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Shallow water sediment structures in a tsunami-affected area (Pakarang Cape, Thailand)

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Abstract

The influence of tsunami on the seafloor is poorly understood. Detailed hydroacoustic surveys and sediment sampling campaigns were carried out in 2007 and 2008 offshore Pakarang Cape (Thailand) to catalogue the geomarine effects of the 2004 Indian Ocean tsunami. A major problem in determining tsunami influence in offshore deposits is the lack of pre-tsunami mappings. Starting in 15 m water depth, a system of sand ridges composed of coarse sand exists offshore Pakarang Cape. Elongated sediment transport structures on the NW-flanks of the sand ridges, slowly fading during the annual cycle, indicate the presence of a current oblique to the coastline. This current might coincide with the 2004 Indian Ocean Tsunami. A several cm-thick event layer found at the base of a sand ridge is composed of silty sediment, which could be related to the tsunami backwash or strong floods during the monsoon. These event deposits are covered by coarse sand. They might enter the geological record.

1 Introduction

Tsunamis are among the largest catastrophic events in the world. They are recorded since historical times and numerous investigations have been done about their origin, wave distribution and energy release along coastlines. On December 26th, 2004 an M 9.3 submarine earthquake was generated off the northwest coast of the Indonesian island Sumatra due to a complex tectonic activity between the Indo-Australian plate and the Sunda-Plate. This generated a giant tsunami which had an impact over many SE Asian coastlines, reaching to the East-coast of Africa (Lay et al. 2005).

Compared to the influence of the 2004 Indian Ocean Tsunami to onshore areas, the impact to the offshore environment is not well understood. Only few studies document tsunami effects offshore (e.g. Van den Bergh et al. (2003), Noda et al. (2007), Abrantes et al. (2008), Feldens et al. (2009), Paris et al. (2009), but influence and physical properties of the sediment-loaded tsunami backwash are largely unknown. Dawson & Stewart (2007) propose that offshore tsunami deposits are more common in the geological record than onshore deposits. A secure identification of offshore tsunami deposits would therefore be of great value for the recognition of paleotsunamis. A major, but common problem is the missing data about pre-tsunami conditions when working on recent tsunamigenic structures on continental shelf areas. It has to be carefully considered, if observed structures have existed before a tsunami hit the area, were created during the tsunami event or were altered by the tsunami impact. We present observations and first results of selected sedimentological and morphological features, recorded during cruises in the framework of the TUNWAT project (Tsunami deposits in near-shore- and coastal waters of Thailand; funded by the Human Research Foundation (DFG), Grant: SCHW/11-1) offshore the tsunami impacted coastline of Khao Lak, Phang Nga Province, Thailand.

2 Investigation area

The continental shelf of the Andaman Sea adjacent to the Malay Peninsula is narrow and slightly inclined; the 50 m isobaths is reached approximately 7 km offshore Phuket and about 30 km offshore Phang Nga Province located towards north. The coastal area is dominated by rocky cliffs altering with sandy lowlands and pocket beaches. From December to February the NE-monsoon dominates while the SW-monsoon is active from May to September (Khokiattiwong et al. 1991). The influence of storms and typhoons on this part of Thailand's coastline is low (Kumar et al. 2008, Jankaew et al. 2008). The tide is mixed semidiurnal, ranging between 1.1 m and 3.6 m (Thampanya et al. 2006).

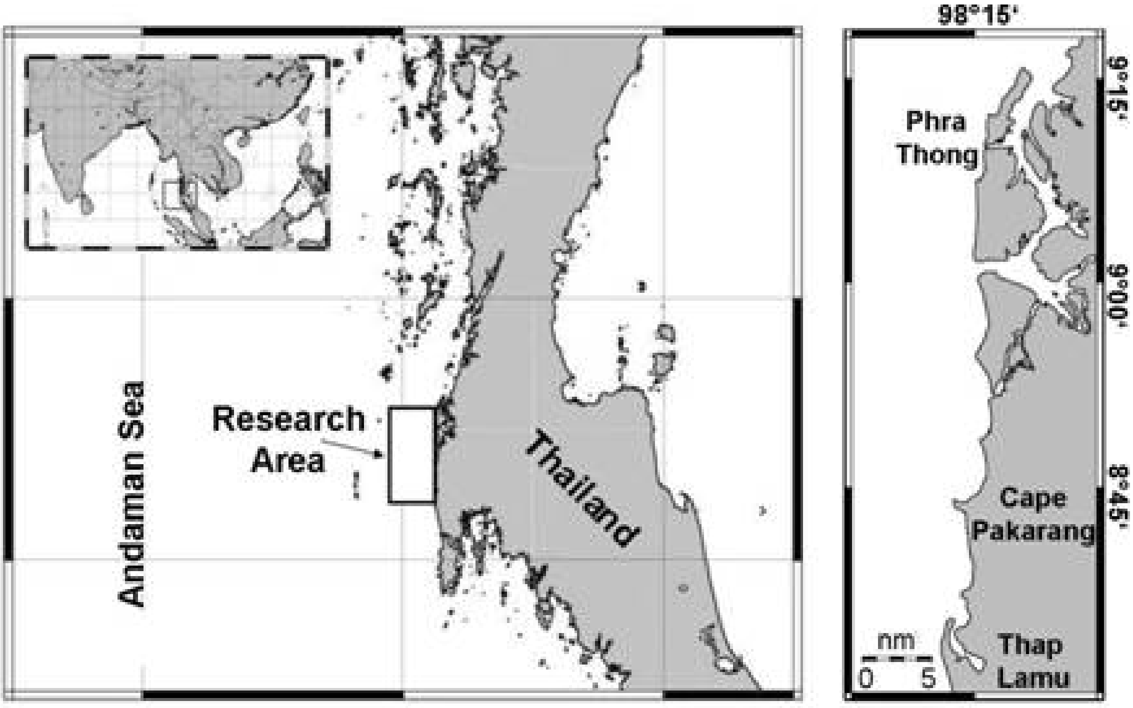

Figure 1: The research area is located in front of Khao Lak, Phang Nga province, Thailand.

The research area, between Thap Lamu and Phra Thong Island comprises of approximately 1.000 km^2 (figure 1). It was selected as it was hit severely by the 2004-Indian-Ocean-Tsunami (Bell et al. 2005, Tsuji et al. 2006). The wave run-up heights reached more than 15 m at Pakarang Cape (Siripong 2006) and up to 20 m at Phra Thong Island (Jankaew et al. 2008). At Pakarang Cape an area of about 12.500 m^2 was eroded by the tsunami (Synolakis & Kong 2006) and hundreds of reef rocks could be observed on the intertidal area after the event (Goto et al. 2007). For the investigation area the fluvial discharge is small, which increases the preservation potential of tsunamigenic features on the seafloor.

3 Methods

Two cruises have been carried out; a first one in Nov./Dec. 2007 with RV CHAKRATONG TONGYAI and a second with RV BOONLERT PASOOK in Nov./Dec. 2008. Both ships are operated by the Phuket Marine Biological Center (PMBC). Different side scan sonar systems were applied; a Klein 595 with digital data acquisition in 2007 and a Benthos 1624 digital side scan sonar system in 2008. Side scan sonar systems measure acoustical properties of the seafloor, which mainly depend on grain size distribution, seafloor roughness and the angle of the seafloor slope (Lurton 2002). Features protruding from the seafloor, e.g. boulders, but as well large ripples are easily recognized in side scan sonar images due to the acoustic shadow formed behind them. In this study, fine grained deposits appear in lighter colours, while coarse grained material is represented by darker colours. For ground-truthing of the side-scan sonar data grab samples were taken on selected positions.

A shallow water multibeam echosounder (ELAC SeaBeam 1185) was used to acquire bathymetric data. Multibeam echo sounders provide many simultaneous depth measurements over a narrow section of the seafloor. The SeaBeam 1185 system is working with a frequency of 180 kHz, which is suitable for a high resolution mapping in shallow waters. The acoustic beam of the system has a fan width of 153°, giving a theoretical swath width of 8.3 times the water depths. Calibration for tidal fluctuations was done by using the software WX-Tide32 (www.wxtide32.com), as no direct water level measurements are available in or close to the research area.

Shallow water high resolution reflections seismics (C-Boom System), in combination with the recovery of short gravity cores, was used to obtain information about the uppermost layers of the seafloor. X-radiography images of thin slabs taken from the core surface were prepared to detect sedimentary structures that cannot be seen otherwise (Jackson et al. 1996). The database of the cruises carried out in 2007 and 2008 include about 1500 nautical miles (nm) of hydroacoustic profiles, 112 Surface sediment samples and 42 short sediment cores.

4 Results

Side scan sonar images offshore Khao Lak show several different sedimentary structures in depths from 7 to 30 m (figure 2). In water depths between 7 and 15 m, extended patches of fine grained sediments are deposited. Connected to these patches is a small scale channel system starting at 10 m water depth. Here we focus on structures appearing at 15 m water-depth. Elongated SW-NE striking morphological ridges are visible in the hydroacoustic data (Figure 2). These structures are common along the whole coastline between Thap Lamu and Pakarang Cape, and up to Phra Thong Island towards north. The continuation of the ridges into deeper waters is yet unknown. The ridges, with a steep NW- and a gently dipping SE flank reach heights of about 2 m, while their length exceeds several kilometres. The distance between two ridge crests varies from several hundred meters to several kilometres. In front of the steep north-eastern side of these ridges, small channels with incision depths of approximately 1 m are sometimes cut into the seafloor. According to seismic data, the ridges are not connected to subsurface structures, but are clearly separated from the sedimentological structures below by an unconformity (figure 5).

For one ridge, a side scan sonar mosaic was draped over the bathymetry (figure 3) to correlate sedimentology and morphology. Grab samples taken around the ridge (figure 3) reveal the presence of different sediment properties in a small area: Generally, the south-western, landward flank of the ridge and the surface of the seafloor surrounding the ridge are composed of coarse sand. Bright elongated sediment structures are deposited on the seaward flank of the ridge and are composed of well sorted fine to medium sand. The patches are separated from each other by thin bands of coarser sediment. From their appearance in the side scan sonar image, the structures resemble large-scale flaser beddings. However, as the genesis of the observed features is different to flaser beddings, which are formed due to tidal activities, the term will not be used.

The sediment patches are commonly observed on the seaward, northern flank of sand ridges along the coastline. Rarely, they are found on the flat seafloor. Boulders are sometimes exposed in close vicinity (figure 3, figure 4). At the base of the ridge flank shown in figure 3, grab samples contain muddy material just a few centimetres below the seafloor.

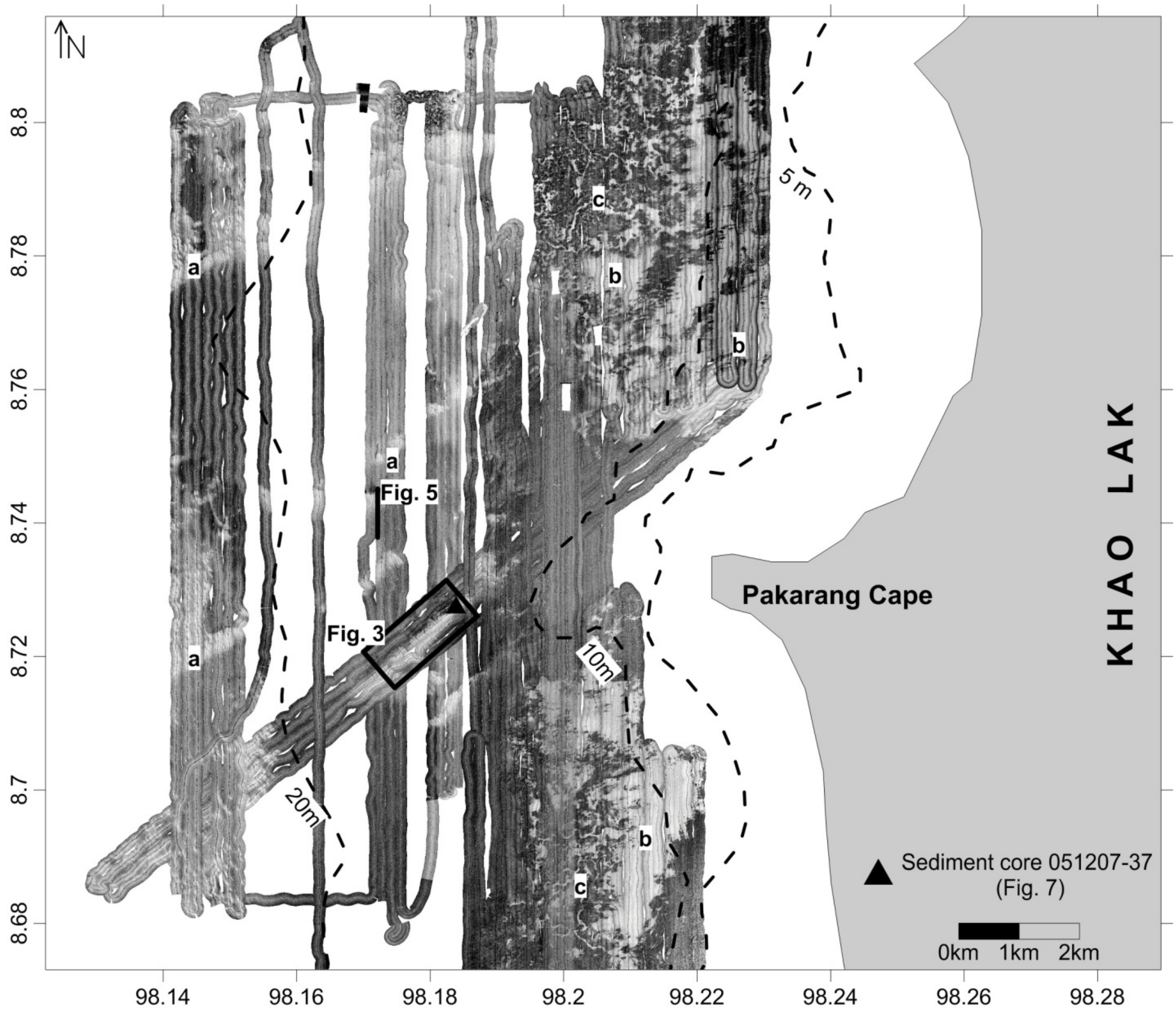

Figure 2: Side scan sonar data around Pakarang Cape. Sampling stations and the positions of fig. 3 and fig. 4 are indicated. Sediment core 051207-37 is shown in fig. 7. This article is focusing on SW-NE striking sediment structures visible as lighter-coloured bands in the side-scan sonar image (a). Closer to the coastline, extended areas of fine grained sediment (b) and a small scale channels (c) are visible.

Core 051207-37 (figure 7) is divided in four sedimentary units. Unit 1 (0-8 cm core depth) is mainly composed of brown sand, including some shell fragments. Between 8 and 11 cm, a layer composed of silt, containing no sand, is apparent (unit 2). The lower boundary of unit 2 is sharp, while its upper boundary is not well defined. Between app. 11 to 12 cm core depth, unit 3A is composed of well sorted sand. Below, unit 3B (12 to 20 cm core depth) contains higher amounts of clay and silt. Various shell fragments are abundant in unit 3B. From 20 cm to the base of the core, unit 4 is composed of sandy silt, and includes some shell fragments. Partly, layers containing higher amounts of sediments in the sand fraction are recognized in the x-ray images.

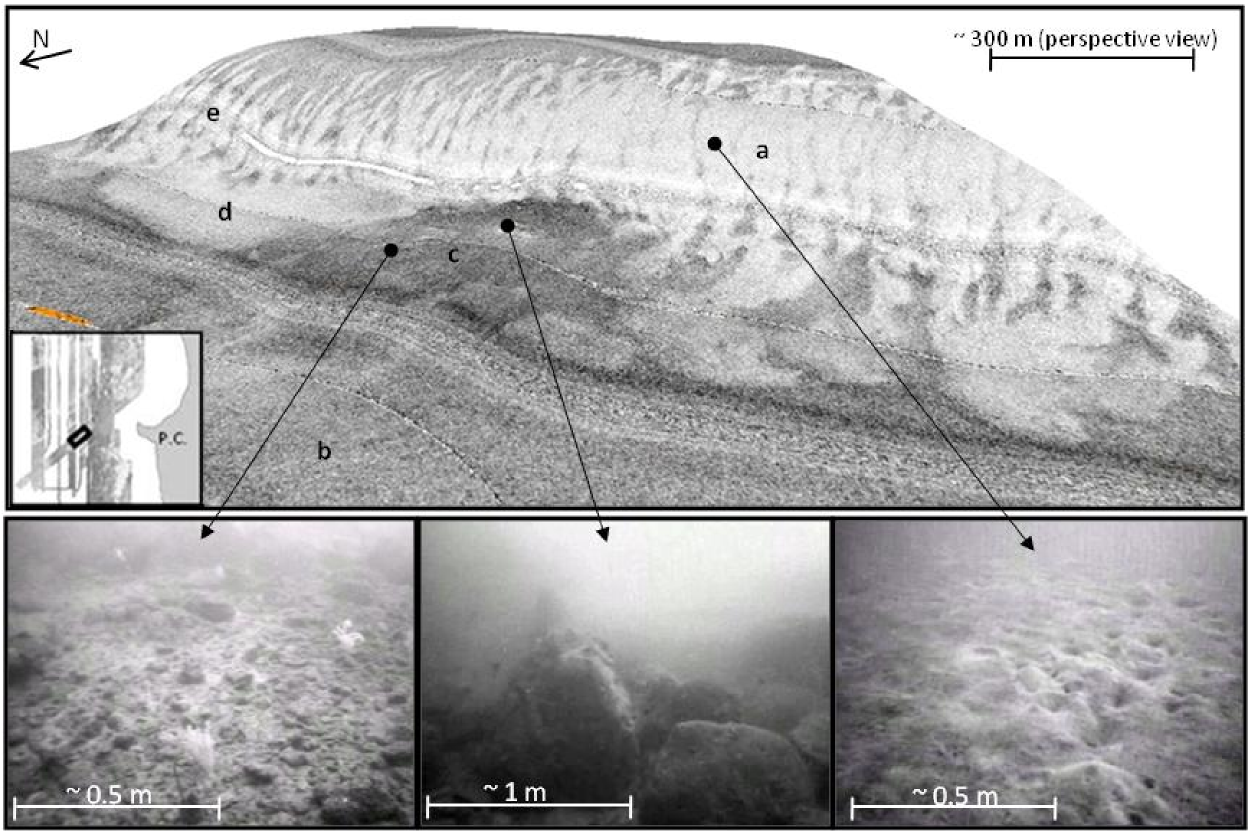

Figure 3: Side scan sonar draped over the bathymetric dataset. For position see figure 2. The length of the ridge is approx. 1500 m (perspective view). a) elongated sediment patches, consisting of fine to medium sand b) coarse sand c) carbonatic gravel and boulders (notice video image) d) sand at the surface, muddy material below e) position of short core (051207-37, fig. 7), composed of sandy material on top and a fine grained layer at 10 cm depth.

5 Discussion

Sand ridges are formed due to regular hydrodynamic processes, e.g. tidal currents in inlets, ocean currents at the shelf margin or during storms (Ernstsen et al. 2006, Flemming 1978, Holland & Elmore 2008), although moribund ridges as remnants from times with a lower sea level are known (Dyer & Huntley 1999). Goff et al. (1999) report that sand ridges on the northeast US Atlantic shelf are asymmetric, having steeper seaward flanks. Holland & Elmore (2008) report that grain sizes across sand ridges typically range from coarse to fine sand. The typical height of storm generated sand ridges is given with 3 to 12 m (van de Meene & van Rijn 2000). Commonly, sand ridges are oblique to the coastline, with the acute angle opening into the prevailing flow direction (Swift et al. 1978, Holland & Elmoore 2008). Most of these features are found in the observed ridge system. The strike direction of the ridges indicates an approximately south-north directed current which was responsible for their formation. This was not the main current direction observed during the tsunami (images of the IKONOS satellite, Goto et al. 2007). Therefore, the ridge system existed prior to the tsunami, although the definite process responsible for its formation has not yet been identified.

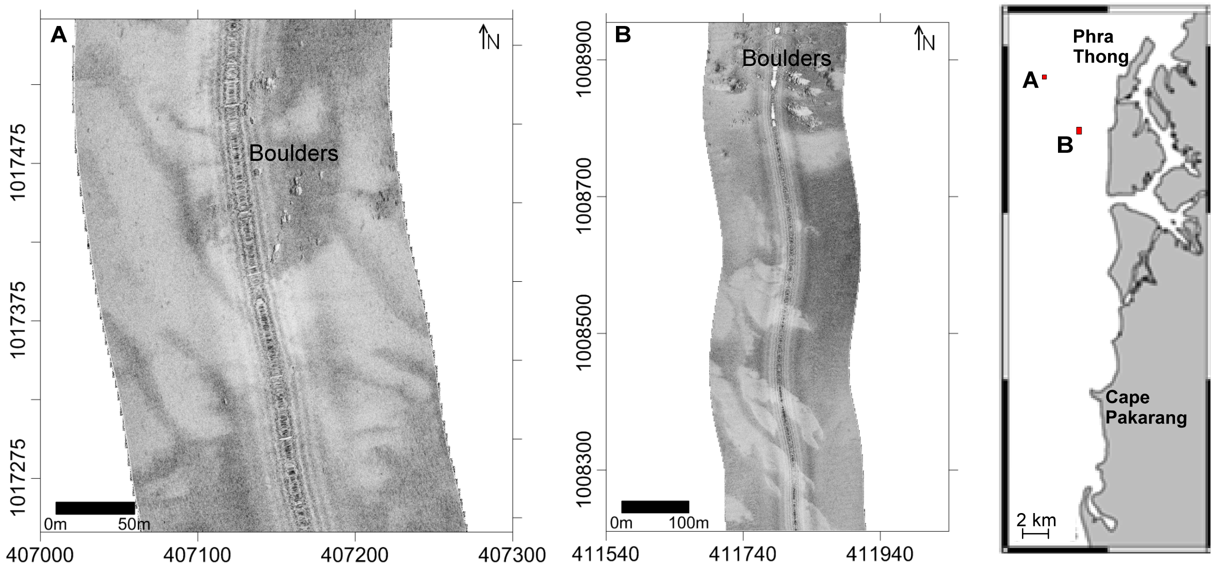

Figure 4: Elongated sedimentary structures offshore Phra Thong. Frequently, boulders are exposed in close vicinity to these structures. Water depth at A: 27 m. Water depth at B: 21 m.

Notable are elongated sediment patches commonly found on the northern flanks of the sand ridges. While finer sediment on the steeper slope of asymmetrical sand ridges is common, in front of storm dominated coasts (Holland & Elmore 2008). Here fine sediments are not visible over the entire length of the flank, but instead they are deposited in small patches separated by coarser sediment. Similar bedforms on the continental shelf offshore Brazil have been formed due to storm events (Moscon & Bastos 2010). The comparison of side scan sonar images from 2007 and 2008 (figure 6) indicates that the general shape of the patches is preserved, but smaller parts begin to fade during one annual cycle, indicating an out-of-equilibrium event based deposition and ongoing reworking of the sediment. Additionally, the existence of identical sediment structures on the flat seafloor further indicates that their formation is not connected with the formation of the sand ridges. Therefore these elongated patches of fine grained sediment have to be interpreted as bedforms created by currents along the north-east/south-west direction. The general stability of these bedforms, combined with the slow fading of delicate structures suggests that no frequently occurring event is responsible for their formation. Since strong storms are rare in the area, and none occurred between the 2004 tsunami and our measurements (based on tracks published by the Regional Specialised Meteorological Centre – Tropical Cyclones (RMSC), New Delhi), it is reasonable to assume that the observed sediment pattern was influenced by the 2004 tsunami, either during the run-up or the backwash.

It is assumed that the muddy material frequently found in grab samples at the base of the sand ridge corresponds to unit 2 in core 051207-37. Therefore, such material is present over a larger area at the base of the sand ridge, and not only locally in one core. Considering the silt separating two units of coarse sand, its deposition likely corresponds to a single event. Similar deposits in cores offshore the Eel River have been described by Crocket & Nittrouer (2004) as flood deposits, which could be generated in the research area by strong monsoon events. But also a tsunami backwash transports large amounts of fine-grained material offshore (Shi & Smith 2003). The process responsible for the formation cannot be determined with certainty. However, a deposition of this material during the monsoon is unlikely, as more regularly occurring structures would be expected. Regardless of the origin of their formation, these event deposits were preserved in the comparably sheltered environments at the base of the sand ridges. They are covered by coarse sand (unit 1), typical for this area of the shelf, indicating some sediment dynamics in the area. This agrees to the change of sedimentological boundaries observed in side scan sonar mosaics between 2007 and 2008 (figure 6). A potential deposition of the sediments beneath unit 2 during an event, indicated for instance by the marked change in sand content of unit 3A compared to unit 3B, or the abundance of shell fragments in unit 3B, is uncertain. Further analysis is needed to identify the origin and the spatial extension of these potential tsunami deposits, especially closer towards the shoreline.

Interesting are frequent observations of boulders close to the elongated patches deposited at the seaward flank of the sand ridges. Many of these boulders show no connection to structures in the subsurface, and must have been transported to their current position. Potentially, this could have happened during the tsunami, either during the run-up from source areas in deeper waters, or during the backwash (compare Paris et al. 2009)

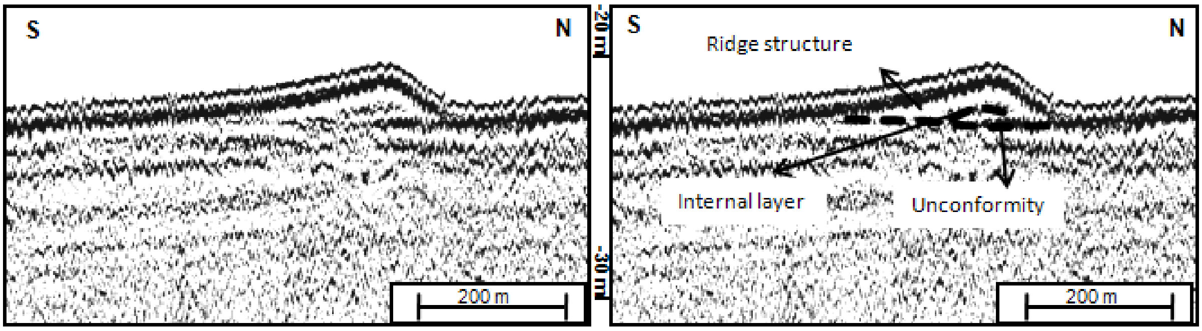

Figure 5: Seismic profile crossing a sand ridge (for position see Figure 2). Clearly visible is the asymmetric form of the ridge which is indicating a transport direction from South to North. Additionally, the ridge is separated from the older surface below by an unconformity.

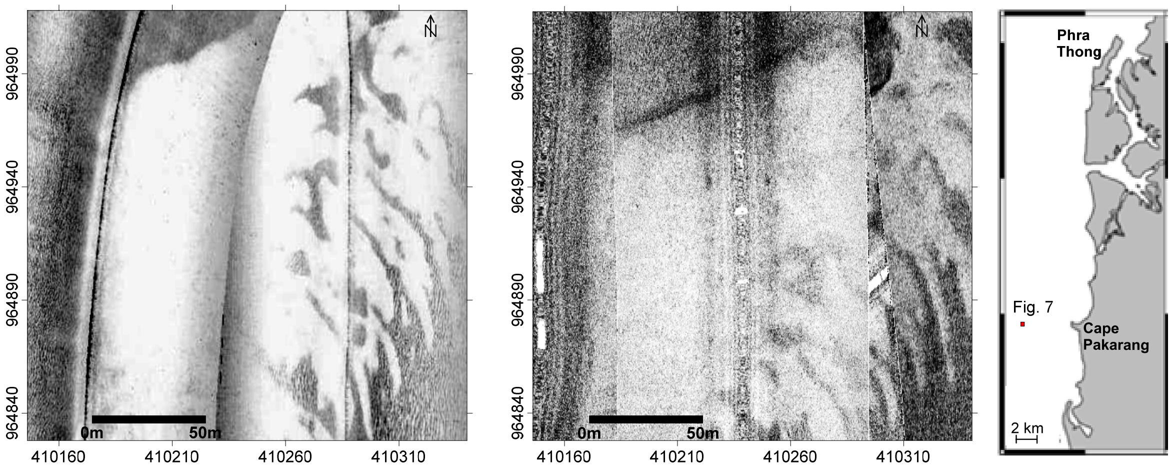

Figure 6: Two side-scan sonar images showing a comparison of a detail of the sand ridge shown in figure 3. The left image was recorded in 2007, the right image in 2008. Small differences are visible. The contours of the elongated sedimentary structures are more pronounced in 2007.

During the tsunami run-up, many boulders were transported towards the intertidal area on Pakarang Cape (Goto et al. 2007). The backwash at Pakarang Cape was modelled by Goto et al. (2007). The authors show that the current speed of the backwash was in the order of 3m/s. This is strong enough to move the observed boulders (Goto et al. 2007, Imamura et al. 2008), which have a diameter of less than 1 meter according to underwater images. Taking into account a channelized backwash (Le Roux & Vargas 2005, Fagherazzi & Du 2007), it is possible that in some areas the current speed was strong enough to transport boulders downslope from the reef platform fringing Pakarang Cape back towards the sea. However, this cannot explain the presence of boulders found several kilometers offshore (Fig. 4).

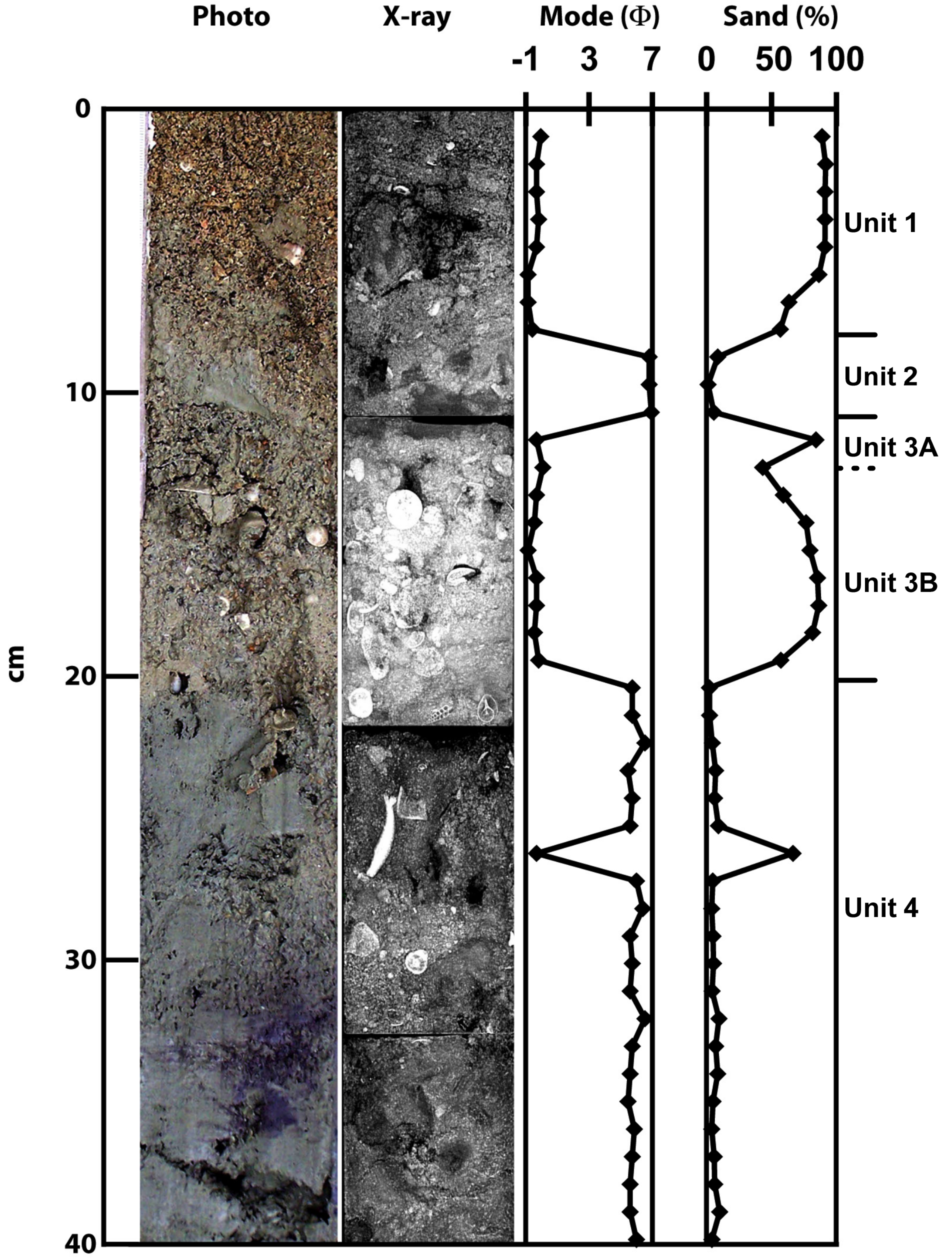

Figure 7: Properties of core 051207-37. From left to right, photo, x-ray image, first mode in phi-degrees, sand content and sedimentary units are presented. For position, refer to Fig.2.

6 Conclusion

Detailed hydroacoustic surveys have been carried out offshore Phang Nga province (Thailand) in 2007 and 2008 and sediment samples have been collected. Starting at 15 m water depth, a system of sand ridges, formed by coarse sand, was discovered. The sand ridges existed prior to the 2004 Indian Ocean Tsunami. Elongated sediment patches on the seaward flank of the sand ridges consist of fine to medium sand, and indicate a current oblique to the coastline. They fade slowly during the annual cycle, and were potentially reworked during the 2004 Indian Ocean Tsunami. An event layer found at the base of a sand ridge is composed of silty sediment, which could be related to the tsunami backwash or floods during the monsoon. These event deposits are covered by coarse sand, and might enter the geological record.

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