Journal of Coastal Research	23	5	1270–1276	West Palm Beach, Florida	September 2007

Erosion and Deposition by the 2004 Indian Ocean Tsunami in Phuket and Phang-nga Provinces, Thailand

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ABSTRACT

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The devastating December 26, 2004, tsunami produced abundant geologic effects along the Andaman coast of Thailand. The tsunami inundated the numerous sandy beaches and flowed over the adjacent aeolian dunes. On some of the dunes, the tsunami scoured circular holes 10–30 cm in diameter, and in its waning phases, it coated the holes with mud. The tsunami locally deposited a sand sheet that ranged from 0–30 cm in thickness, with an average thickness of approximately 10 cm. Sedimentary structures within the sand sheet include ripples from inflow and outflow, graded bedding, parallel lamination, and double-layered deposits. Erosion, locally severe, affected sand beaches and tidal inlets. We use these erosional and depositional features to infer the main processes that acted during inundation from the tsunami.

ADDITIONAL INDEX WORDS: *Inundation, bedform dune, ripple sand, Phuket, Phang-nga, Ranong.*

INTRODUCTION

The December 26, 2004, tsunami that affected the Indian Ocean basin was triggered by a magnitude 9.1–9.3 earthquake along the Indian-Australian subduction zone off the northern coast of Sumatra (LAY *et al.,* 2005). In spite of peninsular Thailand's location facing the northern part of this subduction zone, the lack of any written historical records, together with the lack of any significant local seismic activity, conspired to conceal this hazard from the scientific community. Hitting without any warning, the tsunami causing thousands of fatalities and huge economic losses in the popular tourist regions of Krabi, Phuket, and Phang-nga provinces (Figure 1). Eyewitness and video accounts demonstrate that the inundation lasted 10–20 minutes before draining. By studying the erosional and depositional features left behind by the tsunami, we hope to better understand the processes involved so that further generations can adequately prepare for future tsunamis.

DOI:10.2112/05-0561.1 received 21 July 2005; accepted in revision 12 April 2006.

Japan Society for the Promotion of Science (JSPS) is thanked for providing financial support. Part of the budget that made this investigation possible came from the Research Unit for Earthquake and Tectonic Geology, Thailand Research Fund (EATGRU, TRF; MRG4680091 and MRG4780046), the Ratchadapisek Somphot Foundation, Unisearch, Chulalongkorn University, and the Ministry of Natural Resources and Environment of Thailand.

GENERAL BEHAVIOR OF THE 2004 TSUNAMI IN THAILAND

Tsunamis are ocean waves generated by underwater disturbances of the seafloor or by surface impacts and are triggered by earthquakes and, less commonly, by landslides, volcanic eruptions, and meteorite impacts (CLAGUE, BOBROWSKY, and HUTCHINSON, 2000). These long waves (up to 200 km) travel over the ocean at great velocity. Within the open ocean, the wave height is low, but on reaching shallow water in the vicinity of the coastline, it becomes greatly amplified (BRYANT, 2001). During the process of wave deformation, the height of the wave increases significantly, its velocity decreases, and as the waves strike the coastline, they often cause widespread flooding across low-lying coastal areas (MURTY, 1977). Our field work suggests that decreasing tsunami velocity relies on oceanographic factors such as water depth, shoreface slope, and depth of the tsunami wave base.

The 2004 tsunami hit the Phuket western coast around 0938 local time. However, the records from the nearest tide gauge station on Phuket's eastern coast indicate a delay of nearly 40 minutes before it hit this part of the island. The present altitude of the high-water mark of ordinary spring tides (HWMOST) at the tide gauging station at Tapaw Noi

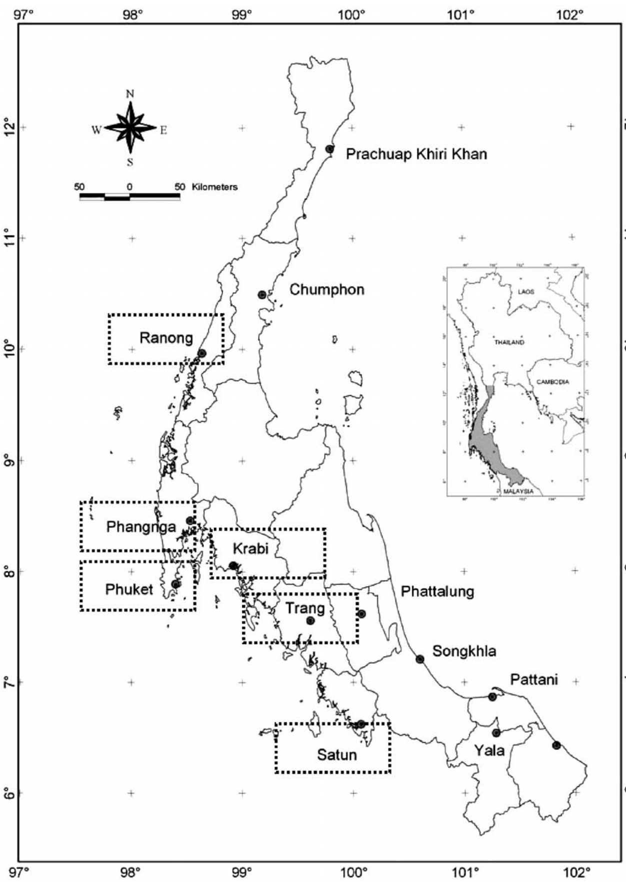

Figure 1. Six provinces of coastal areas along the Andaman Sea, western peninsular Thailand, including Ranong, Phang-nga, Phuket, Krabi, Trang, and Satun, that were affected by the tsunami on December 26, 2004.

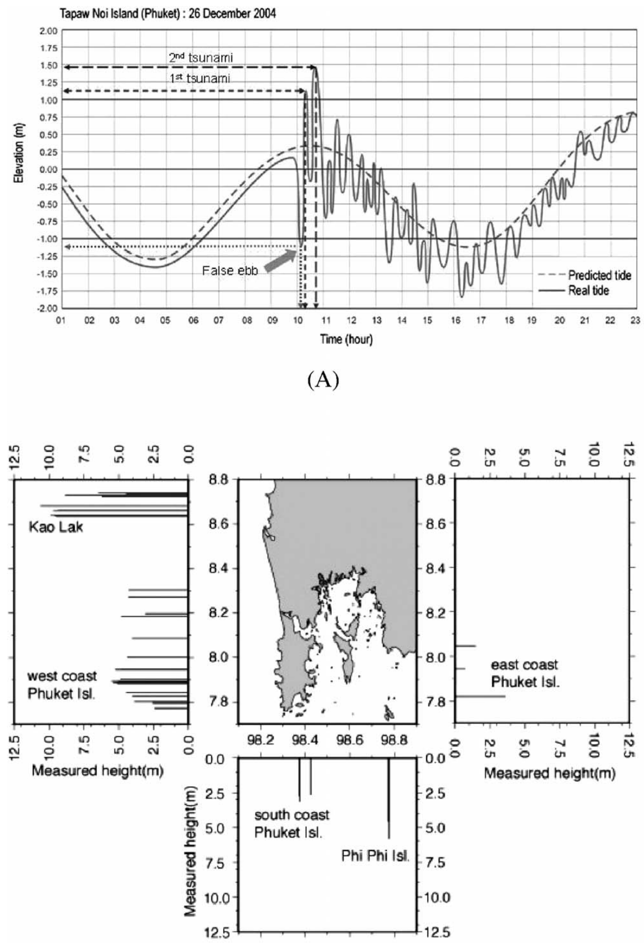

Figure 2. (A) Tapaw Noi Island (Phuket) tide gauge record showing the passage of tsunamis generated by the December 26, 2004, Sumatra earthquake. Three main waves arrived between 1020 and 1042; the second wave at 1029 was the most destructive (modified from Royal Thai Navy [2005]). (B) Tsunami heights from the Andaman coast of Thailand (Matsutomi *et al.,* 2005).

Island, eastern Phuket, is about 1.00 m from the present mean sea level (ROYAL THAI NAVY, 2005). According to this tide gauge (Figure 2A), three main waves struck eastern Phuket between 1020 and 1042. The waves were preceded by a drawdown or withdrawal that began at 1010 and lasted for 10 minutes. The second wave, the most destructive one, arrived at the gauging station at 1029 and was followed by a third tsunami at 1042. Eyewitnesses and video records confirmed that the second wave was strongest, with maximum inundation heights estimated of up to 6.00 m above ground surface and clearly recognized from water marks in the west of Phuket Island. However, tsunami flood level and maximum run-up were different from place to place (Figure 2B).

OBJECTIVES AND METHODS

Tsunamis leave unique physical evidence of their impact, including, indications of maximum run-up elevation, maximum inundation height aboveground, erosional landforms that affect pretsunami topography, and abundant sedimentary structures on and within a sediment layer. These features must be recorded quickly before they are disturbed or destroyed by natural erosion and deposition or by human reconstruction and development. The main objective of this study was to document the geologic evidence left by the 2004 tsunami and to analyze this data to determine what processes acted during this event. To do this, we focused on the following data.

- We mapped the extent of the tsunami inundation on existing 1 : 50,000 scale topographic maps.
- We recorded inundation heights (above ground level) according to indicators such as high-water marks or stranded debris.
- To understand the lateral variations in tsunami run-up and inundation heights, we analyzed pertinent geomorphologic features, such as the local shape of the coast, position of headlands, nearshore bathymetry, and onshore topography.

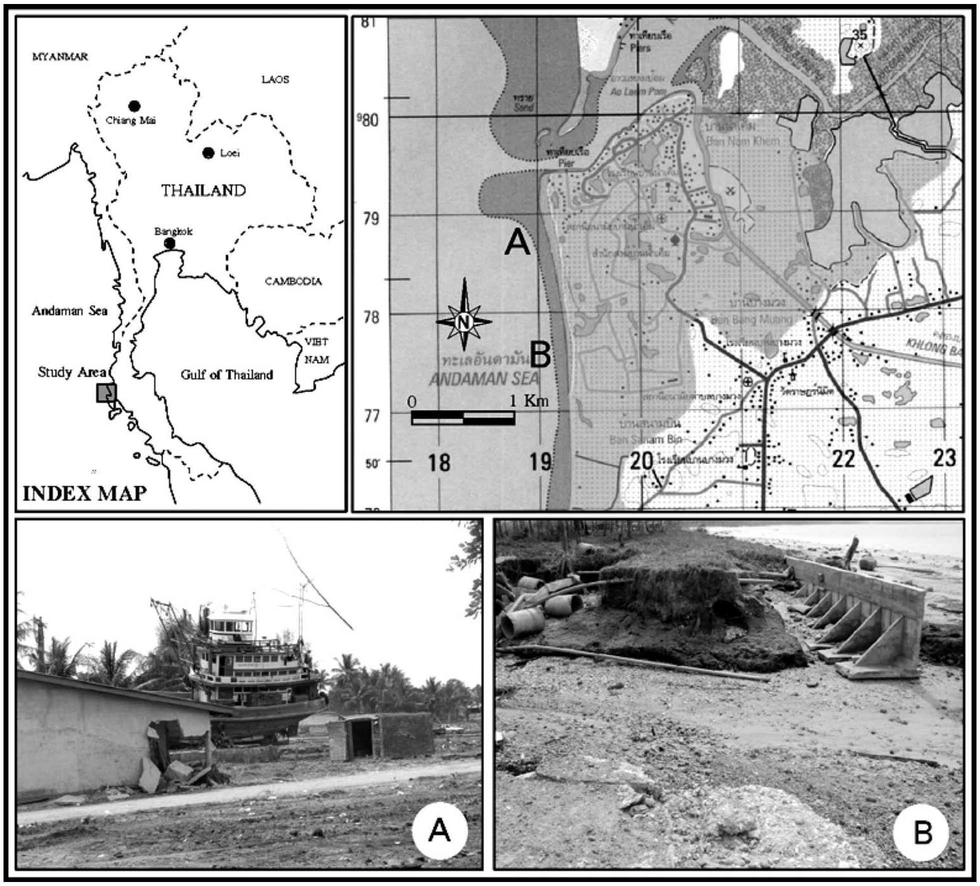

Figure 3. Effect of tsunami flood at Ban Nam Khem, Phang-nga province, showing erosion 100 m inland from the coastline and inundation up to 3 km landward (displayed as shaded overlay on topographic map); (A) the power of the tsunami flood washed a big ship ashore onto the land about 150 m from shoreline. (B) Erosion of the coastline.

- We photographed surficial sedimentary structures and indicators of flow direction on the fresh surfaces of tsunami deposits.
- We trenched the tsunami deposits to record the internal stratigraphy and sedimentary structures of the deposit.

RESULTS

During the period of tsunami standstill inland, a lot of effects were accompanied (*e.g.,* contamination of soil, surface water, and groundwater; shoreface sediments moved up onto the land; changes in morphology of inlet/outlet tidal channel; erosion of beach sediment). We measured maximum run-up, maximum flood level, distance of inundation, and the time the tsunami hit the land in detail and came up with a brief conclusion that the power of the tsunami differed from place to place, dependent mostly on the coastal morphology of the shoreline. One other additional factor is the direction of the tsunami in term of refraction and reflection.

Inundation and Tsunami Height

As a result of our investigation, we found dramatic variations in tsunami run-up extent and height, even in a single location. The tsunami locally ran up to 3 km from the coast and much farther inland via tidal channel. Ban Nam Khem, Phang-nga province, is one good example of this style of tsunami behavior (Figure 3). From video camera record and eyewitnesses, tsunami waves refracted around headlands in parallel with the curve of a sheltered bay or beach. We suggest that the sinuosity of the bay is one of the geomorphologic factors that controlled the behavior of the run-up of tsunami waves onto the land. The greater the curvature of the shoreline, the more the waves were focused on bays. However, tsunami height might also depend on nearshore bathymetry as much as it depends on curvature of the shoreline. Tsunami height where the hills and mountains block the narrow beach were higher than at other places—Khao Lak beach, Phang-nga province, for example (Figure 4).

Tsunami Deposits

Characteristics of sand sheets from ancient and recent tsunamis have been reported from many parts of the world (*e.g.,* Atwater, 1987, 1992; Atwater *et al.,* 1995; Dawson, Long, and Smith, 1988; Minoura and Nakaya, 1991; Nanayama

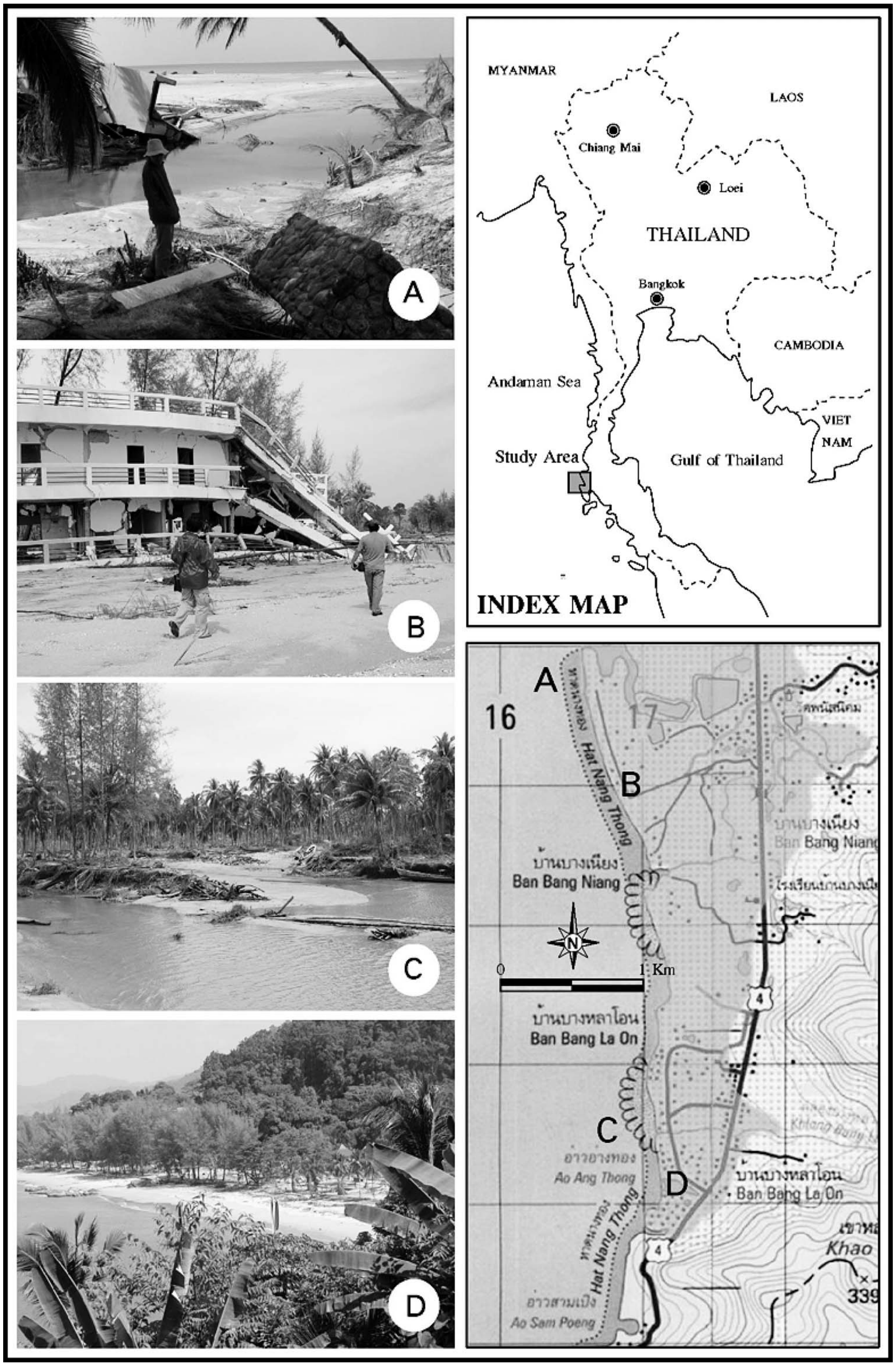

Figure 4. Inundation map (displayed as shaded area on topographic map) along Khao Lak beach; (A) the opening of new inlet/outlet, (B) the collapsed building near Ban Bang Niang, and (C) erosion along a channel bank. (D) The narrow beach morphology indicated that the vast damage occurred in the southern part of Khao Lak beach. **For color version of this figure, see page 1206.**

Figure 5. Tsunami sediments overlying salt marsh and backshore deposits from Bang Tao beach, Phuket province, showing upflow dunes overlain by return-flow ripple sands observed inland (A). Bedform dunes (as geologists stand on the top of each dune crest) indicate landward migration (from left to right) (A and B), whereas small ripple sands show seaward (from right to left) movement during the retreat of the tsunami (C). **For color version of this figure, see page 1207.**

et al., 2000). Particular sedimentologic evidence observed in the Andaman tsunami field includes bedform dunes and ripple sands. The tsunami deposit were preserved as bedform dunes and small ripple sands in seaward and landward current directions. Small seaward ripple sands were also recognized on top of these bedform dunes. The best locality to observe these patterns of tsunami deposits occurred at Bang Tao beach, north of Phuket Island (Figure 5). Detail observations of internal sedimentary structures and grain properties of tsunami sediments from this area indicated that tsunami sediments here were deposited by at least two upflows, which eroded the majority of beach sediments and moved them to deposit as double-layered sand sheets as far as 200 m inland. Similar double layers of landward tsunami sediments were observed from Ban Khuek Khak, Phang-nga province (Figure 6). They also indicate that tsunami upflow deposited sediment twice in this area. However, a very thin mud layer 2–3 mm in thickness coating the tsunami sand sediments was also recognized throughout, and it cracked a week after the tsunami (Figure 7). Signs of a depositional layer indicative of short-term stagnant seawater or slowly draining seawater to the shore is also likely.

Erosional Features on Pretsunami Surface

The evidence of vortices responsible for pretsunami surface sculpturing, especially instant circular holes that eroded into dunes, were found from Ban Nam Khem, Phang-nga province (Figure 8). Circular holes induced by tsunami here displayed as groove holes with small granules inside, and in its waning

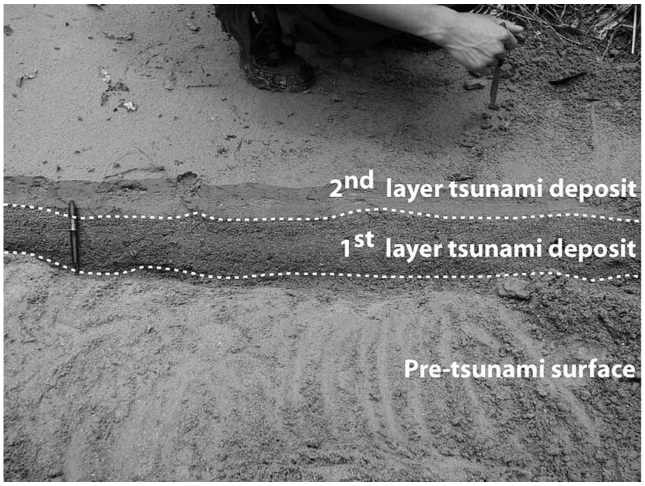

Figure 6. Double-layered upflow tsunami deposits on pretsunami graveled road surface from Grand Diamond Resort and Spa, Ban Khuek Khak, Phang-nga, showing high speed of tsunami wave (first layer), which was characterized by coarse-grained to very coarse grained sands overlain by low-speed tsunami sediment (second layer) of very fine to fine-grained sands.

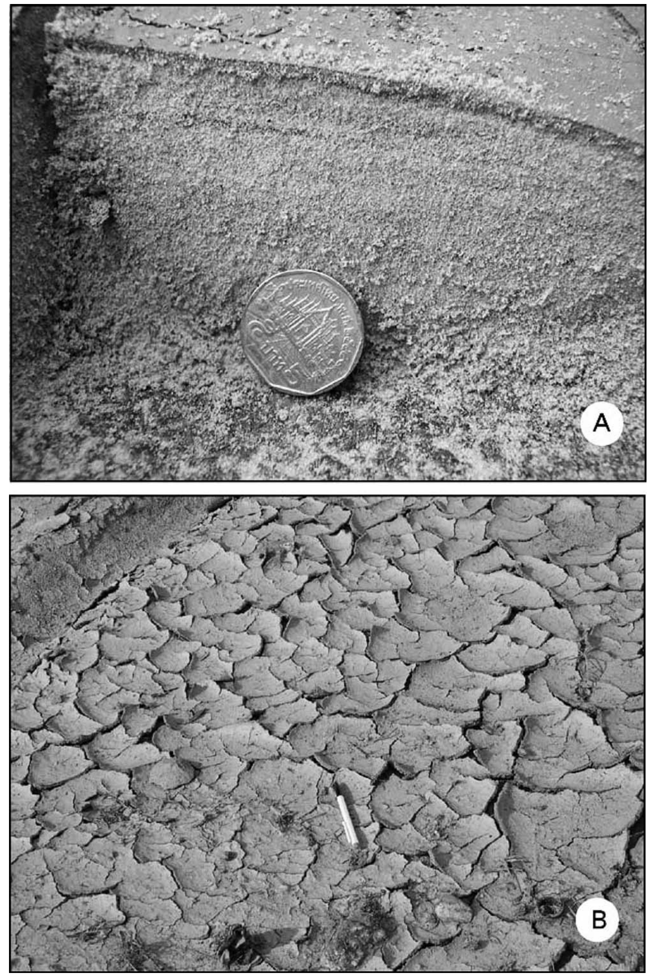

Figure 7. Tsunami sediments at Kamala beach, Phuket province, developed on graveled road surface with average thickness of 10 cm with an upward fining of fine- to medium-grained sand and coated by a thin muddy layer on top (A) and mud cracks photographed a week after the tsunami struck (B). **For color version of this figure, see page 1208.**

phases, the tsunami coated the holes with a thin 2–3 mm layer of mud. On some of the dunes, the tsunami scoured circular holes 10–30 cm in diameter that extended as far as 300 m inland. Such circular holes could be indicative of rapid turbulence and rotation of tsunami upflow. A thin layer of mud then coated the holes from slowly draining stagnant water. This unique circular hole pattern was found only on the surface of pretsunami dune sediments.

Tsunami waves eroded the modern foreshore sands (Figure 9). This erosional feature shows a pattern similar to those of common storm processes and was seen extensively in most foreshore deposits a few days after the tsunami. These kidney-shaped erosional surfaces are seen in pretsunami foreshore sediments, probably filled up by either reworked foreshore sands or offshore sediments induced by the tsunami waves.

DISCUSSION

The 2004 tsunami produced a vast area of erosion on the coastline and, in turn, deposition of tsunami sediments occurred inland. On the basis of sedimentologic clues from Phuket and Phang-nga provinces, the 2004 tsunami cut into the modern sand beaches and aeolian dunes and partly brought those sediments to deposit farther inland by upflows. However, it is still unknown whether any farther offshore sediment sources were brought up onto land by this 2004 tsunami.

It is no surprise that the catastrophic nature of the 2004 tsunami caused the sedimentation rate in 2004 to vastly exceed the average rate of earlier millennia. Erosion and deposition along the Andaman coast of Phuket and Phang-nga provinces have been interpreted with the use of sedimentologic clues in this paper. Characteristics of a sheet of tsunami deposits, in terms of its sedimentologic features, are a very important key to the better understanding of the nature of the 2004 tsunami upflow and return flow depositions. In the future, we can infer these sedimentologic features to help understand the paleotsunami deposits in this region.

ACKNOWLEDGMENTS

This article is dedicated to the people who lost their properties and their loved ones from the December 26, 2004, tsunami. We thank Chulalongkorn University for allowing us to start our fieldwork soon after the tsunami. Special thanks go to Assoc. Prof. Dr. Brady Rhodes, California State University, for his advice during fieldwork and for comment on this manuscript. Dr. Brian F. Atwater, U.S. Geological Survey is also thanked for his wonderful comments during the revision pro-

Figure 8. Erosional depressions (instant circular holes) indicating turbulence and rotation of tsunami upflow developed on pretsunami aeolian dune sediment from Ban Nam Khem, Phang-nga province. The vertical circular hole contains a thin layer of mud, 2–3 mm thick, on fine- to medium-grained tsunami sediments (5-cm thick) with a dimension varying from 2 to 15 cm wide with some granules at its bottom. **For color version of this figure, see page 1208.**

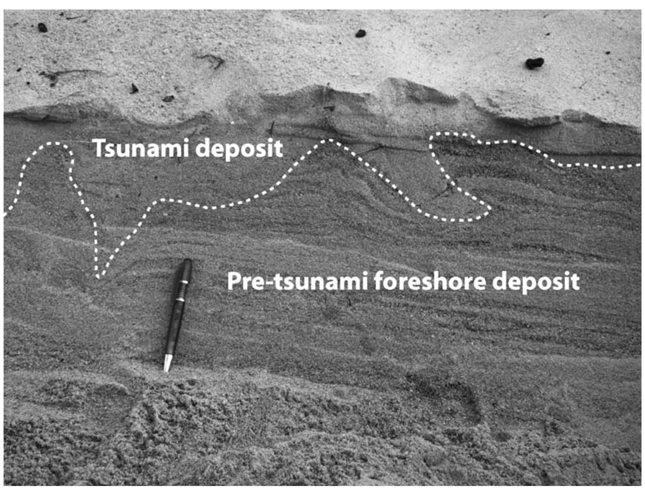

Figure 9. Pretsunami kidney-shaped, deformed foreshore deposits (convolute lamination) superimposed by December 26, 2004, tsunami sediments from Karon beach, Phuket.

cess of this manuscript. Thanks are also extended to P. Silapant, P. Saithong, C. Khaokeaw, K. Khaowiset, R. Ladachart, T. Supawich, and K. Mahothorn for joining in the fieldwork and donating their will, power, and properties to make this field run smoothly. Chulalongkorn geology students are thanked for their devoted time to gain experience with us in the field.

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