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Original Research

Impact of 2004 Tsunami on Seafloor Morphology and Offshore Sediments, Pakarang Cape, Thailand

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Abstract

This study documents seafloor morphology and sediments based on multibeam, side-scan sonar and boomer surveys, as well as sediment samples taken on the inner to mid shelf of the Andaman Sea after the 2004 Indian Ocean tsunami. Preservation of submarine relief in former underwater mining areas points to limited impact of the tsunami, while channel structures parallel to the observed tsunami backwash indicate a possible higher impact. Therefore, the tsunami impact seems to be focused on some areas. The impact was probably most effective during the backwash, when stiff mud deposits containing grass, wood fragments and shells were transported by high density backwash flows. Moreover, several boulders, which might have been deposited during the tsunami backwash flow, were found in the channels in front of Pakarang Cape.

Keywords: 2004 Indian Ocean tsunami, seafloor mapping, tsunami backwash, inner continental shelf, Andaman Sea

Introduction

Most of the research published about erosion and deposition of recent tsunamis focus on the onshore areas. The offshore effects, although theoretically significant [1] and more common in older geological records compared to onshore deposits [2], have only been documented in a few studies [3-5]. Surprisingly, offshore impacts of the well studied 2004 Indian Ocean tsunami are also almost unknown. Few authors reported offshore deposition of muddy sediments [6-8]. Offshore was postulated through analyses of microfossils in onshore tsunami deposits [9-12].

This article presents results of a four-week research cruise, undertaken in November and December 2007, focussing on the inner continental shelf next to Pakarang Cape (Phang Nga province, Thailand). During this cruise, hydroacoustic data (side-scan sonar, multibeam echo sounder, shallow water reflection seismic) as well as sediment samples were collected to obtain further insight about the impact of the 2004 tsunami on the shallow seafloor.

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The Research Area

The Andaman Sea continental shelf adjacent to the Malay Peninsula is narrow and slightly inclined. The area is dominated by two monsoonal winds: the northeast monsoon from mid October to March and the southwest monsoon from May to September. The southwest monsoon generates the highest waves along the coast. The tide is mixed semi-diurnal with a tidal range between 1.1 and 3.6 m, taking into account spring and neap tide [13]. The research area, about

1,000 km², is situated off Khao Lak (Phang Nga province), in water depths between 10 and 70 meters. For decades, tin mining activities took place in parts of the studied area [14], but ceased about 20 years ago. This study focuses on a part of the shelf next to Phang Nga province, especially around Cape Pakarang (Fig. 1). The research area was chosen because tsunami-induced change of the seafloor can be expected in this area, as the coastline was highly damaged during the tsunami [15, 16]. Furthermore, the absence of large river mouths in this area increases the visibility of tsunami-induced structures on the seafloor in hydroacoustic data. The run-up at Pakarang Cape reached a height of more than 15 m [17] due to shoaling processes and the interaction of the tsunami wave with the seabottom. During the tsunami event a layer of a few cm to about 0.5 m thickness, composed of sand and silty sand, was deposited over almost the whole inundation zone [7, 18-20]. According to eyewitnesses reports, the tsunami wave arrived from three different directions at Pakarang Cape [17]. The backwash pattern was documented by satellite images taken after the tsunami (indicated in Fig. 2). Obviously, the waves were forming a complex run-up and backwash pattern, heavily influenced by the nearshore bathymetry [7]. At the tip of Pakarang Cape, an area of about 12,500 m² was completely eroded during the tsunami [21]. Hundreds of reef rocks more than 1 m in diameter were transported landwards by the tsunami and deposited in shallow waters around Pakarang Cape [22, 23]. Tsunamigenic incisions, with a spacing between 50 and 200 m at the coastline of Khao Lak, were created during the run-up, and enlarged during the backwash of the tsunami [24]. Furthermore, it was observed that the channels are fan-shaped, and are wider at the coastline and narrower further inshore. This indicates a control of spacing and dimension of these return channels by the wave height of the tsunami. [24]. Westward of the research area, about 2 m sand from the seafloor have been eroded around a coral reef boulder in 30 m water depth, probably due to the tsunami [6].

Methods

Material for the study was collected during a research cruise on RV CHAKRATONG TONGYAI in November and December 2007. Acoustic properties of the seafloor sediment were measured using a side scan sonar (500 kHz) with digital data acquisition. A shallow water multibeam echo sounder with a working frequency of 180 kHz was welded to the portside of the research vessel to record bathymetric data. Shallow water reflection seismic data were obtained using a high resolution EG&G boomer system (about 500-15000 Hz). The covered area is shown in Fig. 1. For ground-truthing of the hydroacoustic data and for further sediment analysis, 77 grab samples were taken using a Van-Veen-type grab sampler. 40 short sediment cores of up to 125 cm in length were obtained using a gravity corer. However, for the present study only grab sample material was analyzed. To determine the grain-size parameters, sediment samples were dried and sieved. The grain-size statistics were calculated using Gradistat software [25].

Results

Bathymetry

The obtained bathymetric map of the area in front of Pakarang Cape is shown in Fig. 2. Down to 18 m, the slope is inclined with an angle of about 0.8°. Below this depth, the overall slope angle decreases (to about 0.1°), and the seafloor shows a “step like” morphology (Figs. 2 and 3). At the base of the southern slope of these steps, SW-NE striking channels, with a width of several hundred meters

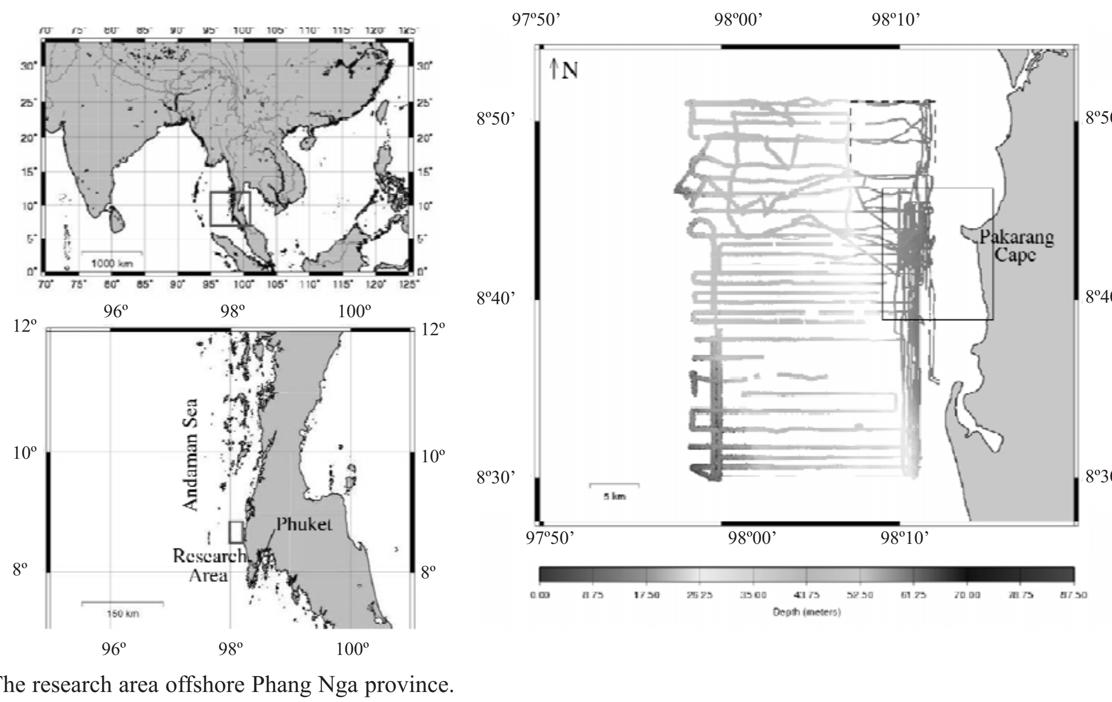

Fig. 1. The research area offshore Phang Nga province.

and a depth between 0.5 to 2 m are cut in the seafloor. Bathymetric cross sections (Fig. 3) reveal that the channels are asymmetrical, with the deepest incisions situated close to their southern slope. The dipping angles of the channels are low, reaching 1 to 1.2° at the southern slopes and about 0.2° at the northern slope. Towards the coastline, corresponding with the onset of the steeper slope angle in water depths between 14 and 18 m, the number of channels increases. The continuation of these channels both in deeper and shallower water is unknown, although first data from shallow water reflection seismics suggests a continuing propagation of the channels further offshore. The seismic data does not show any connection between the channels and subsurface structures. Remnants of these tin mining activities in this area (indicated in Fig. 1) are visible in the form of steep holes up to 7 m deep.

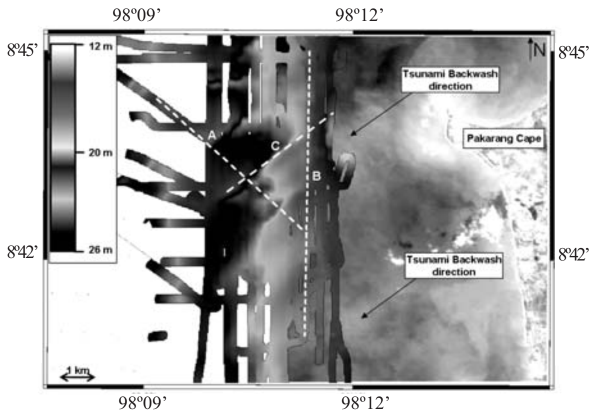

Fig. 2. Bathymetry around Pakarang Cape merged with a satellite image taken shortly after the 2004 tsunami. The dashed lines indicate the profiles shown in Fig. 3. (satellite image: Images acquired and processed by CRISP, National University of Singapore. IKONOS image © 2004. www.crisp.nus.edu.sg/tsunami/tsunami.html, modified.)

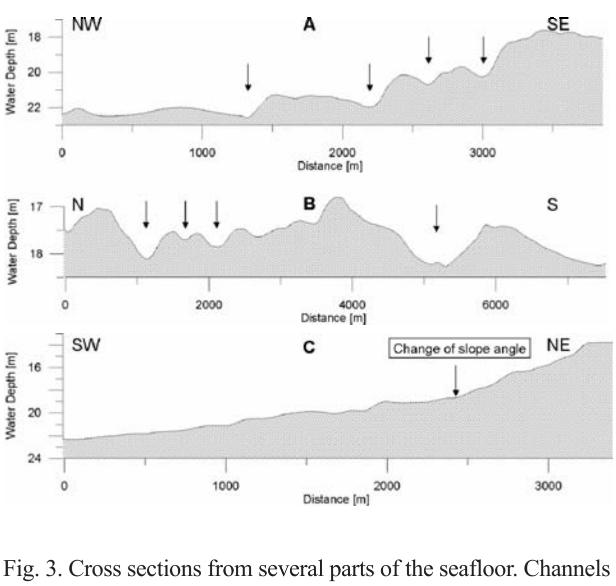

Fig. 3. Cross sections from several parts of the seafloor. Channels are marked by arrows. For the positions, refer to Fig. 2.

Seafloor Sediments

Large elongated sediment patches, appearing nearly white in the side-scan sonar images, with the same strike direction as the aforementioned channels, were documented in front of Pakarang Cape. There is a distinct transition between these areas and the surrounding seafloor (appearing darker in the side-scan sonar image shown in Fig. 4). Light-coloured areas in the side scan sonar data correspond to finer or non-consolidated sediment, while darker areas correspond to coarser or more consolidated sediment. The southern boundary of the elongated patches is very irregular and appears "flame-shaped" (Fig. 5). A combination of side-scan sonar and multibeam echo sounder data indicates that the large elongated areas of fine sediment are situated at the steeper southern slopes of the channels. In many cases, it was not possible to distinguish between the layers of fine to medium sand in the seismic data, taken simultaneously with the side scan sonar data. When it was possible to recognize these layers in the seismic data, their thickness appeared to be on the order of a few decimetres. Small patches of the same, fine sediment are visible closer to the coastline and are commonly situated in smaller channels and depressions (Fig. 6).

The results of the grain size analysis are incorporated in Fig. 4. The elongated sediment patches are composed of fine to medium sand, while the surrounding seafloor consists of coarse sand. Both types of sediment are poorly to moderately sorted. In one grab sample, taken from about 16 m water depth a stiff mud, covered by a 3 cm thick layer of coarse, well sorted sand was found. It contained terrestrial organic remnants: grass and pieces of wood, moreover, clasts of clay were found. Additionally, side-scan sonar data revealed the presence of numerous boulders with diameters around 1 m, as determined on the basis of their acoustic shadows in the side-scan sonar images. Most of these boulders appear between the aforementioned sediment patches close to the

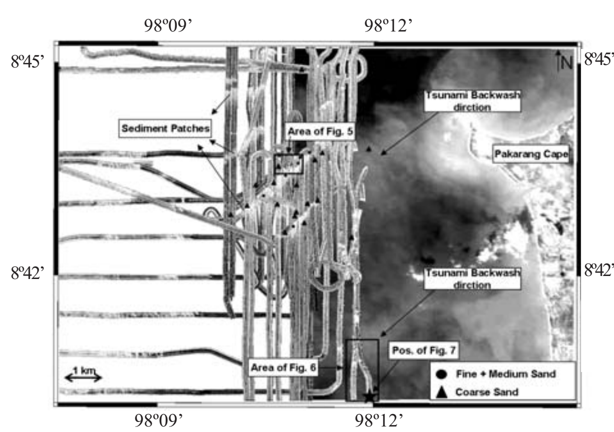

Fig. 4. Side Scan Sonar data merged with a satellite image taken shortly after the 2004 tsunami. Indicated are sediment types based on grain size analysis, as well as the locations of the following figures. (satellite image: Images acquired and processed by CRISP, National University of Singapore. IKONOS image © 2004. www.crisp.nus.edu.sg/tsunami/tsunami.html, modified.)

coastline (Fig. 7). However, some boulders, located at a distance of about 4 to 6 km from the tip of Pakarang Cape, are situated within a larger channel directly north of an elongated sediment patch (Fig. 5).

Discussion

Although the survey took place three years after the 2004 Indian Ocean tsunami, it is likely that several of the observed features may be ascribed to this impact. For instance, the channels and elongated sediment patches observed in front of Pakarang Cape have a striking resemblance to the backwash pattern observed in the satellite images taken after the tsunami event (Fig. 4). The erosion potential of a tsunami run-up and backwash is commonly mentioned in the literature [26, 27]. The impacts of the backwash depend on the amount of water flowing back into the sea, which itself depends on wave height [24], and on the formation of high density hyperpycnal flows [28]. High tsunami run-up heights at Pakarang Cape and the local presence of stiff mud with grass and wood found in offshore sediment samples suggest that both conditions enhancing the erosion potential of the backwash were met. Therefore, it is possible that the observed channels were formed mainly during the channelized tsunami backflow. Although due to a lack of pre-tsunami data it is not possible to exclude that the channels already existed prior to that event, several features suggest their origin or at least reshaping during the tsunami. A good correlation between the spacing of onshore incisions, interpreted to be created during run-up and backwash, and tsunami wave height is reported [24]. River mouths in the Nam Khem plain (north from Pakarang Cape) changed into wedge-shaped channels [29] with a width of 50-200 m, mainly due to the effect of a concentrated tsunami backwash. As the onshore return channels of the tsunami are wedge-shaped, and widening towards the coastline, it could be assumed that a connection between the onshore incisions and the wider channels, observed in shallow waters, exists. The rapid transition of these channels into the deeper, and even wider, channels in water depths of about 17 to 18 m might be caused by a change of the hydraulic behaviour of the backwash due to the changing slope angle of the seafloor (Figs. 2 and 3). The channels in deeper waters are asymmetrical in cross section. Related to this observation, it is interesting to note that regularly spaced, very shallow swales with asymmetrical profiles and filled by very fine-grained sandstones, and interpreted to be created during a paleotsunami event, have been reported [30].

Local erosion (adjacent to a large reef boulder where the formation of scour structures was possible) of up to 2 m

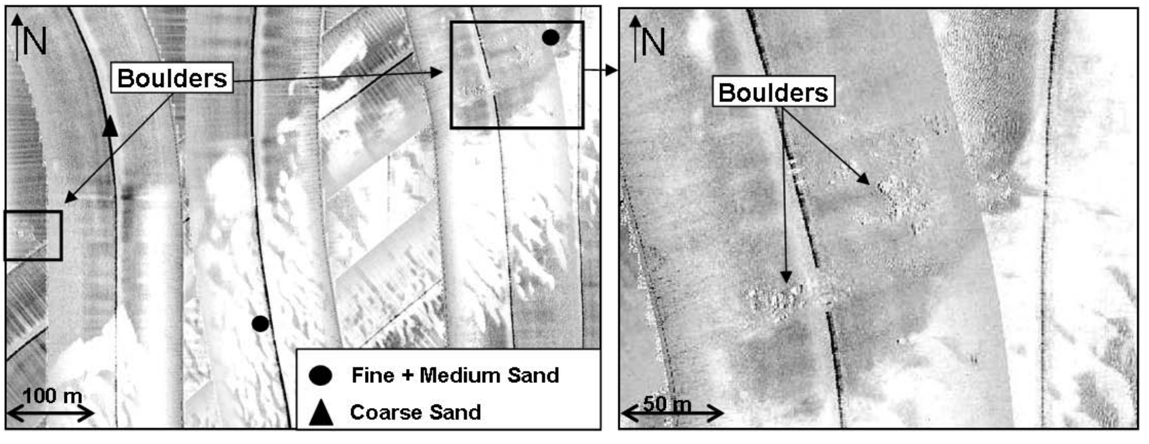

Fig. 5. Detailed view of one elongated sediment patch in front of Pakarang Cape. To the north of the patches, boulders are visible. For the location of the figure, refer to Fig. 4.

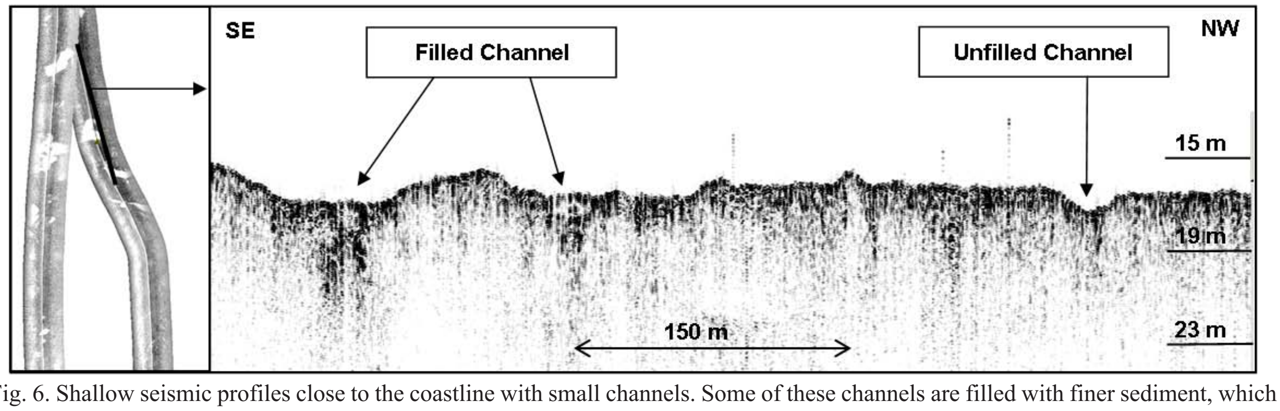

Fig. 6. Shallow seismic profiles close to the coastline with small channels. Some of these channels are filled with finer sediment, which appears white in the side scan sonar data. For the location of the figure, refer to Fig. 4.

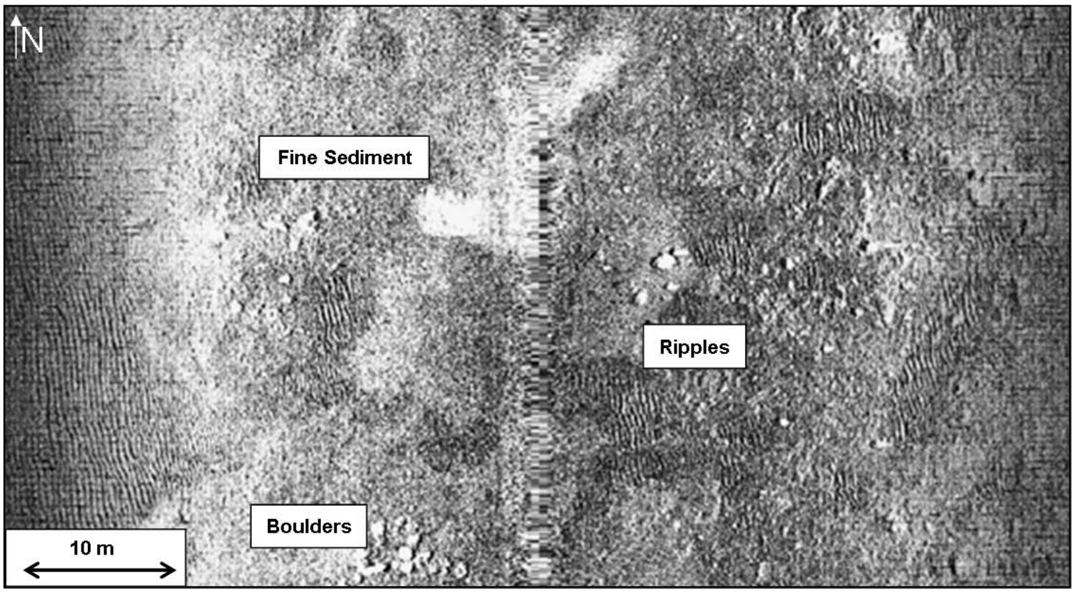

Fig. 7. Detailed view of side scan sonar data from a profile recorded close to the coastline. Different sediment types, including boulders, fine sediment and rippled sand, are deposited within a distance of a few meters. The location of this figure is indicated in Fig. 4.

during the tsunami event in a water depth of 30 m was reported [6]. Our data suggest erosion of a lower but comparable magnitude in the channels, and less erosion of the surrounding seafloor, as indicated by well preserved tin mining holes. This observation confirms previous suggestions [28] that tsunami effects are largely related to confined channelized flows during backwash and, possibly, run-up. The elongated areas and the small patches of fine and medium sand found in the channels and closer to the coastline could have been deposited during the backwash of the tsunami. If these sediments were deposited before the tsunami, one could expect that the tin mining holes would have been filled with the finer material during the past decades. However, the "flame-like" shape (indicating sediment transport) of the fine to medium sand sediment patches, as well as the presence of these sediments on the steeper southern slopes of the channels, may suggest their reworking during the post-tsunami period. In particular, their asymmetrical distribution in the channels may be a result of monsoon-related circulation and preservation of the finer sediments in relatively sheltered locations [8].

The existence of stiff muddy sediments containing pieces of grass and wood, which should be floating unless transported in a high turbidity and high density hyperpycnal flow, is strong supporting evidence of tsunami backwash and its potential erosion power. On the other hand, these deposits being covered by distinctly different coarse sand, typical for this part of the continental shelf, are already preserved in the geological record. This finding is promising for the search for paleotsunami evidence in this setting.

Interesting is the presence of boulders within the larger return channels in front of Pakarang Cape. The backwash velocity was modelled to be around 3.0 m/s at Cape Pakarang [22], slightly higher than the calculated critical velocity to move boulders. While some authors do not believe that the backwash, due to its short duration, transported boulders from the tidal flat back to the deeper waters, [22], it is very likely that boulders could easily be transported downhill from their original position on the coral reef slope during the tsunami backwash.

Conclusions

One of the first studies of offshore impacts of the 2004 tsunami indicates:

- Existence of a system of channels slightly oblique to the coastline, which are partly filled with finer sediments and could have been created during the backwash of the 2004 Indian Ocean tsunami.
- Variability in the channel system, which is changing with water depth and slope angle; probably as a result of changing hydrodynamic properties of the backwash (hyperpycnal flow).
- Validity of the assumptions on a channelized backwash, and maybe even run-up of the tsunami.
- Characteristic sediment deposition during the backwash, suggesting deposition from highly turbulent, high density flow.
- The backwash had enough power to transport boulders from the coral reef slope to deeper waters.

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