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Original Research

Environmental and Geological Impacts of the 26 December 2004 Tsunami in Coastal Zone of Thailand – Overview of Short and Long-Term Effects

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Abstract

Our paper presents selected short- and long-term environmental and geological impacts of the 26 December 2004 tsunami on the Andaman Sea coast of Thailand. The tsunami inundated the coastal zone more than 1.5 km inland and above 10 m a.s.l., causing coastal erosion mainly in the nearshore zone, beaches, river mouths and peninsulas. The tsunami runup was significantly influenced by nearshore bathymetry. Almost the entire inundation zone was covered with up to 0.5 m tsunami-laid sand and silty sand layer burying former soil. The layer has not eroded during subsequent rainy seasons and probably will be preserved in the geological record. The inland waters were salinated and the tsunami deposits were enriched in salts and bioavailable heavy metals and arsenic. Most of them were mobilized during rainy season. Sandy beaches - the most tsunami damaged coastal habitat, recovered quickly after the tsunami event. Also, most of the land vegetation recovered within one year after the tsunami.

Keywords: tsunami; tsunami runup and inundation; tsunami deposits; coastal change; natural hazard; Thailand

Introduction

On the 26th of December 2004 at 00:58:53 universal time (U.T.) an earthquake of surface wave magnitude (M_s) 9.0 occurred off the west coast of northern Sumatra (Fig. 1). The recorded magnitude was second only to the 1960 Chilean earthquake [1]. The earthquake generated large tsunamis that severely damaged coastal communities in countries around the Indian Ocean, including Indonesia, Thailand, Sri Lanka and India. The waves were recorded around the world [2]. The documented death toll exceeded 283,000, with the heaviest loss along the west coast of Sumatra, where more than 1 million people were displaced. Damage to houses, infrastructure and livelihoods

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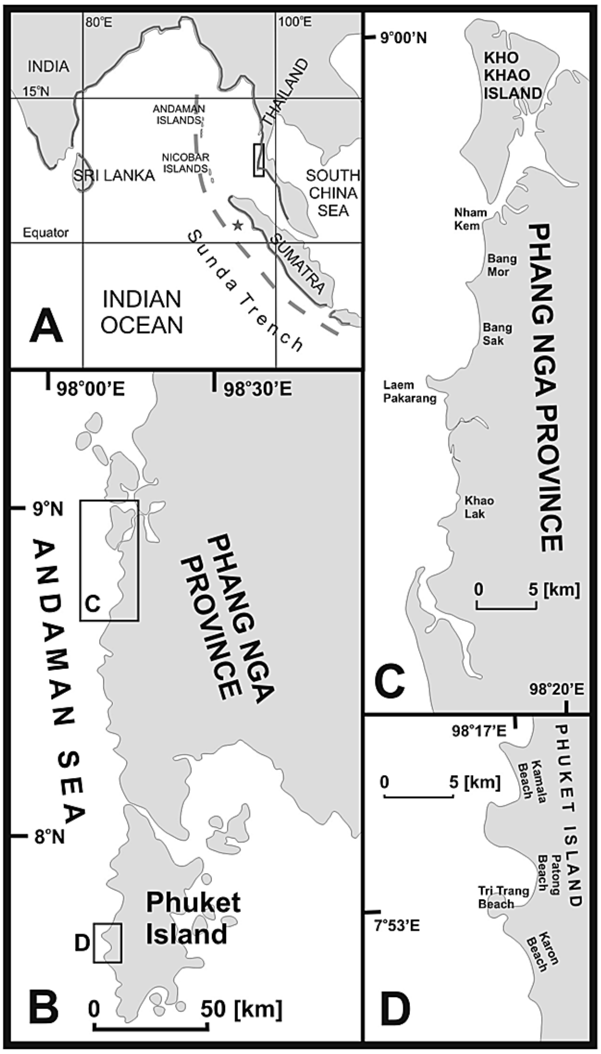

Fig.1. Map of the study area. A) Indian Ocean with marked main epicentre of the 26 December 2004 earthquake (star) and the most tsunami damaged coasts (bold line) [3]; B) Andaman coast of Thailand with the studied areas; C) The surveyed coast and place names between Khao Lak and the northern tip of Kho Khao Island; D) The surveyed coast and place names on the western part of Phuket Island.

are estimated to have exceeded $10 billion [3]. Taking into regard these numbers, the recent tsunami was one of the world's worst natural disasters in decades.

The tsunami affected coastal zone environments by coastal erosion, covering large areas with salt water and contaminated deposits, polluting ground and surface waters causing significant changes in coastal zone ecosystems. Some of the effects were reported in the UNEP rapid environmental assessment [3], a number of post tsunami survey field reports and successive scientific papers on changes of tsunami-inundated areas around the Indian Ocean [3-22]. The effects were the greatest on the island of Sumatra, where the runup reached up to 31 m above sea level and in some places the shoreline moved as much as 1.5 km due to wave scour and subsidence [5]. Some of the consequences of the tsunami are of a short-term nature for example grass-covered areas resembled deserts after the tsunami due to coverage by tsunami sediment layer, salt-water impact and long-lasting draught. One year later plants reoccupied the region (Fig. 2). However, for a lot of affected components of the ecosystems will take decades to recover or are irreversible. For instance, coral reefs, which were locally significantly damaged [6] in places subjected to tsunami action will recover given favourable environmental conditions over the next decade, but the earthquake-caused uplift and tsunami are irreversible (coral reefs around north-west Sumatra and throughout Andaman and Nicobar islands) [18]. Many of the environmental issues are directly related to human health, safety and livelihoods. The tsunami caused contamination of soil and waters but also damaged waste disposal sites, fuel tanks (Fig. 3) and sanitary infrastructure, causing a direct risk for human health [e.g. 3, 4, 9, 19, 25]. Changes in coastal ecosystems and damage to infrastructure resulted in many communities loosing basic livelihoods [e.g. 3, 9, 24]. Some types of coastal ecosystems played protective role for the coastal zone – particularly mangroves and coral reefs. However, their real significance is currently

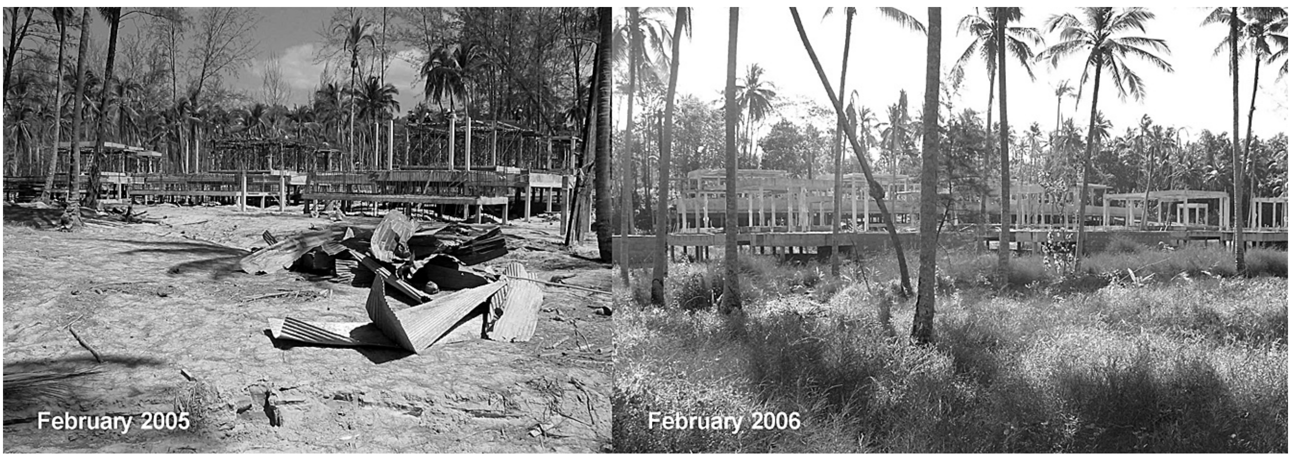

Fig. 2. Short-term changes in ecosystems. One month after the tsunami many lowland areas in coastal zone of Thailand resembled deserts due to coverage by tsunami sediment layer, salt water impact and long-lasting draught. One year later most of those areas were covered with dense vegetation. Views from Ban Bang Sak II in February 2005 (left) and February 2006 (right).

a subject of hot discussion [8, 14, 26-30]. The tsunami focused attention of societies on coastal evolution and assessment of natural hazards in general, and tsunami hazard above all. The latter was not recognized in many countries before the 2004 disaster [e.g. 31]. Using sedimentological analysis, it may be possible to read the geologic record to infer the occurrence of past tsunamis. It would allow extending the relatively short or non-existent historical record of tsunamis in an area, thus improving assessment of tsunami hazard [e.g. 32-40].

In Thailand, the tsunami waves first reached Phuket Island around 100 minutes after the earthquake (sea-level measurements at Mercator Yacht, Nai Harn Bay), initially as the negative part of the wave (trough).The first tsunami peak (wave crest) arrived around two hours after the earthquake (about 10 a.m. local time). Three main waves were recorded in 12-13 minute intervals with the first wave being the largest. Unfortunately, the waves arrived right on high tide for the Andaman coast so the recorded maximum tsunami runup height was unprecedented for this coast and reached up to 14 m a.s.l. in Khao Lak (Fig. 1) [4]. Altogether about 20,300 hectares of land were covered by seawater and over 900 km of coastline was affected in Thailand [3]. Most of that area was also blanketed with a few to several tens of cm thick layer of tsunami sediments [16, 19]. As the disaster response moved from heavy rescue phase to relief and initial reconstruction, Thai governmental agencies, including the Department of Mineral Resources of the Kingdom of Thailand, in cooperation with several foreign institutions (e.g. the British Geological Survey, the Norwegian Geotechnical Institute, Adam Mickiewicz University in Poznań, Poland, New Zealand Society for Earthquake Engineering and others) undertook interdisciplinary survey including study on impacts and environmental effects of the tsunami. The present paper summarizes some results obtained during joint work of Adam Mickiewicz University in Poznań, Poland and the Department of Mineral Resources of the Kingdom of Thailand [16, 19, 41-45] and presents new data gained during two field campaigns: one month and one year after the tsunami in the context of environmental and geological effects of the tsunami in a short- and long-term scale. Any rainfall was reported between the tsunami and the first survey so some of the effects (e.g. tsunami deposits and associated contaminations) were not modified and the real influence of seawater inundation could be observed. The second survey was performed after the rainy season with total precipitation of more than 3300 mm (Fig. 4) and at that time long-term effects could be assessed, for instance: preservation potential of tsunami deposits, mo-

Fig. 3. Tsunami damaged petrol station in Nham Khem village, February 2005.

bility of contaminants or flora recolonization. Specific sites selected for the study included small bays, stretches of open coast, estuaries, beaches along some 80 km of the coast of Andaman Sea (Fig. 1), varying in natural conditions (morphology, vegetation) and human activity (agriculture, fishery, tourism) to document a complete case history of the tsunami effects.

The main objectives of the paper are to present environmental and geological impacts of the tsunami on the coastal zone of Thailand in both short- and long-term periods. Particular attention is given to:
- tsunami wave runup and inundation limits and their relations to nearshore bathymetry and coastal morphology,
- coastal erosion due to tsunami,
- tsunami deposits and associated contaminants,
- damages in coastal vegetation and impact on coastal ecosystems (exemplified by beach meiofauna),
- changes in coastal vegetation cover,
- preservation potential of tsunami record in geological sequences as a link to assessment of tsunami hazard.

Methods

The post–tsunami field surveys took place in two periods: 03.02. - 20.02.2005 and 29.01 – 08.02.2006. Both surveys were conducted on the western coast of Phuket Island (around Patong Bay) and along the Andaman coast between Khao Lak and the northern tip of Kho Khao Island (Fig. 1). During the second survey, besides revisiting the same locations as before, also offshore survey off Nham Khem and Kho Khao Island was made. The survey on land was conducted in transects perpendicular to the shoreline.

The basic survey followed recommendations of the Intergovernmental Oceanographic Commission [46] and included compilations of data, geodetic measurements, observations of damage, erosion, deposition, flow directions, sampling tsunami deposits, measurements of water properties, audiovisual recording and interviews to eyewitnesses. Additionally, sampling for assessment of contamination and the state of beach meiofauna assemblages, paleotsunami record pilot search and offshore survey including echosounder profiling and sediment sampling were conducted.

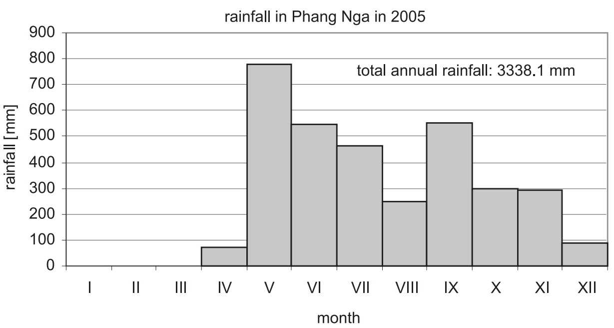

Fig. 4. Monthly precipitation for 2005 from Phang Nga meteorological station.

The geodetic survey was performed with differential GPS (DGPS) system of Leica GPS SYSTEM 500, type SR 530 using differential VHF ground control. The three-dimensional accuracy was in the range of 0.01-0.03 m. The data were used for documentation of post-tsunami coastline morphology and in particular for determination of the tsunami wave maximum runup and inundation. The maximum runup is the difference between the elevation of the maximum tsunami penetration and the elevation of the shoreline at the time of the tsunami attack (i.e. corrected for the difference in shoreline elevation between the time of measurement and the time of the tsunami attack). Inundation is the maximum horizontal penetration, or intrusion, of the tsunami from the shoreline. The 26 December tsunami arrived at the studied coast of Thailand at approximately high tide. Throughout the surveyed region normal tidal range is between about 2.7–2.9 m. Using local tide tables, runup measurements were corrected by noting the date and time of day of the field measurements, and correcting to the tide level at the estimated time of arrival of the tsunami. Due to possible errors in field measurement (the survey was conducted more than one month after the tsunami), in estimation of water level at the time of survey, of the time of the tsunami arrival, and in use of tide tables, the error in the corrected measurements is probably at least ±30 cm, and in some cases greater. A hand-held Garmin Global Positioning System (GPS) was additionally used for locating sampling locations in areas not covered by the DGPS survey. During offshore survey the positioning and bathymetry were obtained by a GPS Map Sounder by Garmin associated with an echosounder using the frequency of 200 KHz. Sampling and description of waters, sediments and biota followed standard methods and are described in detail in analytical works based on the collected material [19, 41, 43]. Samples of tsunami deposits, underlying sediments, modern beach deposits and of possible paleotsunami and associated layers were collected using plastic tools. The samples of marine sediments were taken with sediment grab sampler from a small boat. The surface waters and waters in wells in the investigated areas were examined in the field using a conductivity-meter CC-101 IP 67 by Elmetron to determine the degree to which they were contaminated with salt.

Tsunami Runup and Inundation in Relation to Coastal Morphology

Direct impact of the tsunami on the coastal zone was limited in distance and elevation. Since the coastal zone represents variable relief types, from steep rocky shorelines to wide flat terrain the effects of the impact varied. In some regions (Kho Khao Island, and neighbourhoods of villages Nam Khem, Bang Sak and Bang Mor) the coastal morphology had been altered by human activ-

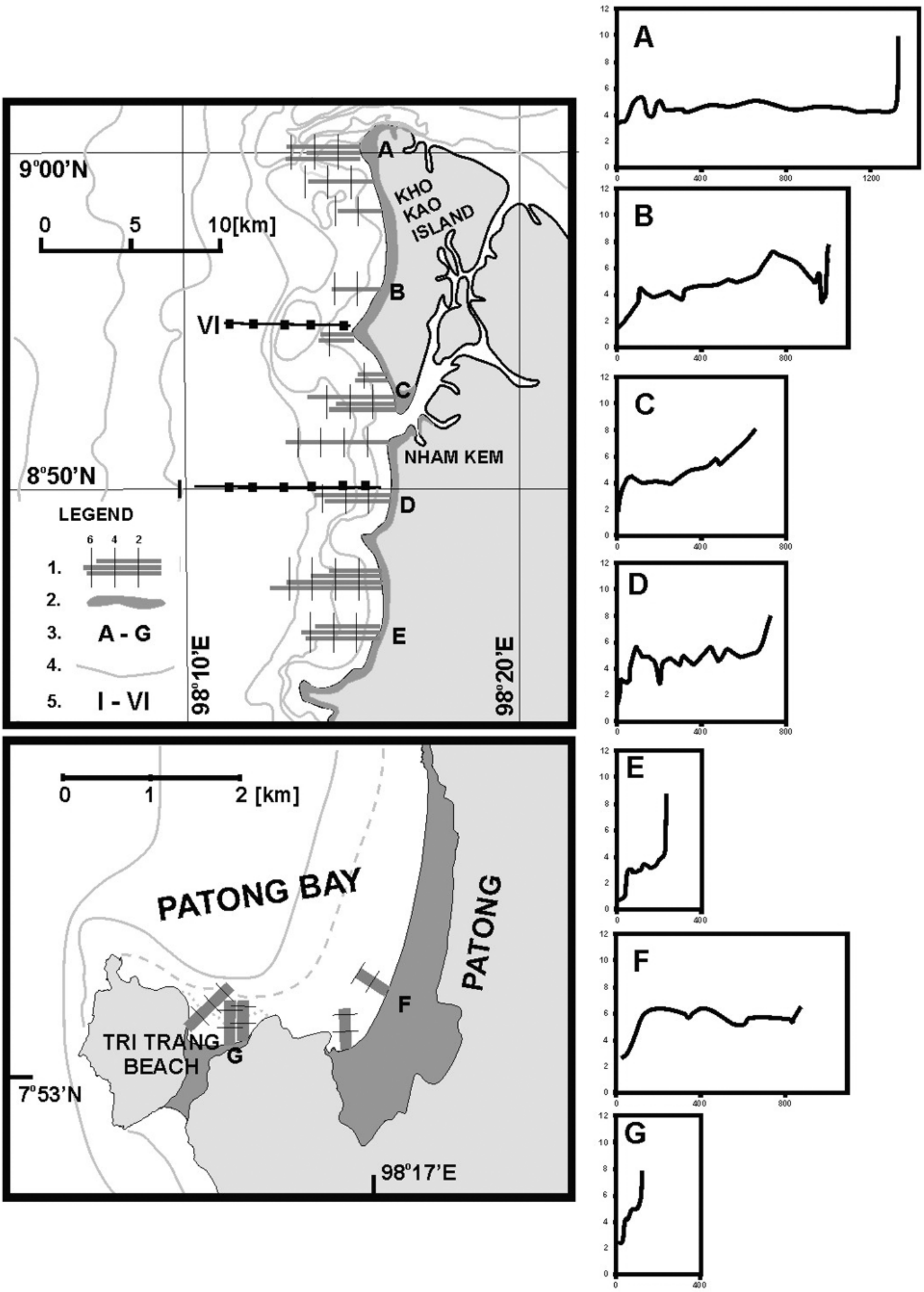

Fig. 5. Overview of the tsunami runup heights and inundation limits. Examples of prevalent morphology of the flooded coastal zone are included in form of morphological profiles perpendicular to the shoreline. Legend: 1) the length of horizontal bars represent the tsunami runup height in m above sea level; 2) tsunami inundated coastal zone; 3) locations of the presented morphological profiles (vertical axis – height in [m] above mean sea level, horizontal axis – distance in [m] from the shoreline inland); 4) water depth contours (every 10 m); 5) offshore survey transects shown on Fig. 8, dots represent sediment sampling locations.

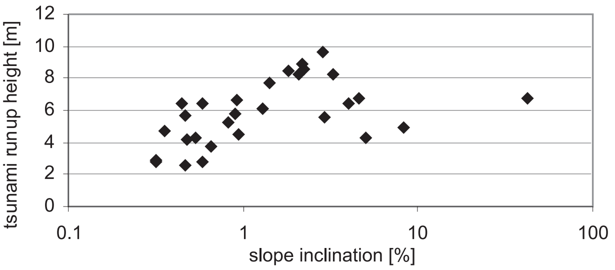

Fig.6. Relationship between the coastal zone slope inclination and the runup height. Note the logarithmic horizontal scale.

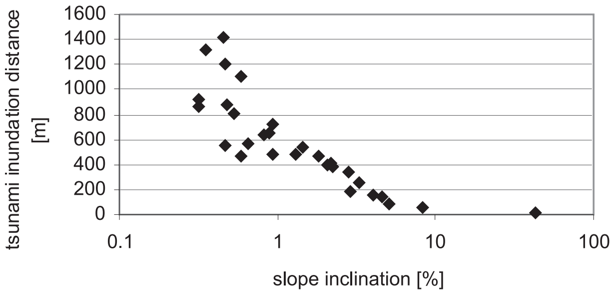

Fig.7. Relationship between the coastal zone slope inclination and the tsunami inundation distance. Note the logarithmic horizontal scale.

ity. Due to open cast mining many depressions were left, which served as basins where salt water could stay for a long time and create potential long-term threats for contamination of ground waters (see morphological profiles on Fig. 5).

The runup heights measured on the southern coast of Patong Bay (Phuket Island) were in the range of 2 m in river valley up to 6.7 m on steep rocky coast. On average the runup in Patong town was about 3 m and on southern shore of Patong Bay about 4.5 m. The inundation distance was variable – depending on local morphology and in general was 340 –560 meters. Along the coastline between Khao Lak and the northern tip of Kho Khao Island, the runup values were in general in the range of 2.5 to 10 m, and the inundation varied from 200 m to more than 1.5 km (Fig. 5). Some areas, for instance the southern part of Kho Khao Island, were completely flooded. The runup heights documented by other surveys [4, 7, 21] are in similar ranges.

Although the slope inclination of the coastal zone is not the only factor influencing the runup height or inundation distance, some relationships between them are observed. The maximum runup heights were documented for locations with the slope inclination ranging from 1.5 to 3% (Fig. 6). The inundation was the greatest at the gentlest slopes (Fig. 7). If the slope inclination was greater than 5%, the inundation did not reach 100 m. The tsunami wave was also affected by the offshore bathymetry. However, the latter is not yet well documented. A pilot survey was conducted in February 2006 in six transects to document bathymetry in front of open coast, estuary and partly sheltered coast in relation to the results of the tsunami inundation mapped on land (Fig. 8). All the profiles showed a depth of more than 20 m at a distance of 12 km from the shoreline. At that depth, the undulation of the seafloor up to 3 m in amplitude was observed, it was probably caused by former mining activity or was formed as sand waves related to alongshore sediment transport. In general all the surveyed transects are characterized by gentle and uniform morphology (e.g. I on Fig. 8), except transects which revealed the presence of a shallow or a reef – at about 4 to 5 km offshore (e.g. VI on Fig.8). From the seaside the reef had a steep slope. A comparison of the bathymetrical profiles with the data on the tsunami wave runup has shown a direct correlation. At the locations with the offshore reef the tsunami runup height was only 2.5 m. Landward from the remaining transects the runup was up to 6.5 m. It shows that the nearshore bathymetry may be significant in controlling a tsunami wave impact. It is important to note that the overall shelf bathym-

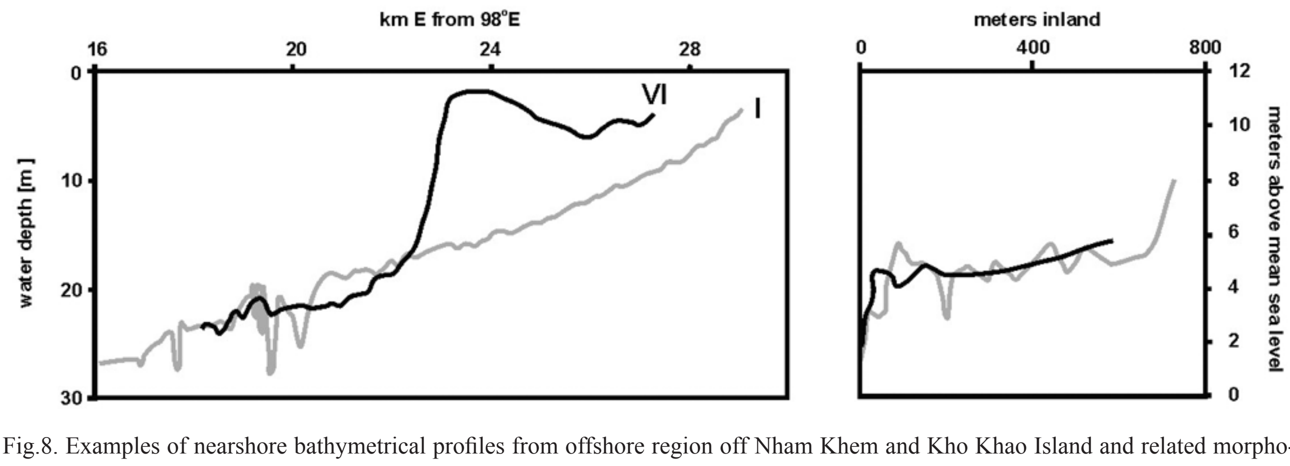

Fig.8. Examples of nearshore bathymetrical profiles from offshore region off Nham Khem and Kho Khao Island and related morphological profiles of the inundated coastal zone. For location of profiles I and VI see Fig. 5. Profile I represents typical nearshore bathymetry and profile VI includes a coral reef with steep wall from the seaside. The tsunami wave runup on the land behind the reef is much smaller than in the case of profile I. The examples clearly suggest that nearshore bathymetry is a very important factor restricting the tsunami wave runup.

etry except the nearshore zone is similar for both cases, as shown on the available marine charts and in the offshore survey by Intasen [48].

In a recent paper on the impact of the tsunami on the structures in Thailand and Sumatra, Ghobarah et al. [9] concluded that the high tsunami runup in Khao Lak occurred "because the beach is surrounded by elevated grounds and hills." Such an explanation is not proved by the results of our study. In Khao Lak, the steepness of the coastal zone is variable – in many places a flat coastal plain is in direct neighbourhood of the beach and the runup height was also high. On the other hand, in other places (e.g. Patong Bay) with steep coasts the runup heights were much smaller. Moreover, as shown in Fig. 6, there is not direct correlation between the slope inclination of the inundated coastal zone and the tsunami runup height. In some reports documenting the recent tsunami runup height (and inundation) the variation in continental shelf width was suggested as their major controls [e.g. 15, 47]. For a part of the coast of India, Jayakumar et al. [9] have found that tsunami runup height was not dependent on the continental shelf width but they tried to explain the runup heights by 200 m water depth contour shape (concave or convex). However, as shown by the example in the Fig. 8, the nearshore shallows and reefs may be much more significant for deterioration of tsunami wave height than previously suggested. A protective role may also be played by coastal dunes. In Thailand it was exemplified by Karon Beach (south of Patong Beach), where damage was much less than on Patong Beach due to dunes along the beach. More examples of the protective roles of dunes during the recent tsunami were documented from Sri Lanka [14] and India [10].

Three waves flooded the coastal zone more or less perpendicular to the coastline. However, wave flow directions were modified to a large extent by local morphology, obstacles, differences in land surface morphology and coverage. The preserved water flow direction marks (Fig. 9) showed a complex pattern. In some places circular pattern of laid grass was observed, probably created by eddies formed during turbulent flow of the water. Due to specific morphological conditions (low gradient) the wave runup was much stronger than backwash.

Fig.9. Indication of water flow direction, dominant water flow was from left to right. Southern Kho Khao Island.

Tsunami Erosion and Damage

Direct impact of tsunami caused severe damage to the land structures and infrastructures (Fig. 10) – including environmental infrastructure, such as water and sanitation systems. The damages were assessed and investigated in detail by several groups [3, 4, 9, 20, 22]. Much less attention was given to erosion and deposit brought by the wave. The erosion was focused in some localities like caps (e.g. Laem Pakarang), river mouths (Fig. 11), tidal inlets and in the nearshore and beach zone. As exemplified by the results of a field survey and satellite pictures [49], in some cases the eroded belt of coastline reached several tens of meters – significantly exceeding longterm erosion rates [50]. Usually erosion was limited to beaches and small cliffs behind them. Fresh scarping of the vegetated coastline ridge was documented in many places; it typically exposed tree roots and destabilized them (Fig. 12). Erosion was associated with both: the onshore flow as well as with the backwash. The latter was weaker but in some places, where the flow was canalized, it created erosional niches and scour depressions. Damage was found up to the maximum inundation of the wave. However, although the tsunami had completely destroyed houses and other buildings, soil erosion was seldom observed – probably partly due to vegetation cover and dry season. Because of the dry season the local soil was dried and hard, as a consequence, more resistant to erosion. The submarine erosion was directly documented on coral reefs [6, 23], and indirectly by large amount of marine sands deposited on land by the wave. Macroscopic comparison of the nearshore sediments and the tsunami deposits on land implies that the latter might be eroded and transported onshore from water depths down to 20 m b.s.l.

Tsunami Deposits – Distribution and Major Features

Sedimentary deposits from the tsunami were found in most places where the flooding occurred. Because no

Fig. 10. Tsunami-damaged bridge in Ban Bang Sak II.

rainfall occurred between the tsunami and the first survey, the observed distribution and characteristics of the deposits may be treated as effected exclusively from the tsunami. Their thickness varied, however, a general decreasing trend with the distance from the shoreline was statistically significant (Fig. 13). In the zone of up to 50 m from the shoreline often no tsunami deposits were preserved. This zone was frequently dominated by erosion. The thickness of tsunami deposits is affected by the distance from the shoreline, local topography, plant cover, obstacles, availability of material for transport etc. (Fig. 11). The average thickness was about 8 cm (on the basis of 98 measurements in 13 transects) and the maximum reached 52 cm. Because of such a blanket of tsunami deposits many plants and former soils were buried. The deposition took place mostly by onshore flow of the first and the second wave - usually effecting in two upward fining sequence starting with coarse sands to fine sands in the upper part (Fig. 14). The third wave left a much thinner layer, in some profiles it was missing. Occasionally at the base of the tsunami deposits layer coarsening upward thin layer was found, which may be a diagnostic feature of shear carpets caused by intense shearing action of a hyperconcentrated flow [51]. The deposits have also formed massive sand or densely laminated layer. An important argument for sedimentation during the tsunami onshore flow is documented by a sequence of the tsunami deposits from the southern Kho Khao Island, the area which was overflown so no backwash occurred.

The tsunami deposits are composed mostly from sand (coarse to fine sand) and silty sand of marine origin. The latter is documented by common shell fragments, marine diatoms (Kokociński, personal communication) and an appearance similar to that of the sediments found during offshore survey in nearshore zone down to 20 m b.s.l. The type of sediments deposited by tsunami depends primarily on their sources. Although the transportation potential of tsunami wave in terms of the maximum grain size is enormous it is often limited by sediments locally available for erosion. So the grain size is usually coarse to medium sand with fine sand to silty sand in more distant locations. The tsunami was capable of transporting large material over considerable distances inland, such as concrete from coastal buildings or coral boulders up to 2 m in diameter. Big mud clasts ripped up from the former deposits were also found in the tsunami sedimentary sequence. The coexistence of large boulders and pebbles with fine and medium sand suggests that in some places the mecha-

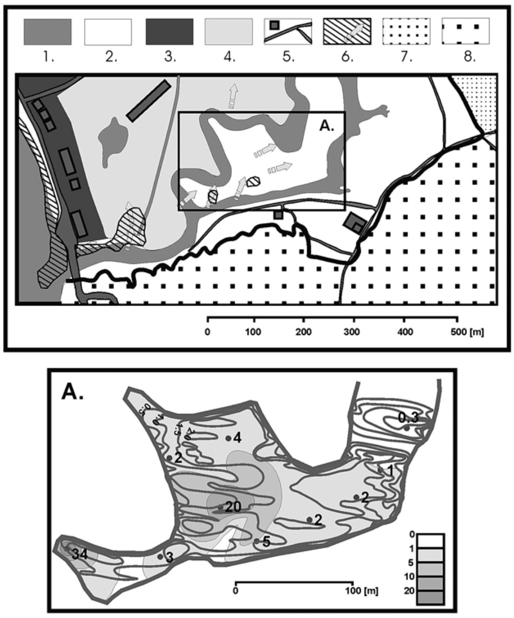

Fig. 11. River-mouth area in the southern part of Patong Town, Phuket Province. The figure is based on own DGPS survey, field measurements of tsunami erosion and deposition, and IKONOS satellite images analysis [46]. Legend: 1 – water, 2 - inundated area with no trees (beach or low vegetation area), 3 - inundated urban area, 4 - inundated coconut palm forest, 5 - buildings and roads, 6 – areas of tsunami erosion and directions of tsunami water flow, 7 – non-inundated areas without trees, 8 – non-inundated forests. On insert (A) a detail topography (contours each 0.5 m above the current water level) and thickness of tsunami sediments in cm (labelled dots and grayscale background) are presented.

nism of transportation was a high-density liquid turbulent flow. The initial optically stimulated luminescence (OSL) dating of the tsunami deposits from the area studied presented by Bishop et al. [52] showed that the deposits were not completely subjected to zeroing of the luminescence signal during the transport and deposition. It may be partly due to turbulent flow of waters with high suspended matter concentration. Overview of some of the tsunami sediment properties are listed in Table 1. The sediment properties observed in Thailand are similar to those of the sandy tsunami deposits observed worldwide [36, 53, 54].

During offshore survey it was found that marine sediments were also altered by the tsunami. It was exemplified by polymodal sediment grain size distribution, with domination of sand or mud and minor fraction of stones and corals pieces even up to several cm in diameter. It is suggested that the latter could be moved from shallows and reefs to deeper waters by tsunami wave backwash.

Tsunami Deposits – Contamination

Although, in the last decade a number of data based on surveys made shortly after the tsunami have been published [e.g. 3, 11, 14, 55-60], we have not come across any earlier report on contaminants in the tsunami deposits except for information on the salt contamination (usually not determined in an analytical way). Probably the first are the reports based on studies in the coastal zone of Thailand after the 24 December 2004 tsunami [19, 43]. These works were concentrated on mobile components of the tsunami deposits which are supposed to be a potential

Fig. 12. Fresh erosion of the vegetated coastline ridge with typically exposed tree roots destabilizing trees.

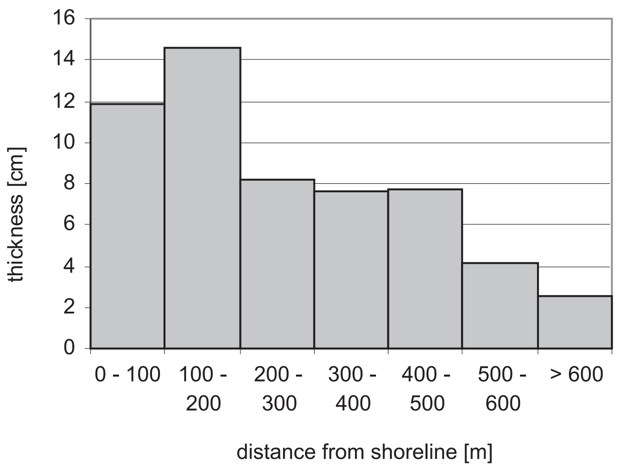

Fig. 13. Changes in tsunami deposits thickness in relation to distance from the shoreline. Diagram based on 98 measurements in 13 transects. The results were clustered in 100 m wide zones.

danger for environment and human health. Because no rainfall occurred between the tsunami and the sampling, it was possible to assess the input of the bioavailable amounts of salts, heavy metals and metalloids in forms associated with tsunami deposits. The sampling locations (behind Tri Trang beach, Patong town, coastal zone close to Bang Mor, Nham Khem village and out of tsunami-inundated on Kho Khao Island as a reference) were selected to combine "natural sites" and places where human activity could cause additional effects in form of direct pollution or via tsunami damage of waste disposal sites, petrol stations etc.

The tsunami sediments were studied [19] for bioavailable metals because their migration from polluted soils to plants is of the greatest concern [61]. It was found that the tsunami deposits contained significantly elevated amounts of cations and anions (Na, K, Ca, Mg, Cl, SO_4) in water-soluble fraction, and of Cd, Cu, Zn, Pb, and As in bioavailable fraction, relative to their contents in the reference sample. The origin of these contaminants is probably complex. Major ions in the water soluble fraction of sediments (K, Na, Ca, Mg, Cl and SO_4) were found to be highly correlated to each other and were delivered in dissolved form with seawater. Heavy metals (Cu, Pb, Zn) were also correlated to the salt content and probably were tied to them in the sediments. However, their source is rather litho – or anthropogenic. Arsenic had

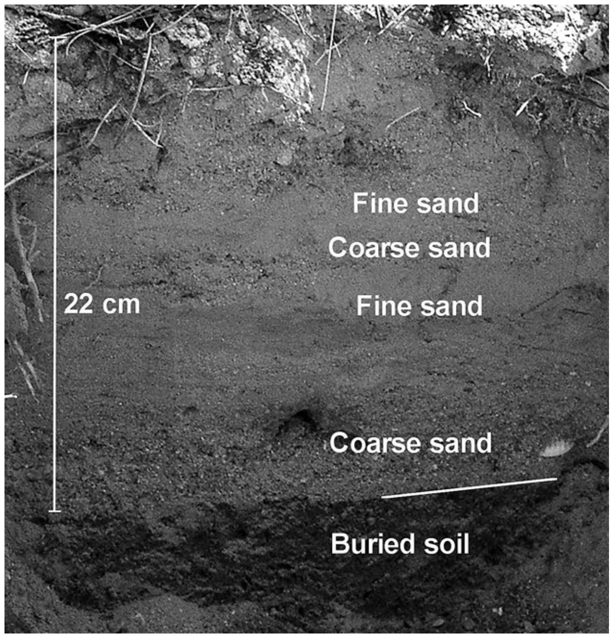

Fig. 14. The tsunami deposit layer overlying buried soil. The deposit is normally graded with coarse sand near the base and fine sand toward the top. Two upward fining sequences are visible, the third sequence is disturbed at the top. Bang Ban Sak I, February 2005.

Table 1. Selected diagnostic characteristics of tsunami deposits documented in the coastal zone of Thailand. Partly after [19].

Sediment property	Description
Grain size	Mostly sands but fractions from boulders to mud were observed. Upward fining sequences starting with coarse grained sand and capped with fine sand or silty sand are the most common. Many man made pieces of structures are often incorporated in the deposits.
Mineral composition	Depending on local source of sediment; in most cases tsunami deposits origin from beach and nearshore sediments and they are dominated by quartz, carbonates (shell fragments) and heavy minerals.
Fossils	Common marine shells (or their fragments), pieces of coral (sometimes bigger than 50 cm), some marine diatoms but also parts of terrestrial plants. Shell-rich units are present.
Spatial distribution	Variable; they can be found in the whole inundated zone. On the beach they are usually difficult to recognize or were not deposited at all (source area). In general, the sediments are finer and more thin inland.
Thickness	Up to 52 cm; 8 cm on average.
Structures	The tsunami deposits may be massive or layered. In many cases there are two or three sequences of fining upwards deposits. The contacts between sequences are sharp or erosional. Intraclasts and mud balls were observed.
Relation to underlying horizon	Mostly sharp but only occasionally erosional; Often underlined by buried soil horizon and in situ vascular plants.
Geochemistry	High salt content; high content of some heavy metals in bioavailable fraction

elevated concentrations in restricted areas - related to mining activity, and was probably of lithogenic origin. It was concluded [19] that the bioavailable metals and metalloids may reach toxic levels in the food chain. The risk was particularly high in areas of human-made land depressions left after mining activity, filled for longer period of time with salty water after the tsunami. Mercury, which is of particular interest because of its high toxicity, the stability of its chemical species and its ability for bioaccumulation was analysed in the same samples for its bioavailability, transformations and migration by Boszke et al. [43]. Sequential extraction method involving five subsequent stages performed with solutions of chloroform, deionized water, 0.5 M HCl, 0.2 M NaOH, and aqua regia was applied in that study. It was found that in the tsunami sediments from Thailand, mercury occurred mainly in the form of mercury sulphide, hardly soluble and hardly bioavailable. Concentration of organomercury fraction in the samples studied was low. However, this fraction could pose a real threat to people and other living organisms because of their extreme toxicity and capability of bioaccumulation and biomagnification in the trophic chains. Though the total mercury content is similar in the tsunami sediments and in the reference sample studied, the highly mobile organomercury fraction contribution is higher in the tsunami sediments.

The above described studies [19, 43] were conducted on samples collected within 50 days after the tsunami. In that period no rainfall occurred. However, later during the rainy season the total precipitation was 3338 mm (Fig.4). The rain could wash the sediments and remove the contaminants to subsoil, groundwater or even to the sea. Since elevated contents of arsenic were documented in ground waters (Chaimanee – personal communication, also in other countries [3, 25]) it was important to find if the tsunami sediments are still potentially dangerous as a source of bioavailable metals and salts to ground waters and plants. The initial results of analysis of the samples collected one year later from exactly the same locations as in February 2005 showed that the amounts of cations and anions (Na, K, Ca, Mg, Cl, SO_4) in the water-soluble fraction were significantly reduced. Also relatively high amounts of heavy metals observed previously in tsunami deposits were smaller. However, their distribution in the soil profile was uneven. Further studies are initiated to understand cyclic changes of heavy metals and metalloids in coastal zone, because the effects of the saltwater inundation are expected not only in relation to tsunami but also to saline water floodings of coastal areas due to other natural hazards, for example as a result of the hurricanes or storms [e.g. 62].

Tsunami Deposits – Preservation Potential and Tsunami Hazard Assessment

During the survey in 2006 most of the locations investigated during the previous study were revisited. This of-

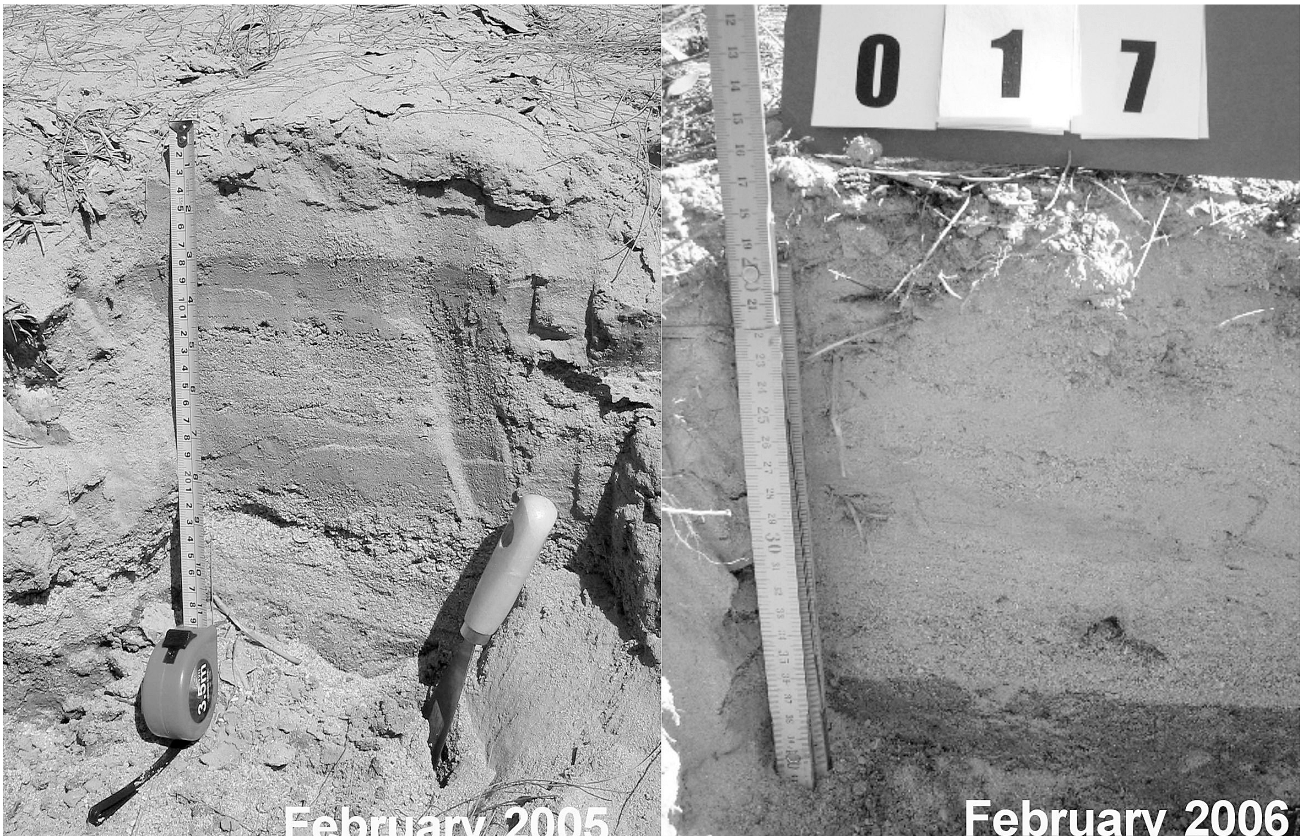

Fig.15. Over 20 cm thick layer of tsunami sediments composed of three upward fining sequences observed shortly after the tsunami (February 2005) and over one year later (February 2006). The sedimentary record is well preserved. Locations: Ban Bang Sak I.

fered a possibility of assessment of tsunami deposit preservation potential in the coastal zone of Thailand. Most of the investigated part of the coastal zone is in the form of open coast beach, estuary or mangroves. In general, except places where man-made changes took place (cleaning, earth works etc.) or where the tsunami sediment layer was very thin (less than 1 cm), the sedimentary record of the last tsunami was well preserved in the coastal plain sedimentary sequence (Fig. 15) despite heavy rainfalls in the period prior to the survey. Usually only the uppermost portion (about 1 cm) was altered, due to rainfalls and growing plants (e.g. Fig. 14). However, at the locations where some sedimentary bedforms were observed on the sediment surface (e.g. in Bang Mor) the elevations (e.g. ripples) were washed and small depressions (e.g. hollows due to eddies) were filled with surrounding sediments. It is concluded that at least several cm thick sequence may be preserved in geological record of sandy coastal plain. Even if some diagnostic features would be masked by new soil development, the presence of buried soil and characteristics of overlying sediments should enable identification of the tsunami genesis. The preservation of a tsunami layer in mangrove setting is minimal due to a reduced power of tsunami transportation in that setting and very high rate of post depositional mixing.

The coastal plain is not a typical setting for preserving tsunami records in sediments. Paleotsunami sediments are best preserved in lakes, lagoons or marsh deposits [e.g. 32, 34, 36, 39, 63-66]. However, such settings are generally absent along the Andaman coast of Thailand. Since the tsunami of December 2004 was the first wave of such a magnitude in this region over human written history, it is important to document any geological record of earlier events. They may then be used to help assess a tsunami hazard - for example to determine recurrence period and potential area of inundation [37, 40]. In some cases this record may be the only evidence that a region may be at risk from a tsunami. Where more than one tsunami deposit is preserved in a stratigraphic sequence, the record may help determine how often a tsunami is likely to occur. However, on the Andaman coast of Thailand it may be very difficult. First of all, probably only a very large tsunami may create a sediment layer thick enough to be preserved in geological record. Secondly, sea level is not stable and marine deposits on land may not be evidence of tsunami but of higher sea level. It may be particularly difficult to distinguish the effects of mid-Holocene sea level high stand of 3-4 m a.s.l. from about 5,000 to 4,500 years BP [67, 68] from any tsunami event. Until now there is no unquestionable paleotsunami record in that region. It forced researchers to look for alternative ways of predicting a tsunami recurrence period. Karlsrud et al. [69] estimated the tsunami hazard for the Andaman coast of Thailand on the basis of earthquake statistics and plate tectonics and concluded that accumulation of the energy released during the December 2004 earthquake would take at least 300 to 400 years. They estimated that within the next 50–100 years a tsunami with runup height of 1.5 to 2 m is possible; such an event would cause significantly less destruction than the recent tsunami.

Tsunami Impact on Surface and Ground Waters

Inland surface and ground waters were salinated by the tsunami in the inundated zone. As reported from a number of sources [e.g. 3, 25] shallow wells and groundwater supplies were contaminated with salt water – particularly on small islands. In some cases, faecal bacteria from damaged or destroyed septic tanks and pit toilets infiltrated water supply systems. In Phang Nga Province (Fig. 1) nearly 190 out of 530 wells were unsafe due to sewage-related contamination [3]. Contamination by other compounds, for example by the above-mentioned arsenic, was also documented [3, 25]. Short duration of the flooding was likely to have caused negligible infiltration of saline water into groundwater. However, water that remained in pools, lakes or depressions after the tsunami, could lead to saline infiltration impacting ground water. Such local land lowerings are common in the studied area (see morphological profiles in Fig. 5) and are mainly remnants of former open cast mining, which was not subjected to recultivation. In the longer term, salinization of groundwater might occur by deposited salts leaching from unsaturated zones (tsunami deposits) into groundwater.

During the survey conducted one month after the tsunami, water conductivity was measured in standing, flowing and ground waters in the area inundated by the tsunami wave [19]. Measurements were limited by the detection ability of the instrument used (between 0 and 19.99 mS cm^{-1}). In all cases water conductivity was much higher than in typical freshwater. Ground waters measured in wells on tsunami inundated peninsula on the southern side of Patong Bay had a conductivity of 0.8 mS cm^{-1}. The conductivity of flowing waters was measured in five small creeks (with maximum water discharge about 10 dm^3 s^{-1}) along the coast. The values ranged from 1.31 (in stream with the greatest water discharge) to 15.20 mS cm^1. The highest conductivity values were documented from a dozen ponds and lakelets in the coastal zone. The lowest value was 6.2 mS cm^{-1} but in most of these standing water bodies conductivity was out of the scale of the instrument (>19.99 mS cm^{-1}). After the rainy season surface water conductivity was much lower, however, detailed data are not yet available.

Changes in Coastal Ecosystems after Tsunami

The tsunami also impacted the coastal ecosystems and, as a consequence, local economies. The affected coastline in Thailand consists largely of sediment habitats (sea grass beds, mangroves and sandy beaches), whose productivity underpins inshore fisheries and coral reefs, which are the main sources of direct income from tourism. Because of the importance of coastal ecosystems for local communities their changes due to the tsunami were investigated in Thailand and around the Indian Ocean by numerous researchers [e.g. 3, 6, 8, 12, 23, 26, 41, 70-73]. Below, some of their findings and our own results for the coast of Thailand are summarized.

Coral reefs on the Andaman coast of Thailand were in 13% severely damaged and in 60% were very little or undamaged [71]. The most affected were shallow water reefs. The impact was site-specific and included mud and sand sedimentation, partial damage by debris swept away from land by backwash, and dislocation or removal of coral heads [3]. Natural recovery of the reefs is likely over the next 5–10 years [23]. It is important to note that the reefs also played a protective role for the coastlines (Fig. 8).

Sea grass beds along the coast of Thailand cover an area of almost 8,000 hectares and are important for fishery production and coast stability. About 3.5% of them were impacted by silatation and sand sedimentation, and 1.5% suffered complete habitat loss [3]. In many places sea grass beds appeared to have mitigated coastal erosion in the inter-tidal zone [3].

Mangroves were impacted in less than 0.2% of their area [3]. Within the radius of 20 meters from the coastline the mangrove trees were destroyed. Their small amount of damage is due partly to mangrove structure, and partly because they naturally occupy less energetic, protected environment. Mangrove forests helped stabilize coastlines and through reduction of wave energy protected land behind. The mangroves also protected reefs from terrestrial sediments which were trapped. The visited locations on naturally protected east coast of Kho Khao Island covered with mangrove forests showed almost no tsunami damage.

Long open beaches belong to the coastal ecosystems that suffered the main tsunami impacts. Yet even here the effects are not uniform, presumably dependent on the nearshore bathymetry. In general, most of the beaches were significantly eroded (e.g. Fig. 12). However, many of them were subjected to intensive natural beach accretion after the tsunami [41] (Fig. 16). Comparison of pre- and post-tsunami beach sediments [12] revealed an increase in the coarse fractions, often with increased shell debris and distinct layering. In February 2005 slightly impacted beaches on Phuket Island and almost completely eroded on Kho Khao Island were studied by Kotwicki and Szczuciński [41] for their sediments and meiofauna assemblages. Altogether at 10 sampling locations, 11 major meiofaunal taxa were recorded in the investigated area. Nematoda and Turbellaria were present at all the stations while Harpacticoida, Polychaeta and Copepoda nauplii were less frequent - present only in 8 and 6 correspondingly. Ostracoda, Tardigrada and Oligochaeta were found on 5, 3 and 2 sampling sites, respectively. Bivalvia, Gastrotricha and Chironomidae larvae were noted only at one sampling location. It appeared that the investigated sandy beaches were fully functional ecosystems 50 days after the tsunami in terms of meiofaunal communities. This indicates that they recovered very fast after the tsunami, or were only slightly impacted by the wave. During the survey in 2006 the sampling was repeated to assess long-term trends. The fast recovery of beach ecosystems in Thailand was also documented by Kendall et al. [12]. Four months after the main impact, the common faunal elements were returning and the main zonation patterns have re-established themselves. Studies on the beach meiofauna in India [73] showed that a recovery to the pre-tsunami state may occur shortly (few days) after the tsunami impact.

Terrestrial Vegetation Cover Changes after Tsunami

Terrestrial vegetation suffered from the tsunami in several ways. First of all due to direct impact of the wave many trees in coastal zone were broken (Fig.16), their roots were exposed by erosion (Fig. 12) or the whole trunks were completely removed. Secondly, due to a com-

Fig. 16. The tsunami caused significant beach erosion (left photo), which was followed by beach progradation (right photo). Northern coast of Kho Khao Island in February 2005 and February 2006.

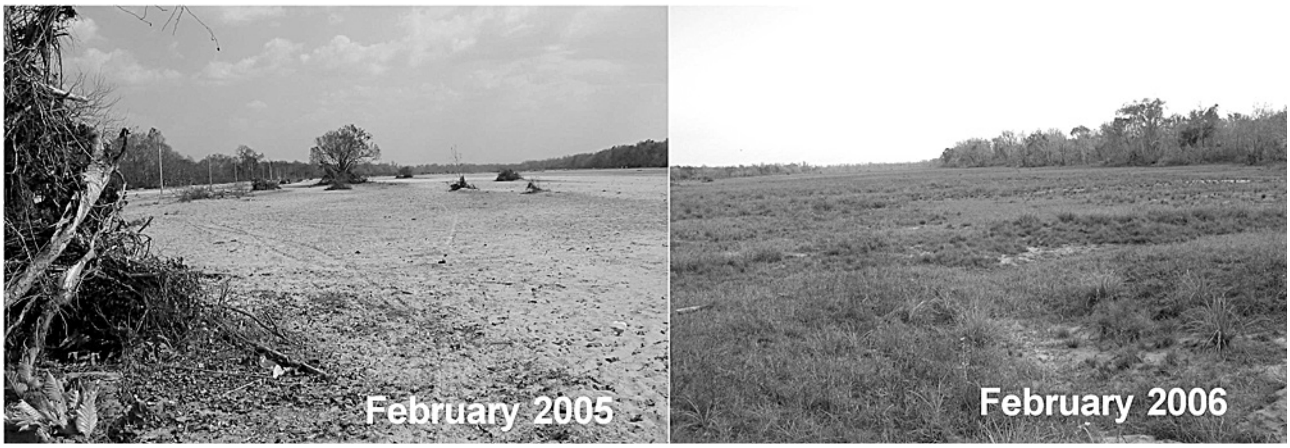

Fig. 17. One month after the tsunami many lowland areas in the coastal zone of Thailand were still covered by tsunami sediment layer and were lacking vegetation due to salt water impact and long-lasting draught. One year later most of those areas were reclaimed by vegetation. Exemplary view from northern Kho Khao Island.

bined effect of saltwater inundation and covering with a layer of sediments, most of the vascular plants in the inundation zone withered and/or were buried in tsunami deposits. The disaster was magnified by a several month long drought (Fig. 4). It had obvious impact on local communities because of pasture loss. However, as observed one year later along the coastal zone, most of the vascular plants reoccupied the previous areas (Figs. 2 and 17). Many trees withered but the new plants reached in some places a height of 2 meters. In general, coconut trees and pines, if not broken by direct tsunami impact, were also well preserved.

Overview of Some Short-Term and Long-Term Tsunami Impacts

Table 2 presents a list of selected environmental and geological tsunami impacts classified in relation to the duration of the effects (short- or long-term). The short-term effects are those that were significantly reduced by the first rainy season. The long-term effects are still noticeable one year after the tsunami.

Most of the changes must be analyzed and their real impact estimated in context of long-term coastal evolution [50, 74, 75] of this region and continual ecosystems

Table 2. Selected short- and long-term environmental and geological effects of the tsunami in the coastal zone of Thailand.

	Short-term	**Long-term**
Tsunami runup	Flooding of terrestrial ecosystems; filling depressions with saltwater; transport of sediments and debris onshore and offshore	Only indirect effects
Tsunami erosion	Beach and intertidal zone erosion	Channels, peninsulas and river mouth erosion; coastal erosion partly masked by beach accretion; however, sometimes the erosion is continuing
Tsunami damage	Broken trees, damaged infrastructure (also waste disposal sites, fuel station, etc.)	Damaged coastal forests; damage to buildings and infrastructure (if not rebuilt)
Tsunami deposits	Damage to terrestrial vegetation and burial of soil horizon. Sedimentation on sea grass beds	Changes of soil properties – new initial soil is developing on sand deposits; deposition of coarse sediments in nearshore zone; aggradations of coastal zone by several cm and forming geological record of the tsunami
Tsunami deposits and soil contamination	Contamination with salt and bioavailable heavy metals and arsenic	Leaching of contaminants to ground waters
Water contamination	Salination of all the surface and ground waters in inundated zone	Local ground water pollution due to migration of contaminated waters and successive leaching of compounds contained in tsunami deposits
Coastal ecosystems	Beach erosion and disturbance of beach fauna communities; siltation of sea grass beds	Damage to coral reefs; local loss of mangroves
Terrestrial vegetation	Broken trees and branches near shoreline; vascular plants covered with tsunami deposits and flooded with saltwater; significant loss of lower plants in the inundated zone	Loss of broken trees; some trees withered; coverage of soil by several cm thick sand layer - new soil developing from initial state

change caused by changing environment and increasing anthropopressure. However, the pre tsunami data from the Andaman Sea coast is insufficient for reliable long-term assessment

Conclusions

The key findings of the surveys undertaken to assess environmental and geological effects of the 26 December 2004 tsunami in the coastal zone of Thailand are:

- The tsunami wave inundation and runup vary along the coast investigated, from tens of meters to more than 1.5 km for the first and from about 3 to more than 10 m for the second. They were strongly dependent on the morphology of the nearshore zone (presence of offshore reefs) and partly on coastal zone morphology – a correlation is found between the runup heights and the coastal zone inclination.
- As a result of earlier mining many depressions were left in the coastal zone, where salt water could stay for long time and created a potential long-term threat for contamination of ground waters.
- Tsunami-caused erosion is limited mostly to nearshore (down to 20 m b.s.l.), beaches, river mouths, peninsulas and channels. Soil erosion on land was relatively rare.
- Tsunami deposits covered almost the entire inundation zone and some parts of nearshore zone. They are composed mainly of coarse silt to medium sand fraction and contain many bigger pieces of rocks, corals etc. The thickness of the tsunami sediment layer on land depends on many local factors but generally decrease from about 30–40 cm close to shoreline to a few mm close to the inundation limit. The layer buried former soils.
- The tsunami sediment layer was well preserved after the rainy season (with more than 3,000 mm of rainfall) and its preservation potential may be greater than expected; good preservation of the tsunami sediment layer in coastal plain setting suggest a new direction in search for paleotsunami record in this region, which might help in establishing a better estimation of tsunami hazard.
- All the tsunami sediments were highly contaminated with salts and enriched in heavy metals and arsenic in bioavailable fraction. The presented reports of bioavailable contaminants in tsunami sediments from the Thailand coastal zone are probably the first published results on contaminants in tsunami deposits.
- The initial analysis suggests that the above-mentioned contaminants were partly remobilized during rainy season.
- All the surface and ground waters were still saline 50 days after the tsunami; surface waters were cleaned during the rainy season.
- One month and one year after the tsunami a natural accretion of tsunami-eroded beaches was observed.
- The most tsunami damaged coastal habitat – sandy beaches – recovered very fast after the tsunami event.
- Most of the land vegetation recovered one year after the tsunami.

In this study the direct and indirect effects to local societies are not addressed extensively because they cover a wide range from humanitarian, sociological, psychological to engineering and spatial planning aspects. The environmental issues are only related to some of them. However, they are also important and some conclusions from the study of the last tsunami environmental and geological effects may be useful in case of possible future tsunamis but also other natural hazards resulting in coastal flooding like storm surges, hurricanes, etc.

The 26 December 2004 tsunami in Thailand inundated a coastal zone of about 1 km and reached elevation of 10 m a.s.l. Although it was one of the world's worst natural disasters in decades, its geological effects were relatively small in comparison with those of the disasters known from the geological record [e.g. 33, 76]. Studies around the Indian Ocean have shown that the effects were significant locally but the overall erosion or deposition was usually in a range of magnitude met during seasonal storm events [e.g. 11, 12]. The effects varied a lot depending not only on the tsunami impact but also on shelf bathymetry, nearshore profiles, the presence of coral reefs, type of coastal habitats and vegetation (mangroves, coastal forests, open land), morphology of coastal zone, sediment character in nearshore zone, type of infrastructure and building and many others. Compilation of data from around the Indian Ocean may help establish some more rules, which may be tested by numerical and experimental models. Many effects were of short-term nature but some of them will last for several years or decades – for example the development of new soils on tsunami deposit layer. However, assessment of many long-term effects is often not possible because of insufficient knowledge on coastal environment (both physical and biological aspects) before the tsunami and on a long-term scale. So, future studies in the coastal zone are required for a better understanding of the sediment balance, material fluxes and coastal zone functioning with particular attention given to feedback effects between different components of the ecosystem and human activity.

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