Sediment distribution on the inner continental shelf off Khao Lak (Thailand) after the 2004 Indian Ocean tsunami

P. Feldens¹, K. Schwarzer¹, D. Sakuna^{1,2}, W. Szczuciński³, and P. Sompongchaiyakul⁴

¹*Institute of Geosciences, Kiel University, Otto-Hahn-Platz 1, 24118 Kiel, Germany*

²*Oceanography and Environment Unit, Phuket Marine Biological Center, P.O. Box 60, Phuket 83000, Thailand*

³*Institute of Geology, Adam Mickiewicz University, Maków Polnych 16, 61-606 Poznań, Poland*

⁴*Department of Marine Science, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand*

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The coastline of Khao Lak (Thailand) was heavily damaged by the 2004 Indian Ocean tsunami. Onshore tsunami deposits and satellite images, which show large amounts of sediment transported offshore, indicate that the seafloor was impacted by tsunami run-up and backwash. In this study, high-resolution maps of sediment distribution patterns and the geological development of the seafloor are presented. These maps are based on multibeam, side-scan sonar and seismic profiling surveys offshore Khao Lak. Paleoreefs, with associated boulder fields and sandy sediment dominate the inner continental shelf. Patches of fine-grained (silt to fine sand) sediments exist in water depths of less than 15 m. The sediment distribution pattern is stable between 2008 and 2010, apart from small shifts regarding the boundaries of the fine-grained sediment patches. In one sediment core and several grab samples an event layer was documented, situated below a cover of modern sediments which is only a few cm thick. The event-layer is traced down to 18 m water depth. It consists mostly of sand and contains compounds of terrigenous origin. It is interpreted as a 2004 Indian Ocean tsunami deposit. However, over large areas of the study-site, the impact of the tsunami is hardly identifiable by seafloor morphology or sediment distribution.

Key words: 2004 Indian Ocean tsunami, offshore tsunami deposits, continental shelf, nearshore deposits, Andaman Sea.

1. Introduction

Tsunami may cause erosion and sedimentation in various environments, including coastal lowlands, lakes, lagoons, tidal flats, beaches, and continental shelves, but also the deep sea (e.g. Shiki *et al.*, 2008; Bourgeois, 2009). Among these environments, tsunami impacts in the marine realm are the least known, although, as discussed by Dawson and Stewart (2007), in theory, offshore tsunami deposits may comprise a large percentage of tsunami records in geological history.

In contrast to onshore tsunami deposits with a relatively well-established set of diagnostic features, based on many studies of recent tsunami events (e.g. Dawson and Shi, 2000; Goff *et al.*, 2001; Shiki *et al.*, 2008; Bourgeois, 2009; Chagué-Goff, 2010; Goto *et al.*, 2010a), offshore tsunami deposits are poorly known. They have been investigated in only a few cases (e.g. van den Bergh *et al.*, 2003; Noda *et al.*, 2007; Abrantes *et al.*, 2008; Goodman-Tchernov *et al.*, 2009; Paris *et al.*, 2010). The existing data are far from sufficient to establish universal key criteria for the identification of offshore tsunami deposits and to understand the controlling processes of deposition associated with tsunami passages. Even less is known about the ero-

sion of the seafloor due to tsunami flows. Most information about seafloor erosion is derived from studies of onshore deposits containing marine microfossils like foraminifera (e.g. Nanayama and Shigeno, 2006; Uchida *et al.*, 2010) or diatoms (e.g. Dawson, 2007; Sawai *et al.*, 2009).

The geological impacts of the 2004 Indian Ocean tsunami are likely to lead to the most detailed investigation in the history of tsunami research. Despite that, limited literature exists regarding the resulting offshore effects, which have been found to be variable. For instance, Paris *et al.* (2010), applying side-scan sonar mapping nearby Banda Aceh (Sumatra), documented a large boulder field deposited in a water depth from 5 to 25 m, mainly by tsunami backwash flow. In the nearshore zone off India and Sri Lanka, a change in bathymetry was observed after the tsunami, caused by both erosion and deposition (Narayana *et al.*, 2007; Anandan and Sasidhar, 2008; Goto *et al.*, 2011). Local erosion at a water depth of approximately 30 m on the continental shelf of the Andaman Sea, adjacent to the coast of Thailand, was reported by Chavanich *et al.* (2005). Post-tsunami change in shallow water sediment distribution was documented by Kendall *et al.* (2009). Meanwhile, tsunami backwash deposits were reported from a few sites on the inner continental shelf (Feldens *et al.*, 2009; Sugawara *et al.*, 2009; Sakuna *et al.*, 2012).

Most of the evidence of offshore effects is based on a few scattered observations or sampling sites, and does not allow an overall assessment of the tsunami impact on the

seafloor of the inner shelf. Topographical variations lead to changes in the tsunami run-up height and impacts onshore (e.g. Szczuciński *et al.*, 2006). Therefore, it is reasonable to expect the submarine effects of tsunami to vary spatially as a result of differing bathymetry. Moreover, satellite images show large amounts of suspended load transported offshore in plumes, due to the commonly channelized tsunami backwash flow (Umitsu *et al.*, 2007; Fagherazzi and Du, 2008; Yan and Tang, 2009). Consequently, local variations in run-up and backwash may cause variations in the characteristics and distribution of the resulting erosion and deposition caused by the tsunami. Further issues concern the potential of preservation and recognition of offshore tsunami impact. Potential offshore tsunami deposits are subjected to several processes, which may remove or alter them. These processes are, for instance, waves, currents, tides, and bioturbation. After the 2004 tsunami, the beaches along the Thai coastline, which had been heavily eroded, were rebuilt naturally. Coastal systems returned to equilibrium conditions within only a few years (e.g. Choowong *et al.*, 2009; Grzelak *et al.*, 2009). One may also expect similar transformations to occur in shallow marine areas.

The assessment of tsunami effects on the seafloor of the inner shelf, without detailed information of pre-tsunami conditions, requires repeated high-resolution seafloor mappings. This is due to the variability of tsunami impacts and the dynamics of post-tsunami processes. Seafloor mapping helps to identify modern sediment distribution patterns and annual dynamics, and, in particular, to locate sheltered environments where offshore tsunami deposits might be preserved. Offshore tsunami deposits identified in such environments may supplement the paleo-record already established from onshore deposits (e.g. Jankaew *et al.*, 2008).

The present study focuses on the inner continental shelf offshore of Khao Lak (Thailand), an area which was strongly impacted by the 2004 Indian Ocean tsunami. The major objectives are:

1. to map geological structures, to document seafloor morphology and to elaborate sediment distribution patterns;
2. to identify the interannual seabed sediment dynamics by reinvestigation of the same areas;
3. to identify sediments, deposited by the 2004 Indian Ocean tsunami, and to gain information concerning their preservation potential.

2. Investigation Area

The study area, offshore of Khao Lak (Thailand), covers about 105 km² ranging from a 5- to 35-m water depth. Here, the coastline consists of beaches adjacent to coastal lowlands, alternating with rocky cliffs. The tides are mixed semidiurnal and range from 1.1 to 3.6 m (Thampanya *et al.*, 2006). From December to February, the NE-monsoon dominates the weather patterns, while the SW-monsoon is active from May to September (Khokiattiwong *et al.*, 1991). Calm conditions prevail in between. Offshore wave heights during the SW-monsoon can reach up to 5 m (Choowong *et al.*, 2009). During the NE-monsoon, wave influence is negligible, yet strong typhoons can occur in this part of

Thailand, although they are generally rare (Kumar *et al.*, 2008; Brand, 2009; Phantuwongraj and Choowong, 2011). No such events occurred between the 2004 Indian Ocean tsunami and the period of our measurements (data by the Regional Specialized Meteorological Centre—Tropical Cyclones, RMSC, New Delhi).

There are no large rivers discharging into the study area. Meanwhile, longshore currents and sediment transport are commonly directed from south to north (Choowong *et al.*, 2009; Di Geronimo *et al.*, 2009), leading to the formation of common coastal features such as sand spits. Offshore Khao Lak, carbonate and granitic outcrops are common on the seafloor (Di Geronimo *et al.*, 2009). In the past, extensive tin mining activities took place in Phuket-, Ranong- and Phang Nga-province on land, and offshore down to a 50-m water depth (Suwanwerakamtorn *et al.*, 1990). Mining pits, up to 100 m in diameter and 7 m in depth still exist offshore (e.g. Feldens *et al.*, 2009).

The 2004 Indian Ocean tsunami had a strong impact on the coastal areas along the Andaman Sea (Bell *et al.*, 2005; Thanawood *et al.*, 2006; Tsuji *et al.*, 2006; Szczuciński *et al.*, 2006). The maximum tsunami run-up height, in the study area, reached 15 m at Pakarang Cape (Siripong, 2006). About 12,500 m² of Pakarang Cape were eroded by the tsunami and a large number of boulders were transported from an offshore reef platform into the intertidal zone (Goto *et al.*, 2007). Onshore tsunami deposits contained numerous indicators of a marine origin. Microfossils suggested that seafloor erosion by the tsunami in the intertidal, nearshore and open marine (continental shelf) environments had occurred (Hawkes *et al.*, 2007; Kokociński *et al.*, 2009; Sawai *et al.*, 2009).

3. Methods

Full-coverage side-scan sonar mapping, supported by multibeam echosounding and shallow reflection seismic soundings, were performed during three cruises (Nov.–Dec. 2007, Nov.–Dec. 2008, Jan.–Feb. 2010). In 2008 and 2010, selected areas were reinvestigated to obtain information about interannual sediment dynamics. The available dataset comprises about 2000 nautical miles (nm) of hydroacoustic profiles, ranging from 5 to 90 m along the coastline off Khao Lak. Approximately 105 km² of full-coverage side-scan sonar images, taken offshore from Pakarang Cape in water depths ranging from 5 to 35 m, are presented in this paper.

Bathymetric data were collected using a SeaBeam 1185 multibeam system (180 kHz, ELAC Nautic GmbH). Seismic data were collected using an EG&G boomer (2007) system and a low-voltage boomer device (C-Boom, 2008 and 2010) combined with an 8-element single-channel streamer for signal recording. A high- and low-pass filter (0.3 kHz and 7 kHz) was applied to remove acoustic disturbances. A Klein 595 side-scan sonar (384 kHz) with digital data acquisition and a Benthos 1624 side-scan sonar (100 and 400 kHz) were used to obtain information about sediment distribution patterns on the seafloor. The data were mosaiced and the resulting images were improved by adjusting the white and black values in order to better display the contrast of the side-scan sonar data. In this study, low

backscatter values are displayed in a light grey, while high backscatter values appear in a darker grey.

A collection of grab samples, as ground-truth data, enables the calibration of the side-scan sonar data. Sediment cores were collected using a Rumohr type gravity corer (7-cm internal diameter). In the laboratory, the cores were cut in two halves, photographed and sampled for X-ray analysis (1-cm-thick slabs) as well as for grain-size analysis. Depending on the sediment composition, the grab samples from the sediment surface were either sieved, or analyzed using a Mastersizer 2000 laser diffraction device. Samples from the sediment core, discussed in this paper, were analyzed with the Mastersizer 2000.

For the grain-size analysis by laser diffraction, carbonate and organic material were removed by HCl and H₂O₂ prior to analyses. Moreover, Na₄P₂O₇ was added to avoid the aggregation of fine particles during the measuring process. Grains exceeding 1.7 mm in diameter cannot be analyzed with this method. This is an important restriction as the sediment core contained layers of coarser material. It was not possible to combine sieving and laser diffraction measurements for the analysis of core material as no representative sieving results could be obtained due to the limited amount of sediment available. Therefore, the obtained grain-size distributions do not fully represent the grain-size distributions of the sediment, when grains with a diameter >1.7 mm are present.

Grain sizes are presented in the Phi (Φ) scale with $\Phi = -\log_2 d$, where d is the grain size in mm (Krumbein, 1938). The mode of the grain-size distribution was chosen as a central statistical parameter because it is not affected by removing coarse (laser diffraction based method) or fine (sieving) parts from the grain-size distribution. Modes can also be used for bimodal sediments. Sorting values, based on unimodal samples, are given using the geometric method of moments (calculation with the software Gradistat (Blott and Pye, 2001)).

4. Results

4.1 Seafloor bathymetry

A dead fringing reef complex near Pakarang Cape (Sanfilippo *et al.*, 2010) forms a platform that extends down to a water depth of approximately 10 m (Figs. 1 and 2). Seaward from this reef platform, the seafloor gently declines by 0.1° down to a 25-m water depth, which is the depth reached about 10 km offshore of the tip of Pakarang Cape (Fig. 1(A)). North and south of Pakarang Cape, in water depths between 5 and 10 m, a system of small channels, up to 2 m deep and generally between 30 and 100 m in width, is incised into the seafloor (Figs. 1(B) and 2).

Further offshore, SW-NE striking sand ridges are present (Fig. 1(C)). Their height above the seafloor reaches up to 2 m. The distance between two sand-ridge crests varies from several hundred meters to several kilometers. The length of the ridges exceeds 5 km. These sand ridges are asymmetric, with a steeper flank exposed to the NW and with a slope of up to 1.2°. They are also marked by a gently dipping flank exposed towards the SE. In some areas, small incisions up to 1 m deep exist in front of the northwestern flanks. Most of the sand ridges can be easily recognized in

Fig. 1. Overview of the research area offshore Khao Lak and the location of bathymetric profiles (A–C, vertical exaggeration $\approx 100\times$). Areas shown in subsequent figures, and the position of core 050310-C3 are indicated.

the side-scan sonar images; sediment with a lower backscatter intensity is exposed on the steep northwestern flanks (seafloor type E, Fig. 3). The sand ridges are no longer found in an approximately 25-m water depth, meanwhile a slightly elevated platform is observed in the bathymetry (Fig. 1(A)). Seawards of the platform, the morphological gradient of the seafloor is greater, reaching an average descent angle of 0.5° down to a 35-m water depth.

4.2 Seafloor sediment distribution patterns and their interannual dynamics

Side-scan sonar mosaics based on backscatter intensities and the sedimentary composition of grab sample material

Fig. 2. Side-scan sonar image (left) and the interpretation as a map of different types of seafloor (right), down to approx. 15-m water depth. The seafloor types are determined by the classification of side-scan sonar data and are verified by surface sediment samples—Inserts A, B, C and D show details discussed in the text.

identified eight major types of seafloor (named A–H; see Figs. 2 and 3): A) silt to fine sand, B) coarse sand with coral fragments, C) coarse sand, coral fragments and boulders, D) medium and coarse sands, E) medium sand, F) bedrock outcrops, G) boulders (reef platform), and H) fine and medium sands.

Sediments composed of silt to fine sand (type A), are common north and south of the reef fringing Pakarang Cape. This sediment type extends down to a 15-m water depth (Fig. 2). The landward limit of seafloor type A is above the 5-m water depth contour. It is recognized by patches of low backscatter intensity, displayed in light-grey colors in the side-scan sonar mosaics. The offshore boundaries of the patches of sediment type A are irregular, and, in some places, extend seaward filling in shallow channels. The grain size analyses revealed these sediments to be poorly, to very poorly, sorted. Samples close to the coast-line are partly bimodal, with modes situated in the range of medium to coarse silt (4.6 to 5.4Φ , Fig. 4(A)), and partly in the fine-sand fraction (3.7 to 4.0Φ). The first mode generally decreases with increasing water depth (Fig. 4(A)). Notable exceptions include a coarser sample collected from a channel (sample 26 in Fig. 4(A)) and a finer sample found in a sheltered environment next to a bedrock outcrop (sample 36 in Fig. 4(A)).

Patches of seafloor type A are separated by seafloor

type B (coarse sand, including coral fragments) north of Pakarang Cape and seafloor type C (coarse sand with coral fragments as well as boulders) south of the Cape. Boulders are only observed in water depths less than 15 m. Seafloor types B and C are characterized by high backscatter values, displayed in dark-grey colors. Boundaries separating seafloor types A and B, or A and C, can be either sharp (Fig. 2(B)) or transitional (Fig. 2(C)). The modes of the poorly sorted sediments representing seafloor types B and C are within the coarse-sand fraction (-0.9 to 0.4Φ). The landward limit of seafloor type B and C is situated above the 5 m depth contour. Offshore, a transitional boundary separates seafloor types B and C. A sharp boundary exists between seafloor type B and seafloor type D sediments in a water depth of 16 to 18 m (Fig. 2(A)). However, sediments classified as seafloor type B reappear further offshore and extend down to approximately a 27-m depth (Fig. 3). No correlation between the first mode and water depth is recognized in samples retrieved from seafloor types B and C (Fig. 4(B)).

Seafloor type D is composed of medium to coarse sand, which covers the seafloor between 15- and 22-m water depth. Only a few coral fragments are found within these sediments; therefore, they are recognized by intermediate backscatter values. The sediments are moderately to poorly sorted due to mixing with some coral pieces of various

Fig. 3. Side-scan sonar image (top) and seafloor type map (bottom) offshore Khao Lak, down to approx. 35-m water depth. The seafloor type map is based primarily on the classification from side-scan sonar data and is verified by the analyses of surface sediment samples. The insets A and B show details of the borders of the seafloor types and peculiar features of the seafloor, which are discussed in detail in the text.

sizes. Their first mode varies between 1.1 to 1.4 Φ . Moderately well sorted medium (first mode of 2.4 Φ) sand is found in water depths from 15 to 25 m. These sediments are classified as seafloor type E (Figs. 2 and 3). They commonly occur on the northwestern flanks of the sand ridges (Fig. 3(B)). Type E sediments are easily recognized due to their elongated form, sharp boundaries with adjacent seafloor types and low backscatter intensity (Fig. 3(B)). The mode of the grain size of samples retrieved from seafloor type E is independent of the water depth.

Bedrock outcrops form parts of the seafloor. These areas are classified as seafloor type F, which occurs south of Pakarang Cape in water depths less than 10 m (Fig. 2), and further offshore in depths greater than 25 m (Fig. 3). The interface with other sediment types is very sharp (Fig. 3(A)). The appearance of the bedrock outcrops is variable in side-scan sonar mosaics, depending on the inclination angle of the outcrop surfaces in relation to the position of the side-

scan sonar towfish.

The seaward boundary of the dead reef fringing Pakarang Cape is covered by a field of boulders (seafloor type G, Fig. 2(D)). This type of seafloor extends down to 10–12-m water depth. It is marked by a transitional boundary with other sediment types. The boulders are numerous and their diameter often exceeds 1 m. They are recognized as black dots with a bright acoustic shadow behind. The boulder density on the fringing reef is higher towards the offshore boundary of the reef platform (Fig. 5(A)) compared with the boulder density on its landward boundary (Fig. 5(B)).

Fine, and medium, sand below a 25-m water depth is classified as seafloor type H. This type of seafloor has a composition very similar to the sediments of type E (poorly to moderately sorted). However, type H sediment does not show specific bedforms (Fig. 3(A)). Modes of sediment comprising seafloor type H do not correlate with water depth, which is similar to samples from seafloor type E

Fig. 4. Grain-size data of surface sediment samples. For sampling positions see Figs. 2 and 3. (A) The first mode of grain size versus water depth, based on samples retrieved from sea floor type A, showing a decreasing first mode with increasing water depth. Samples 19 and 27, and 21 and 31 were taken at the same positions in 2008 and 2010, respectively. (B) The first mode of grain size versus water depth based on samples from sea floor types B, C and D show no correlation. (C) The grain size distribution of samples 5, 6, 7, 10, 12, 33 obtained from sea floor type A and H. All samples have the first mode at 2.4Φ .

(Fig. 4(C)).

Repeated side-scan sonar surveys of the selected areas reveal variations in the boundaries of sea floor type A. Between 2008 and 2010, the area covered by type A sediments changes in the order of several tens of meters, either increasing or decreasing the size (Fig. 6(A)). The grain-size composition of surface sediment changes not only at sediment type boundaries, but also in the center of sea floor type A. Here, sediment changes from a sandy to a silty composition (e.g. Fig. 6(A)), or vice versa (Fig. 6(B)). Repeated grab sampling from the same position shows a slight coarsening

of the first mode of the surface sediment in the center of a sea floor type A patch south of Pakarang Cape (samples 19 and 27, Fig. 4(A)), and no change in the first mode of two samples located close to Pakarang Cape (samples 21 and 31, Fig. 4(A)).

4.3 Structure of the subsurface sediments

Data concerning the subsurface sediments and the geological structure derive from three sources: reflection seismic (boomer system), grab samples and sediment cores. The seismic data provide information down to 8 m below the seafloor. Information about the development of the sub-bottom structure was mainly available from areas covered by sea floor type A sediments. Analysis of grab samples not only gave information about the sediments deposited directly on the seafloor, but also about sediments in 10 to 15 centimeters depth. In several cases, sediments different to those at the seafloor surfaces were found in these depths. Moreover, results of the analysis of a 55-cm-long core, taken from the area of sea floor type A, are presented.

According to the seismic records, the silty sediments comprising sea floor type A form a thin cover, usually less than 1 m thick (seismic unit 3, Figs. 7(A) and 7(B)). Within the channel system, or in areas where patches cover deeper incisions, the thickness of these deposits can reach several meters. In those cases, two sediment layers (seismic units 2 and 3), separated by an unconformity, are observed. Towards the seaward boundaries of the sea floor type A, the thickness of seismic unit 3 decreases below the resolution of the boomer system. Silty sediments still appear in the side-scan sonar images, but they can no longer be distinguished in the seismic data as a distinct layer. The surface of the cover of silty deposits is generally on the same, or at a slightly lower, morphological level as the surface of the surrounding sand (Fig. 7(B)), and at a distinctly lower level near the hard-rock outcrops (Fig. 7(A)). In part, the appearance of seismic unit 3 is homogenous; however, internal reflectors indicating layering can be observed as well. Seismic unit 2 is separated from units 1 and 3 by a distinct reflector. Moreover, internal reflectors terminating against this boundary are apparent. In some areas, the sediments forming sea floor type B can be identified in the seismic record and are situated above the acoustic basement (seismic unit 4, Fig. 7(C)). The penetration depth is generally poor, and the acoustic basement is situated close to the surface.

Sediment samples retrieved from sea floor type A occasionally contain, at depth, material different from the surface sediment. These sediments at the base of the grab sample include oval-shaped patches of dark sand (first mode at 3.7 to 4.0Φ , samples 29 and 31). They are found close to the coastline and in the channel system at the seaward boundary of sea floor type A. The subsurface sediments from grab samples, retrieved close to the coastline, also contain irregular clasts composed of coarse sand with a first mode at 0.8Φ . Gravel-sized pieces of granite (sample 21) are included as well. The latter is also frequently embedded in grab samples retrieved seawards of bedrock outcrops (e.g. sample 36). At the seaward boundary of sea floor type A, lateritic fragments are found in the lower part of grab samples (sample 22). Seaward of the boundary of sea floor

Fig. 5. The boulder density on the reef fringing Pakarang Cape (seafloor type G) is higher towards its offshore boundary (A, approx. 11-m water depth), compared with the landward boundary (B, approx. 9-m water depth). For positions, refer to Fig. 2.

Fig. 6. Examples of repeated side-scan sonar surveys. The results focus on the sediment dynamics along a boundary of seafloor type A sediment patches (for positions, see Fig. 2). (A) Close to the coastline (water depths down to 10 m) the boundaries between the different seafloor types change in the order of tens of meters and are increasing (1), or decreasing (3), in coverage of type A sediments. Changes are observed also within the sediment patch (2). (B) Further offshore, observed changes are smaller. A change from silt to sand in the center of a type A sediment patch is marked with an arrow.

type A, plant material—embedded in mud and covered by sand—was found in grab samples retrieved from sediments of seafloor type D.

Sediment core 050310-C3 collected at a 11.2-m water depth (Fig. 8) provides an insight into the composition of seismic unit 3 (covered by seafloor type A). It is composed of variable grain sizes ranging from silt, silty sand to sandy silt, sand and intercalations of gravels. The sediments in the core are composed of six major units which can be further divided into subunits. The uppermost layer, unit 1 which is 5 cm in thickness, is mainly composed of upward fining silt (the first mode increase from 4.2 to 4.6 Φ from base to top). Grain-size analysis reveals that the sediments of the upper 1 cm show a second mode in the sand fraction (0.9 Φ). Therefore, it is identified as a separate subunit (1A). Unit 1 does not reveal well-preserved laminations. This is likely

due to bioturbation; traces of which can be recognized in the X-ray image.

Unit 1 conformably covers a 1-cm-thick laminated layer which is composed of coarse sand containing more fine-grained material towards the surface (mode at 0.3 Φ). This layer forms the uppermost part of unit 2 and is defined as subunit 2A. The lower boundary, separating units 2A and 2B, is sharp and likely to be erosional. From 5 to 18 cm, the sediment comprises poorly sorted deposits with bimodal grain-size distributions ranging from silt to gravel (unit 2B). This subunit contains reworked shells and coral debris. The sorting is slightly better towards the top of the unit. There is also an upward decrease in size and number of gravel-sized components, and an associated decrease in clay and silt content towards the top of the unit. The first and second modes in the analyzed samples range from 0.8 to 1.1 Φ ,

Fig. 7. Shallow-water reflection seismic profiles and side-scan sonar images in the area of seafloor types A, B and C (Fig. 2). Four seismic units are identified. The sediment of type A belongs to seismic unit 3, which forms a meter-thick cover. P.C.: Pakarang Cape.

and 4.0 to 5.1Φ , respectively. Unit 2 is separated from the underlying unit 3 by an erosional unconformity at 18-cm depth (Fig. 8). Small amounts of the older sediments are incorporated into the basal part of unit 2.

Compared with unit 2, sediments of unit 3 are characterized by a higher percentage of silt. The structure of unit 3 shows distinct horizontal, and cross-, stratifications. The first mode in the grain-size distribution ranges from 0.8 to 1.4Φ . A second mode is observed only in the upper and lower parts of the unit (subunits 3A and 3C) and ranges between 5.1 and 6.0Φ . This unit may be divided into the two silty sand subunits 3A and 3C, separated by a sand layer (3B). Subunit 3A is about 9-cm thick and is composed of almost horizontally-laminated sediments with several small-scale unconformities. At a depth of 24 cm, a pocket containing sand and gravel interdispersed with some snail shells exists. The inclined sandy layer forming subunit 3B is situated at a depth of 26 to 28 cm. It is composed of coarse sand. The layer contains numerous shell fragments and patches of finer sediments. Its lower contact is partly erosional. The 4-cm-thick subunit 3C is composed of layered silt and sand inclined in the same direction as subunit 3B. In the upper part of this subunit, a cross-lamination is preserved within an inclined silty sand layer. In general, the sediments in this subunit are coarser towards the surface. Laminae of the lower part of the unit downlap onto the upper surface of unit 4, situated at a 33-cm depth. Unit 4 is composed of similar types of sediments as the above

units—bimodal silty sand with the first mode ranging from 0.8 to 1.1Φ . However, the sedimentary structure of this unit is chaotic. It reveals remnants of horizontal laminations and patches of finer sediments with shells scattered throughout. Its lower boundary is sharp. Sediment between a 42- and 52-cm depth is defined as unit 5 and consists of coarse sand with a unimodal grain-size distribution (mode between 0.8 and 1.0Φ). Shell fragments and coral debris are abundant. In some parts, it reveals a faintly visible lamination; however, in general, it has a massive structure with a chaotic distribution of sediment patches containing finer material between sand grains. The lower boundary of this unit is uneven and erosional. The lowermost part of the core consists of poorly sorted sandy silt to silty sand (unit 6), with the first mode between 3.7 and 4.7Φ . No clear sedimentary structures can be recognized in this unit.

5. Discussion

5.1 Geological features of the inner continental shelf off Khao Lak

The obtained data indicate three seabed facies offshore Khao Lak in water depths ranging from 5 to 35 m, which are differentiated by seafloor morphology and sediment composition. They are related to: (a) the fringing reef at Pakarang Cape and potential paleoreefs nearby, (b) the dominating sandy inner shelf environment, and (c) shallow water patches of fine-grained sediments.

The fringing reef offshore Pakarang Cape is covered with

Fig. 8. Photo of sediment core 050310-C3. From left to right, X-ray image, photo, sedimentary units and the 1st and 2nd modes of grain size, and the sedimentological parameters d10 and d90 are presented.

boulders (sediment type G, Fig. 2). This reef terminates abruptly offshore (Fig. 2). Only a few coral boulders are observed seaward of the reef slope. In contrast, high amounts of coral debris, including boulders, are located north and south of the reef (seafloor types B and C, Fig. 2). Cobbles from this area, which are covered by colonies of organisms indicating a stable environment, were recently reported by Sanfilippo *et al.* (2010). Additionally, the acoustic base is situated just beneath the surface north and south of Pakarang Cape (Fig. 7), which suggests the presence of hard rock and/or very coarse material close to the seafloor. This can be seen below seismic unit 4, which is composed of coarse sand (Fig. 7(C)). It is likely that the areas directly north and south of Pakarang Cape are remnants of old reef platforms. The channel system at a depth of 15 m (Fig. 2) is incised into the surface of this old platform. The elevated morphological platform found in an approximately 25-m water depth (Fig. 1(A)) is interpreted as a paleoreef as well. This interpretation is based on its morphological appearance, which is typical for a drowned reef platform (e.g. Finkl *et al.*, 2005).

The dominant seafloor type on the shelf is composed of sandy sediments, which form a smoothly-inclined seafloor. Several kilometers-long sand ridges occur on the surface of the seafloor (Fig. 1(C)). These ridge structures are frequently observed in sandy inner continental shelf settings. They can be formed both by storm events and by regular hydrodynamic processes; for instance, tidal currents or ocean currents (Holland and Elmore, 2008). Relict ridges, so-called moribund ridges, formed during lower sea level stages also exist (Dyer and Huntley, 1999). The sand ridges in the study area have no connection to the underlying sedimentological strata, and were eventually influenced by the 2004 tsunami (Feldens *et al.*, 2010). With the applied methods, no movement of the sand ridges was observed between 2008 and 2010. However, it is not possible to explicitly conclude that these ridges represent a relict form. The presence of fine sands (seafloor type E) on the leeward side of the ridges may suggest that these structures are actively being shaped.

A remarkable feature within the research area is the fine-grained (mainly silt) sediment cover observed close to the coastline (seafloor type A, Fig. 2). This material is deposited in depressions of the inferred paleoreef platform and in the channel system north and south of Pakarang Cape (Fig. 7). The mechanisms responsible for the deposition and preservation of such fine-grained material in the inner shelf environment are still poorly understood (e.g. Hill *et al.*, 2007). However, it was found that once deposited (for example, during large floods) mud deposits can be retained even in wave-dominated, highly-energetic, inner shelf environments (Scully *et al.*, 2002; Crockett and Nittrouer, 2004). Since large rivers are absent in the study area, the source of these sediments may be associated with recent anthropogenic activities (tin mining, deforestation, earthworks), or local small river and creek flooding during the rainy season.

5.2 Mud deposits on the inner continental shelf

Accumulation of mud is observed on various continental shelves, normally due to the discharge of large rivers supplying significant amounts of fine-grained sediments (e.g. Walsh and Nittrouer, 2009). However, such a sediment source is missing in the study area. From other studies, it is known that the mud supply to the shelf has increased in historical times due to direct or indirect anthropogenic impact (Wolanski and Spagnol, 2000; Sommerfield and Wheatcroft, 2007; Szczuciński *et al.*, 2009). An increased supply of fine sediment during the last century may also be expected in the study area offshore Khao Lak, due to intensive tin mining activities, agriculture, tourism and related land-use change (e.g. deforestation).

The thickness of the fine-grained sediments offshore Pakarang Cape (sediment type A, Fig. 2, seismic unit 3, Fig. 7) decrease from a local maximum of 2 m to only a few cm, with increasing distance from the shore, and increasing water depth. Dominating sediments grade also from fine sand to silt-sized particles with increasing distance from the shore. This suggests an onshore source of these sediments. Available data indicate that most of these sediments were deposited during the last hundred years. The rate of sediment accumulation is very high, reaching more than 1

cm per year according to Pb210-dating of a sediment core taken from a mud patch at a 9.6-m water depth (Sakuna *et al.*, 2012). This is in agreement with an estimation of the sediment accumulation rate for the presented core 050310-C3 (11-m water depth, Fig. 8). Here, the uppermost 5 cm of mud (unit 1) lies above sediments interpreted as a 2004 tsunami event deposit (see Section 5.3 for the discussion). As the core was retrieved slightly more than 5 years after the tsunami occurred, the estimated accumulation rate is 0.95 cm/year.

The presented assessments of mud accumulation refer to normal conditions without influence from strong events. However, muddy sediments were also transported offshore during the tsunami, which is the most recent extraordinary event influencing the sediment distribution in this area. Observation by eyewitnesses, videos, and satellite images, show large amounts of fine-grained material transported offshore by the 2004 Indian Ocean tsunami (Umitsu *et al.*, 2007; Fagherazzi and Du, 2008; Mård Karlsson *et al.*, 2009; Yan and Tang, 2009). The suspended load extended more than 10-km offshore (IKONOS satellite images) and could be recognized for several days after the event. Therefore, a large layer of mud, transported and deposited offshore due to the tsunami, would be expected. Several post-tsunami sediment sampling surveys have been performed in the present study area or nearby, but the expected widespread layer of tsunami fine-grained deposits was never detected (Szczuciński *et al.*, 2006; Di Geronimo *et al.*, 2009; Feldens *et al.*, 2009; Sugawara *et al.*, 2009; present study). Since all of these surveys were carried out at least one year after the tsunami, it is possible that these fine-grained tsunami deposits were mostly redeposited and dispersed over a larger area by hydrodynamic activity due to the SE-monsoon. Di Geronimo *et al.* (2009) identified areas covered with mud deposits in some parts of the inner shelf off Khao Lak. They interpreted these layers as tsunami deposits due to their unusual location in shallow water. However, these muds are in the same area as the seafloor type A fine-grained sediments, which, as discussed above, seem to be the result of normal sedimentation.

Repeated side-scan sonar surveys in 2008 and 2010 allow for the assessment of the annual dynamics of seafloor type A sediments. The magnitude of change of the boundaries between seafloor type A and the surrounding sea bottom is greater closer to the coastline (Fig. 6(A)), and can reach several tens of meters. The change of the coverage of type A includes both increases and decreases in the area. The decrease may be either due to erosion, or to being covered by surrounding sediments. The available data does not allow for a determination of which situation took place. However, a change in the surface sediment type is also observed in the center of type A sediment patches (Figs. 6(A) and (B)). Therefore, it can be assumed that the sediments of type A are at least partially reworked during the annual cycle.

The evidence gathered on shallow water areas covered by fine-grained sediments (seafloor type A) imply that these regions might be affected by some kind of specific local circulation pattern, generating preferential conditions for a good preservation of the fine-grained deposits in specific, slightly lowered areas. These areas may also be prefer-

ential for the preservation of event deposits; the 2004 offshore tsunami deposits were mostly found in these regions (present study—see Section 5.3, Sakuna *et al.*, 2012).

5.3 Identification of offshore tsunami impact

The results obtained on the seafloor morphology and surface sediment distribution do not show widespread features which could be directly related to a tsunami event. It is observed that offshore tsunami deposits having the form of event deposits are restricted to specific areas. They are documented as unit 2 (Fig. 8) in sediment core 050310-C3. Large storm, and typhoon, events are generally rare in the investigation area (e.g. Phantuwongraj and Chooiwong, 2011) with a return period in the range of decades. Their influence is generally minor (Kumar *et al.*, 2008; Brand, 2009). No severe storm event affected the area between the time of the 2004 tsunami and the end of our sampling campaigns. Therefore, unit 2, being the most recent event layer, is interpreted as an offshore tsunami deposit. Several characteristics reported as typical for such deposits (e.g. van den Bergh *et al.*, 2003; Goodman-Tchernov *et al.*, 2009; Sakuna *et al.*, 2012) can be found in this unit. It is deposited above an erosional unconformity, contains abundant shell fragments, and is generally poorly sorted and embedded within ambient sediments. Material forming unit 2 derives partly from the nearby vicinity where similar sediments can be found both further onshore and offshore (seafloor type B, Fig. 2). The unit is composed of two subunits—2A and 2B—separated by a sharp, erosional boundary. The subunits may reflect various phases of the tsunami event, but further differentiation into run-up and/or backwash is still not possible. Macroscopic terrigenous material, which would point towards backwash influence, is not found, and the observed sedimentological structures could be formed during both tsunami phases. However, a lack of terrigenous components cannot be used to exclude a tsunami origin of unit 2. Erosion on land was observed to be limited (e.g. Szczuciński *et al.*, 2006; Umitsu *et al.*, 2007; Fagherazzi and Du, 2008), and minor in comparison with beach and nearshore zone erosion. Due to the channeled nature of the backwash (Le Roux and Vargas, 2005), it cannot be expected that land-derived material was distributed evenly throughout the inner shelf. It is also difficult to exclude explicitly the tsunami origin of unit 3; however, the laminations in its fine-grained part (units 3A and 3C) indicate recurring, more regular events (Palinkas *et al.*, 2006) in the past. Therefore, we assume that unit 3 was likely deposited before the tsunami event.

The inferred tsunami deposits of unit 2 were covered by only 5 cm of muddy material since 2004. For this reason, the tsunami deposits could also be traced by grab samples, as a penetration of up to 10 cm is possible. Indeed, several grab samples were marked by different sediments at their base than those on the surface. The subsurface sediments contain pockets of fine sand, gravel, pieces of laterites and plant materials. Such deposits are found down to a depth of 18 m, approximately 8 km offshore. The composition of these subsurface sediments varies greatly among grab samples retrieved from different locations. It is assumed that their different compositions reflect both the difference in sediments locally available for erosion and deposition,

as well as the varying spatial impact of the tsunami run-up and backwash at different locations. This is further supported by the varied internal appearance of seismic unit 3 (Fig. 7), which indicates a different composition of the first few decimeters of the seafloor beneath sediment type A. As laterites and plant material are of a terrigenous origin, parts of the material were transported offshore during the backwash.

It is interesting to note that the most inferred tsunami deposits are present below the seafloor of type A. The most likely explanation is that these sediment depocenters allow for a better preservation of tsunami deposits. It is also possible that the major tsunami influence during both run-up and backwash was focused spatially due to small-scale morphological variations both on- and offshore (Le Roux and Vargas, 2005; Umitu *et al.*, 2007; MacInnes *et al.*, 2009).

No influence of the 2004 Indian Ocean tsunami has been found within the sediments of seafloor types B and C. This supports the findings of Sanfilippo *et al.* (2010), who reported a minor influence on corals living on cobbles in these areas. These areas seem to be mostly unaffected by the tsunami event. No direct traces of tsunami impact below an 18-m water depth were found in hydroacoustic data or sediment samples. Seafloor type E (Fig. 2), deposited on the northwestern flanks of the sand ridge system, indicates a SW-NE directed current. In incisions at the base of the sand ridges, event deposits composed of silty material covered by coarse sand were found (Feldens *et al.*, 2010). However, it is uncertain whether these features can be attributed to the 2004 Indian Ocean tsunami.

Due to the sediment dynamics in the investigation area, it is likely that existing tsunami deposits are subject to erosion and reworking processes. Tsunami deposits were not found directly at the surface, but are only covered with about 5 cm of sediment deposited after the tsunami (unit 1, Fig. 8). Therefore, we assume that deposits of the 2004 Indian Ocean tsunami are preserved only in sheltered environments offshore Khao Lak; for instance, in the channel system and in depressions seawards of granitic outcrops where post-tsunami deposition of mud or sand has taken place. This is supported by the findings of Sakuna *et al.* (2012).

The occurrence of tsunami deposits only in specific areas is in contrast to onshore tsunami deposits, which commonly form a continuous sand layer covering the inundation zone directly following flooding by the tsunami (Shiki *et al.*, 2008). Although offshore tsunami deposits were speculated to be more common than onshore deposits (Dawson and Stewart, 2007), their actual deposition and subsequent preservation depends strongly on the local geomorphological configurations of the shelf and nearshore area and onshore conditions. It is proposed that in coastal environments similar to our study area, a higher amount of tsunamigenic material is deposited and subsequently preserved onshore than offshore.

Frequently reported, and more easily preserved onshore and offshore tsunami deposits are boulders (e.g. Goto *et al.*, 2007; Scheffers, 2008; Goff *et al.*, 2010). On the seafloor off Sumatra, the movement of boulders several meters in di-

ameter, in water depths down to 25 m, has been described and modeled by Paris *et al.* (2010). Goto *et al.* (2007) described that the offshore transport of hundreds of boulders towards the intertidal zone of Pakarang Cape is due to the 2004 Indian Ocean tsunami. They explained this transport through a numerical model showing that the majority of these boulders were transported onshore from a water depth of less than 10 m. In fact, the boulder density at the offshore boundary (10–12-m water depth) of the boulder-covered reef platform is higher than in the shallower part (indicated in Fig. 5). This supports the boulder transport model developed by Goto *et al.* (2010b), as the lower density in the shallower water depth might be due to the removal of some of the boulders towards the shoreline during the run-up phase.

6. Conclusion

The objectives of this study include the documentation of seafloor morphology and geological features, as well as the sediment distribution and its interannual changes in order to support the identification of the 2004 Indian Ocean tsunami impact to the seafloor offshore Khao Lak (Thailand). Large areas of the seafloor are dominated by coarse sediments, including sand and boulders, associated with fringing reefs. Moreover, in depressions and in a small channel system, which is incised in a palaeoreef platform, a layer of silt to fine sand is deposited down to a 15-m water depth. These sediments were found to be mobile.

An impact of the tsunami could not be identified over large areas of the study site in the seafloor morphology, the sediment distribution pattern, grain-size composition or specific morphological features. Offshore tsunami deposits could be identified only in a limited area down to an 18-m water depth. Typical features of these event deposits include layers composed of coarse sand and gravelly silty sand with a basal erosional contact. The event deposits are sandwiched by modern muddy sediments. Terrigenous compounds (laterites and plant remnants) indicate the influence of the tsunami backwash. The deposits with terrigenous constituents were already covered with a few cm of sediments. They were found in local sediment depocenters likely created by the local water circulation pattern. Although onshore tsunami deposits and satellite images indicate that the seafloor was impacted by tsunami run-up and backwash, five years after the tsunami the lasting impact offshore Khao Lak was found to be minor.

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P. Feldens (e-mail: pfeldens@me.com), K. Schwarzer, D. Sakuna, W. Szczuciński, and P. Sompongchaiyakul