trench location, elevation and thickness	Major tsunami-lain sediment characteristics	Major foraminiferal characteristics
Khuk Khak Beach, Khao Lak, Thailand	1	1000 m–2000 m	8.7 m above msl	65 m at ~2 m above msl, 15 cm thick	Four units with three fining upward sequences. A sharp erosive contact separates the pre- and tsunami sediment of medium and coarse sand	Three Zones: KKI, no foraminifera in pre-tsunami sediment. KKII inner-shelf species dominant (Ps and Qs). KKIII increase in shelf species (Cr and Bs)
Tonsai village, Phi Phi Don, Thailand	2	>450 m	9.2 m above msl	281 m at 3.6 m above msl, 11 cm thick	Three units with two fining upward sequences. A sharp undulating contact separates the pre- and tsunami sediment of medium and fine sand	Two Zones: PPI, pre-tsunami sediment with Ag, Am and Ee. PPII, has Ps and Am. All are inner-shelf species
Somewhere Else Resort, Ko Lanta Yai, Thailand	2–3	>52 m	6.3 m above msl	47 m at 3.2 m above msl, 30 cm thick	Five units with three fining upward sequences. A sharp contact separates the pre- and tsunami sediment of medium and coarse sand	Four Zones: SEI, SEII and SEIII composed of inner-shelf and shelf species (Ec, Ps). SEIV contains a change of source with Ap
Kuala Teriang, Pulau Langkawi, Malaysia	3	250 m	4.3 m above msl	7 m at 1.9 m above msl, 23 cm thick	Three units with one fining upward sequence, A sharp contact between the pre- and tsunami sediment of medium, fine and coarse sand	Three Zones: KTI, KTII and KTIII where Am is the dominant species. Ap present in KTIII
Sungai Burong, Pulau Penang, Malaysia	3	1500 m	2.4 m above msl	44 m at 2.9 m above msl, 14 cm thick	Three units with one coarsening upward sequence. A sharp contact separates the pre- and tsunami sediment of medium and coarse sand	Three Zones: SBI intertidal and inner-shelf species (Am, Es and Pl). SBII a mix of mangrove (Hw and Hm) and SBI while SBIII contains no SBI species (except Am)

Number of waves are derived from observations of interviewees. Foraminifera species acronyms are as follows, *Pararotalia stellata* (Ps), *Quinqueloculina seminulum* (Qs), *Cibicides refulgens* (Cr), *Brizalina spathulata* (Bs), *Amphistegenia gibbosa* (Ag), *Ammonia* sp. (Am), *Elphidium excavatum clavatum* (Ee), *Elphidium craticulatum* (Ec), *Ammonia parkinsonia* (Ap), *Elphidium* sp. (Es), juvenile planktonics (Pl), *Haplophragmoides manilaensis* (Hm) and *Haplophragmoides wilberti* (Hw). Only the more abundant foraminifera are included in the table.

McSaveney et al., 2000; Gelfenbaum and Jaffe, 2003; Goff et al., 2006). At Sungai Burong, grain size distribution throughout the tsunami sediment remained relatively consistent. However, there was a lack of fine sediment in the upper 7 cm, which may indicate two episodes of deposition. Firstly, a tsunami wave entraining medium and coarse sand eroded and mixed with the underlying silt and clay from the pre-tsunami sediment. Second, an overlying unit with no fine-grained sediment from the pre-tsunami sediment was deposited and may represent deposition by a subsequent wave.

Studies of historical tsunami deposits by McSaveney et al. (2000) of the July 17, 1998 Papua New Guinea Tsunami, Goff et al. (2006) of the 1975 Kalapana Tsunami and Dawson et al. (1996) of the June 2nd and 3rd 1994 Tsunami in Rajegwesi, Java, have shown that the difference between the pre-tsunami and tsunami sediment is often defined by two characteristics: 1. a sharp or erosional boundary between sedimentary units, generally accompanied by a change in color and often associated with a change in lithology; and 2. the overlying tsunami sediment is coarser than the pre-tsunami unit. Although one or both of these characteristics were common to all five sites, Kuala Teriang and Sungai Burong provided the most obvious examples where silt was overlain by medium-coarse sand. Loss on ignition was 3% to 4% higher in the pre-tsunami sediment at Kuala Teriang and Sungai Burong than the tsunami sediment. Tsunami sediments that showed little change in grain size or lithology from the underlying pre-tsunami sediment would be difficult to identify as paleo-tsunami deposits in the future. For example, Tonsai village and Somewhere Else Resort where grain size analysis could not differentiate between pre-tsunami and tsunami sediment, the addition of foraminiferal analysis proved useful in differentiating pre-tsunami from tsunami sediment.

6.3. Foraminiferal analysis

Foraminiferal assemblage analyses of Tonsai village and Somewhere Else Resort revealed assemblage segregation between the pre-tsunami and tsunami sediment. At Tonsai village, the pre-tsunami sediment (PPI) contained individuals of *A. gibbosa* and *E. excavatum clavatum*, which were not common in the overlying sediment. This was also mirrored in foraminiferal test size, with pre-tsunami sediment containing only medium tests and tsunami sediment contained ~25% large tests. Thus, the probable origin of the pre-tsunami sediment is shallow marine sand that aggraded between the rocky headlands. This was later exposed as sea level fell after the mid

Holocene highstand (Tjia, 1996; Scoffin and Le Tissier, 1998; Kamaludin, 2001; Horton et al., 2005). At Somewhere Else Resort, the pre-tsunami sediment (SEI) lacked the two dominant species of the tsunami sediment, *P. stellata* and *A. parkinsonia*, and contained higher numbers of *A. gibbosa* and *E. craticulatum* than the tsunami sediment. Similar to Tonsai village the origin of the pre-tsunami sediment at Somewhere Else Resort was probably a shallow marine environment reflecting a time of higher sea levels. Khuk Khak Beach, Kuala Teriang and Sungai Burong also show foraminiferal assemblage segregation but these are also supported by grain size analysis. At Khuk Khak Beach, Tonsai village and Somewhere Else Resort the Fisher's alpha diversity index increased into the tsunami sediment, whereas at Kuala Teriang and Sungai Burong the diversity decreased.

Foraminiferal assemblages within the tsunami sediment may also be capable of revealing information about sediment provenance or wave characteristics from species content (e.g., Clague and Bobrowsky, 1994; Guilbault et al., 1995, 1996; Reinhardt et al., 1996; Shennan et al., 1996; Dawson and Shi, 2000; Hayward et al., 2006). They indicated that the presence of foraminifera uncommon to the surrounding pre-tsunami environment could be evaluated and categorized by species niche to estimate provenance. At Kuala Teriang and Sungai Burong, the pre-tsunami (KTI and SBI) assemblages were composed of intertidal and inner-shelf species (i.e. *Ammonia* spp., *E. hispidula* and juvenile planktonic spp.; Frerichs, 1970; Murray, 1991; Hayward et al., 1997) typical of the present intertidal zone, but may indicate a slightly deeper quiescent marine environment, which was formed during the early Holocene transgression (Chaimanee et al., 1985; Tiyaunte and Threerungsikul, 1988; Tjia, 1996; Kamaludin, 2001; Horton et al., 2005). The tsunami sediment at Sungai Burong also contained a minor but important addition of mangrove species, such as *H. wilberti* and *Haplophragmoides manilaensis* (Murray, 1991; Hayward et al., 1999; Horton et al., 2003; Hayward et al., 2006) and a radiolarian species. The mangrove species and radiolarian species may reflect the chaotic nature of deposition where uprush and backwash waves combine creating turbulence, mixing the assemblages together. This also may account for the lack of stratigraphic characteristics within this deposit.

At Khuk Khak Beach, no foraminifera were present in the pre-tsunami terrestrial sediment. The tsunami sediment in Zone KKII was composed dominantly of inner-shelf species such as *P. stellata* and *Q. seminulum* (Frerichs, 1970; Murray, 1991), whereas Zone KKIII recorded an increase in shelf species (*C. refulgens* and *Brizalina*

spathulata; Frerichs, 1970; Murray, 1991; Loeblich and Tappan, 1994). Therefore, the sediment source of Zone KKIII may have been further seaward of the inner-shelf. At Tonsai village, the tsunami sediment showed only one zone, Zone PPII composed of inner-shelf species (*A. gibbosa*, *P. stellata* and *Ammonia* spp.; Frerichs, 1970; Murray, 1991; Hayward et al., 1999). At Somewhere Else Resort, Zones SEI, SEII, and SEIII were dominantly composed of inner-shelf and shelf species (*P. stellata* and *E. craticulatum*; Frerichs, 1970; Hayward et al., 1997) while in the upper zone, SEIV, a subtidal species was dominant (*A. parkinsonia*; Frerichs, 1970; Murray, 1991; Hayward et al., 1999). At Kuala Teriang, *Ammonia* spp. (Frerichs, 1970; Murray, 1991) is dominant throughout Zones KTII and KTIII. Zone KTIII contains the same subtidal species as Zone SEIV at Somewhere Else Resort.

Foraminiferal abundance within the tsunami sediment varied between ~50 and ~7000 individuals/5 cm³ sample. Dawson (1996) found that total abundance of foraminifera increased toward the top of tsunami sand units. At Khuk Khak Beach and Tonsai village the total number of individuals increased toward the top of the tsunami sand layer but the tsunami sediment was overlying pre-tsunami sediment with either no assemblage (Zone KKI) or very few foraminifera (Zone PPI). At Somewhere Else Resort and Sungai Burong, a maximum number of individuals were reached midway through the tsunami sediment.

Dawson (1996) also found that the foraminiferal assemblage within the tsunami sediment was composed of juvenile foraminifera. Within a 120 ka tsunami deposit on the large Island of Hawaii at Kohala, McMurtry et al. (2004) found that the foraminifera tests present within the tsunami unit were robust, large, and of similar dimension (0.5–1.85 mm). McMurtry et al. (2004) suggest that the absence of smaller, thin-tested species is due to turbulent depositional processes that destroy them. We found that the occurrence of large tested species was related to an increase in *P. stellata* (Zone PPII and SEIII), *C. refulgens* (Zone KKIII), *E. craticulatum* (Zone SEII) and *Ammonia* spp. (Zones SBII and SBIII) and was often correlated with coarser grain size distributions and stronger wave energy, with the exception of Tonsai village and Kuala Teriang.

7. Conclusions

The thickness of tsunami sediments ranged from 11 cm to 30 cm at our five study sites and was composed of between three and five stratigraphic units of fine, medium and coarse sand. The contact between the pre-tsunami sediment and tsunami sediment was

always sharp. Between one and three fining upward sequences were recorded at each site with the exception of Sungai Burong, which contained a subtle coarsening upward sequence. There was no one-to-one relationship between the number of waves observed and the number of fining upward sequences presumably because of the complex nature of tsunami deposition including partial or complete successive uprush and backwash wave erosion. Fining upward sequences were likely deposited during periods of waning wave flow whereas their underlying coarser sediment reflected periods of turbulent uprush or backwash deposition.

Only at Kuala Teriang and Sungai Burong was the pre-tsunami sediment finer than the overlying tsunami sediments grain size distribution. At locations such as Tonsai village and Somewhere Else Resort, where grain size distribution could not differentiate pre-tsunami from tsunami sediment, foraminiferal assemblages were capable of locating the change in sediment source associated with the tsunami sediment. This was accomplished in two ways: no foraminiferal assemblage present in the pre-tsunami sediment and foraminifera were present in the overlying tsunami sediment; or the foraminiferal assemblage in the pre-tsunami sediment differed from the assemblage in the tsunami sediment.

Foraminiferal assemblages within the tsunami sediment were also able to provide information about sediment provenance and wave characteristics. At Sungai Burong, species assemblages in the tsunami sediment revealed at least two separate episodes of deposition that contained uprush species from the inner-shelf, which differed to those of the pre-tsunami sediment, and additionally a small radiolarian component, as well as backwash species from the mangrove environment. Foraminiferal assemblage zones within the upper sediment units from Khuk Khak Beach, Somewhere Else Resort and Kuala Teriang successively recorded changes in sediment sources. We found that foraminiferal species diversity was higher in the tsunami sediment at Khuk Khak Beach, Tonsai village and Somewhere Else Resort but higher in the pre-tsunami sediment at Kuala Teriang and Sungai Burong.

At Khuk Khak Beach and Tonsai village the total number of individuals increased toward the top of the tsunami sand whereas at Somewhere Else Resort and Sungai Burong, the abundance was highest in the center of the tsunami sediment. We found that the occurrence of large-tested species was related to an increase in *P. stellata* (Zone PPII and SEIII), *C. refulgens* (Zone KKIII), *E. craticulatum* (Zone SEII) or *Ammonia* spp.

(Zones SBII and SBIII) and was often correlated with coarser grain size distributions, with the exception of Tonsai village and Kuala Teriang.

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