Original Research

Geomorphology and Superficial Bottom Sediments of Khao Lak Coastal Area (SW Thailand)

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Abstract

Submerged and subaerial coastal morphology, nature and distribution of bottom sediments are among the key factors influencing the environmental impact by tsunami. Here we show our results of the post 2004 tsunami surveys in both offshore and nearshore zones. After the 26 December 2004 Indian Ocean tsunami, new bathymetric map and beach profile measurement along Khao Lak area, SW Thailand were made in 2006. Sedimentological analysis data of 144 bottom sediment samples together with many observation sites by scuba diving and the echosounder profiles were used for creating a detailed map of sediments and rocky bottoms in this area, with a basis scale of 1:30,000. Bottom morphology of the offshore bathymetry, sediment features and distribution patterns in relation to the nature of run-up heights are also discussed. As a result, bottom morphology shows the tsunami impact and run-up reflect the different nature of each contiguous coastal area, and explains how the coastal stretches that were eroded by the tsunami waves were almost fully restored by natural processes of sediment redistribution two years after the catastrophic event.

Keywords: 2004 Indian Ocean tsunami, Khao Lak, offshore morphology, offshore sediments, coastline change

Introduction

The 26 December 2004 catastrophic tsunami wave severely damaged the coastal environment and human communities in almost all countries around the Indian Ocean. Soon after the event, international solidarity started immediate assistance to people and analysis of the tsunami wave impact on the environment. Several pioneer reports and published papers on this extraordinary destruction wave aimed [1] to document the effects and to better understand the dynamic event, the cause and the factors that impacted coastal area. The tsunami death toll and numbers of injured in Thailand exceeded 8,500 [2] and in terms of geomorphological impact, Phang Nga province was the most severely damaged area.

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Many papers have been published to document such a tsunami field signature and describe the characteristics of tsunami deposits along the Thai coast [1, 3-9]. Other researchers attempted to model tsunami wave propagation and compare the model with the observed effects on the land [7, 10-12].

Three major components in the mathematical modelling of tsunami that were considered by those authors include:

1) the source;
2) sea bathymetry;
3) wave propagation and the run-up model.

But wave propagation and run-up models on a regional scale seemed likely to not fully satisfy a comparison with small local coastal areas. However, those publications provided the best key parameters that will be useful for coastal hazard mitigation in the future. Before the 2004 event, the inland topography and geomorphology of the coastal area of Thailand were well studied; in contrast, the marine bottom configurations were less known. The previous available bathymetry data are satisfactory only to model wave propagation in a regional scale starting from deep sea and on the most outer part of the continental shelf, but looked inappropriate for modeling localized bathymetry near the coast. In the last miles, west of the coastline, bathymetry and morphology changes are the main factors that strongly affect wave parameters and propagation. This is due to the fact that the sea level, as recorded by eyewitness personal video and photographs from Khao Lak, showed an initial withdrawal of sea water to about 6-7 metres deep (Fig. 1). Later on, the first and second front waves appeared when the wave crest overturned just a few miles from the coast. The front wave earlier propagated as an almost straight line, but later on changed direction near Khao Lak beach, owing to the articulated bottom morphology and lithology, with different measure rises and fragments (Fig. 1). A white foam crest became bigger and higher, and at last changed colour to brown owing to the high grain concentration as both traction and suspension sediments were pulled up from the bottom and entrained to the land. The evidence of run-up heights surveyed at Khao Lak area was between 4 and 20m, with the maximum observed at Ban Bang Sak [10, 13].

It is evident, then, that offshore bathymetry and morphology, and the characteristics of sediments and rocky bottoms of the coastal area in place where the tsunami crossing through in last marine mile are important factors to calculate more accuracy of run-up and wave energy values for tsunami hazard evaluation and mitigation. On the basis of these remarks and because the most detailed marine map previously available of the area was 1:60,000 scale [14], the construction of a detailed bathymetry and bottom sediment map of the Khao Lak area (1:30,000 scale) was the primary goal of our project. At the same time, coastal evolution after the tsunami was also studied.

Methods

Our post tsunami fieldwork was conducted in three periods, each lasting one week during February, April and December 2006, along the offshore area of the Andaman coast between Ban Thap Lamu and Ban Bang Sak, Khao Lak, Phang Nga Province (Fig. 2).

A local small boat was equipped with a Lowrance LCX-25C echosounder with GPS. The surveyed lines covered a total distance of 363km, with 64 shore normal transects approximately 350m apart, extended as far as 15m depth. Additionally, supplementary shore parallel transects were made covering a total distance of 55km.

For sedimentological study, 144 sea bottom samples (84 by means of a Van Veen grab and 60 hand corers by a scuba diver) were taken. The sediments, analyzed following standard methods, were described by gravel-sand-silt proportions [15] (Table 1). For a better interpretation of sea bottom topography, geomorphology and sediment distribution patterns, many scuba diving visual surveys, plus photograph and video documentation were performed.

All the data collected were used for the construction of a new 1:30,000 topographical and sedimentological map of the area [16] (Fig. 2).

Different satellite images taken from 2002 to 2006 were used to calculate areas of eroded shoreline, especially within the foreshore and beach zones. The Geographical Information System (GIS) was applied as a tool for more precise calculation of beach areas and helped in planning line surveys of beach measurements.

Detailed field investigation included measurement of beach profiles at four selected tidal channels where the 2004 Indian Ocean tsunami eroded extensive amounts of beach sediment and widened the channel mouth. Systematic collection in beach sediments along the survey lines from early 2005 to late 2006 were carried out [17, 18].

Morphology

At Ban Bang Niang bay, between Laem Pakarang and Laem Po, the open bay is the main coastal feature along this coastline. It also covers the small Khao Lak bay that partially protected by the Laem Ao Kham rocky peninsula, located south of Laem Hin Chang. On the Pakarang northern side, this area covers the southern half of Ban Bang Sak bay, closed to the north by Laem Hua Krang Noi. Khao Lak, a sandy coast, is generally affected by tsunami that ran up the opened small river mouths and tidal channels with

Fig. 1. Arrival of 26 December 2004 tsunami to the Khao Lak coast. Pictures from a eyewitness personal video at Laem Hin Chang. a) Withdrawal of the first depression wave at approximately 10:15 a.m. b) Just after the arrival of the first wave, approximately 10:22 a.m. 1) refracted wave from Laem Hin Chang northern side, 2) backwash from Ao Sam Poeng, 3) The front of first wave still not arrived to the Ban Bang Niang and Laem Pakarang coast, owing the bottom morphology and lithology.

Table 1. Granulometric composition of the sampling sites.

Samples	Gravel	Sand	Mud	Samples	Gravel	Sand	Mud	Samples	Gravel	Sand	Mud
1	0	98.93	1.07	**51**	0.89	20.68	78.43	**103**	11.4	86.97	1.63
3	1.42	88.75	9.83	**52**	21.06	77.36	1.57	**104**	0.09	96.71	3.2
4	3.85	94.15	2.01	**53**	18.46	80.87	0.67	**105**	0.06	16.06	83.87
5	28.95	71.05	0	**57**	35.4	60.95	3.65	**106**	0	42.23	57.77
6	19.21	77.12	3.67	**58**	23.69	71.21	5.1	**107**	10.24	88.43	1.33
7	28.39	71.45	0.16	**61**	0	80.54	19.46	**108**	37.04	60.55	2.42
8	28.47	59.24	12.28	**64**	4.77	25.4	69.83	**109**	16.13	80.67	3.2
9	0.44	60.61	38.95	**65**	10.99	87.99	1.01	**111**	52.34	45.05	2.6
10	8.26	87.02	4.72	**66**	21	77.62	1.38	**112**	21.05	76.86	2.09
11	0.12	99.75	0.12	**67**	0	24.43	75.57	**113**	0.11	86.13	13.76
12	36.38	53.69	9.94	**68**	0	17.16	82.84	**114**	0,00	1.67	98.33
13	0.49	81.51	18	**71**	0.16	60.87	38.97	**115**	50.55	47.89	1.56
14	0.55	93.97	5.48	**72**	0.23	60.48	39.29	**116**	3.33	95.8	0.87
18	6.99	83.37	9.64	**73**	19.14	79.4	1.47	**117**	2.63	96.07	1.3
19	14.16	84.3	1.54	**74**	0,00	3.99	96.01	**118**	1.21	97.05	1.74
20	0	10.53	89.47	**75**	0.58	95.57	3.86	**119**	36.52	61.97	1.57
21	0	74.78	25.22	**76**	47.4	51.12	1.43	**120**	36.59	41.8	21.6
22	0	94.38	5.62	**77**	8.59	11.53	79.88	**121**	26.78	69.76	3.46
23	0	25.41	74.59	**79**	13.17	85.87	0.96	**122**	28.84	69.19	1.96
24	10.08	74.58	15.34	**80**	5.69	94.19	0.12	**123**	7.37	89.34	3.28
26	0.38	23.85	75.77	**81**	14.11	84.74	1.15	**124**	65.25	32.09	2.66
28	18.53	65.81	15.65	**82**	0,00	6.29	93.71	**125**	0.85	85.75	13.41
29	0	17.37	82.63	**83**	19.67	79.47	0.85	**126**	0.02	87.37	12.62
30	24.86	55.72	19.42	**84**	18.66	79.2	2.15	**127**	0	46.24	53.76
31	0	90.86	9.14	**85**	0,00	2.15	97.85	**128**	0.53	25.3	74.17
33	0.1	80.59	18.32	**86**	12.07	86.38	1.55	**129**	35.9	60.4	3.71
34	2.24	94.84	2.93	**87**	18.73	79.2	2.06	**130**	0.02	50.4	49.58
35	24.47	71.3	3.74	**88**	0.65	97.14	2.21	**131**	9.35	85.21	5.45
36	39.84	55.3	4.85	**89**	71.49	28.01	0.51	**132**	24.33	72.85	2.82
37	23.55	74.6	1.85	**90**	0.34	97.67	1.99	**133**	12.03	84.33	3.64
38	16.02	32.64	51.34	**91**	0.08	95.51	4.41	**134**	33.41	63.63	2.96
39	0.48	11.96	87.56	**92**	19.99	78.26	1.75	**135**	11.03	86.42	2.55
40	0	42.12	57.88	**93**	0.01	97.09	2.9	**136**	35.53	61.6	2.86
41	1.76	93.94	4.31	**94**	18.06	80.77	1.18	**137**	22.75	75.11	2.14
42	2.51	60.44	37.06	**95**	25.25	73.45	1.3	**138**	17.47	78.46	4.07
43	11.61	79.77	8.62	**96**	33.31	65.7	0.99	**139**	14.12	83.72	2.15
44	32.83	66.67	0.5	**97**	37.17	61.52	1.31	**140**	16	81.8	2.2
45	17.9	81.15	0.95	**98**	62.04	33.11	4.85	**141**	37.13	59.88	2.99
47	49.49	47.74	2.77	**99**	0.6	49.4	50	**142**	50.32	49.06	0.62
48	23.91	74.9	1.2	**100**	56.79	41.41	1.8	**143**	15.92	73.3	10.78
49	15.3	79.3	5.4	**101**	39.03	59.08	1.89	**144**	0.33	30.03	69.64

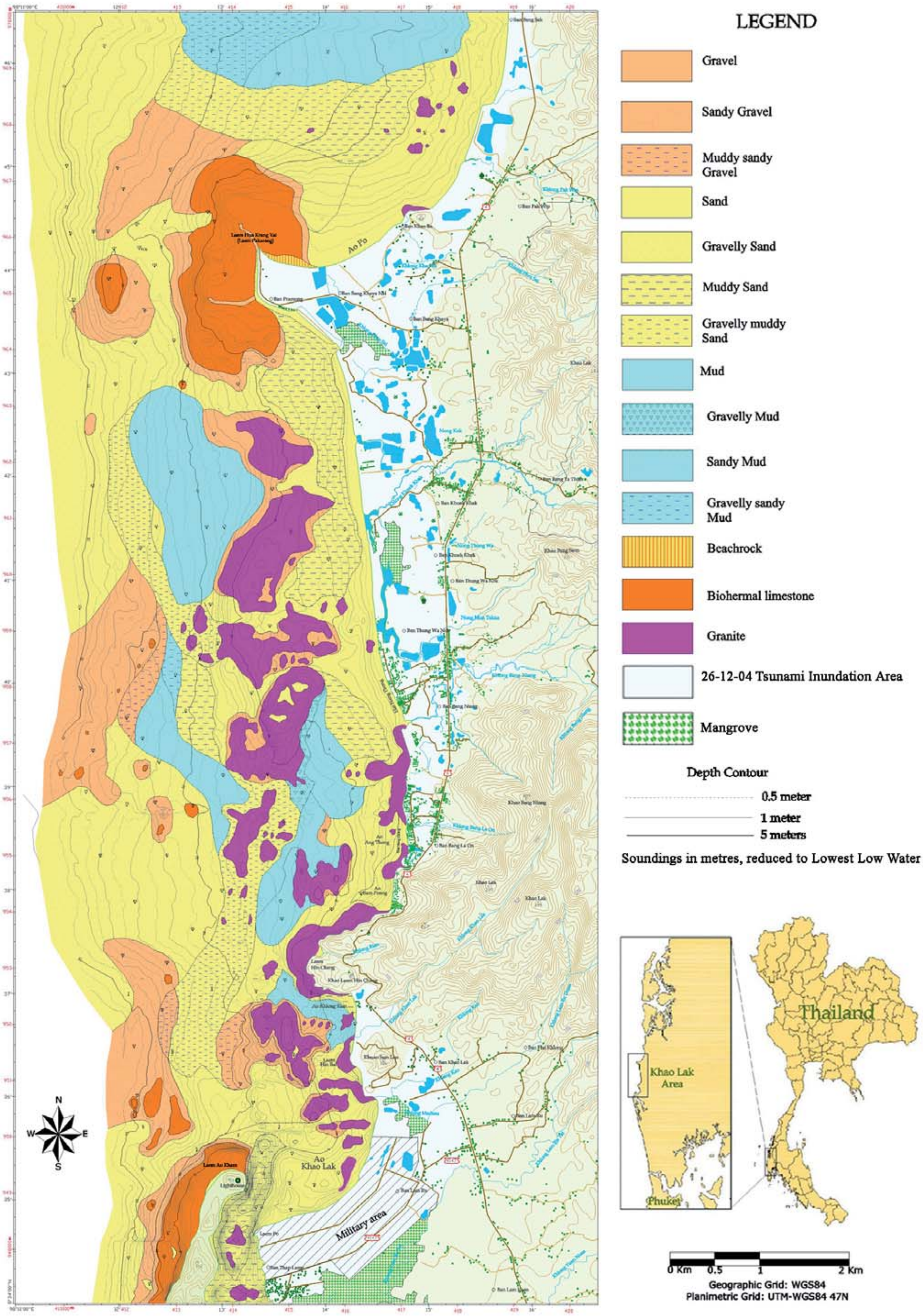

Fig. 2. Topographical and sedimentological map of Khao Lak study area modified from [16].

widened cut banks. Mangrove areas are locally along Khlong Phru Sai, Khuek Khak and at Ao Khlong Rian. The rocky coast is dominated as headlands in the north and the south side of Laem Hin Chang and at Laem Ao Kham peninsula.

The seafloor north of Pakarang is gently and uniformly degrading up to 15m of depth with dip values of 0.20% (Fig. 3A, prof. 1), except for a narrow coastal area where bottom configurations are quite irregular owing to the presence of several small granite outcrops and large blocks scattered on the sea floor.

From Pakarang to Laem Hin Chang the bottom morphology is even more complex and articulated. Off the coast, Laem Pakarang is surrounded for a length of 3km by a reef tidal flat with more than 800m wide. After dipping as much as 10.5m, the bottoms high up again in correspondence with a reef shoal extended in a northsouth direction and reaching its top at a depth of 8.5m (Fig. 3B). As a whole, the area along the slope off the Pakarang reef edge and that one surrounding the shoal is scattered by several boulders and blocks up to over 2m in diameter; some of them emerging from the bottom sediment, others simply resting on the bottom surface. The shoal is colonized by several species of corals, but only some of them are horned corals. These horned corals are instead totally lacking along the slope of the tidal flat. Similar shoals are slightly smaller and located in a deeper part (-12m) to the northwest of Laem Ao Kha (Fig. 3B). The bottom area between these two shoals, from 9-10m to 15-16m deep, shows 0.30% mean dip and is mainly characterized by scattered small rocks consisting of biohermal limestones. These biohermal limestones are located above the bottom 1.5m at most and are more frequent in the area off the coast of Bang Niang.

To the South of the Pakarang reef flat as far as Ao Khao Lak, the bottom is extremely indented for a length of ca. 15km and presents a great amount of shoals and coastal rocks. These latter are abundant to the South of Bang Niang and constitute the extension in the submarine environment of the granite outcrops from the mainland.

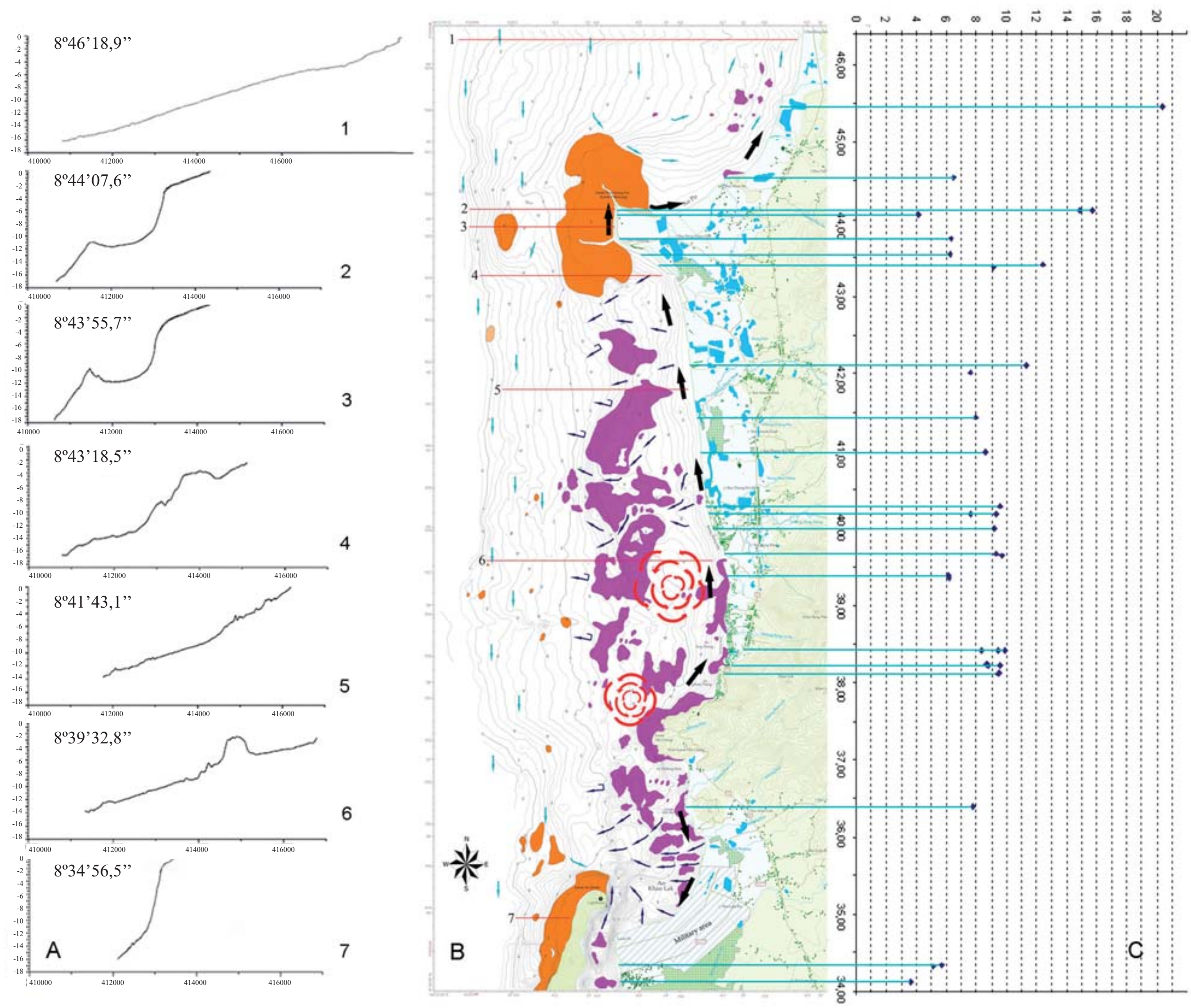

Fig. 3. Relationship between the coastal zone slope inclination, the submerged morphology and lithology and run-up height. A) Significant morphological bottom profiles (vertical axis-depth in m, horizontal axis-distance). For each profile the latitude value position is indicated. B) Bathymetry map with rocky bottoms; length and position of profiles (1-7). The arrows represent the Andaman current to the south, the littoral drift to the north, the bottoms current by storms to the open sea. The circular arrows represent the two tsunami vortexes. C) Run-up height values observed by [10, 13] and their position at the Khao Lak coastline.

The upper parts of some shoals emerge also at high tide levels (Hin Krang Nok, Hin Khi Nok). On their upper surface, especially on the larger ones, sedimentary pockets consisting of sands and sandy gravel are present. Channels and their pathways occur within such shoals representing the preferential passage in which backwash streams and sediments were canalized during monsoon storms (Fig. 3B).

Lastly, in the most southern area, the narrow and long peninsula of Laem Ao Kham presents on its western side as a reef tidal flat (wide up to 350m and ca. 2km long), which forms a steep slope as far as -16 m and more, 2.22% dipping on its upper part and 0.71% on its deeper bottoms (Fig. 3A prof. 7).

The Coastline and the Shore

One year after the tsunami event the shoreline has almost recovered, and the characteristics of coastal type in the study area did not change from the day before the tsunami event. Before the 2004 tsunami, the rate of coastal erosion along Laem Pakarang to Khao Lak area was documented and the characteristic of coastal behaviour in this area into three types were classified [19]. Firstly, coastal areas from the southern part of Laem Pakarang to the south tidal channel, where the Blue Village Pakarang Resort is located, was characterized as a depositional coast with the accretion rate of 1-5m/year. Secondly, from the Blue Village Pakarang Resort down south to Ban Bang Niang, this zone was defined as a stable coast with depositional rate of ±1m/year. Lastly, the area extending from Ban Bang Niang to Khao Lak was identified as a moderately eroded coast with erosional rate of 1-5m/year. After the tsunami event the characteristic of coastal behaviour in this area is still the same.

Results of remote sensing and GIS analysis in shoreline change and beach area recovery show that the recovery of shoreline in the northern part of the study area from Blue Village Pakarang Resort down south to Klong Khuek Khak was 98% recovered, whereas at Ban Bang Niang recovery of the shoreline was 96%. Recovery of beach area is also similar [17, 18].

The Offshore Sediments

At Khao Lak, the distribution of offshore sediment shows a N-S discontinuous muddy strip landward by sands and towards open sea by sandy gravels and gravelly sands bound (Fig. 2). A longitudinal fragmented and submerged rocky shoal line divided the muddy strip into two parts [16]. The deeper outer strip is made mostly by gravelly sand, but near the biohermal limestone rocky bottoms and seaward along the reef edges of Laem Pakarang and Laem Ao Kham, sandy gravels are common. This strip is as much as 3km wide and starts from approximately 10m deep. The sands are medium-coarse grained in size, with rounded or subrounded quartz granules and a small percentage of carbonates. The organogenic fraction is mainly made by brown colour, strongly eroded, rounded and bioeroded molluscs and coral fragments. The sandy gravels, in a similar way, have almost completely biolithic gravel fraction pebbles and are almost completely old, rounded and eroded.

The shallow water coastal sand strip is narrower, about one hundred meters on average, but more than 1km wide and 9m deep off Ban Bang Sak and Ban Bang Niang. These quartz sands are composed of medium and coarse grains in the south, gradually becoming fine to the north, ending at the Khlong Phru Sai channel mouth. Just a little further along the western side of Laem Pakarang, sands suddenly become coarser, sometimes gravelly and consisting mainly of coral fragments.

Based on the sediments with prevailing or secondary mud fractions with patches of different areas, shape and origin are genetically arranged from north to south. At the northernmost part, a bigger patch in the middle of the Ban Bang Sak Bay is characterized by sandy mud and gravelly sandy mud that extend to the south and then gradually become muddy sand and gravelly muddy sand. Further to the south (to Laem Hin Chang), there is a 10 km long and 4 km wide muddy strip, cut off on the eastern coastal side offshore of Ban Bang Niang in two parts and with granite rocky shoals down a longitudinal line in the middle. In the southern one, offshore of Bang La On and northwest of Laem Hin Chang, there are two pure black mud patches (Fig. 2) covering sand and sandy gravel sediments. This superficial mud layer is up to 20cm thick, anoxic, bad smelling and sometime sticky. In the Ao Khlong Rian, south of Laem Hin Chang , attached to the coast, there is a last sandy mud and muddy sand small patch.

At Laem Pakarang, on the tidal reef flat and along the reef slope until the base, there are hundreds of reef blocks of several tons weight, and uprooted big coral colonies moved by tsunami waves [7, 20] (Fig. 4c, d). The blocks are located in the middle and in the proximal tidal flat area; some scattered mega-blocks lie very close to the coastline. Other several ton granite blocks were moved by tsunami till 150 m inland, at Poseidon Resort [3] (Fig. 5).

On the Pakarang northern side, at Ao Po, 1km long and 200 metres out is a large strip of Holocene beachrock (Fig. 2, 6).

Discussion of Results

Sediment Source and Transportation

Sediment patterns along the coast of Khao Lak area are influenced from oceanographic factors (currents, waves, tsunami waves), climatic conditions (rain, storms, monsoon winds, post-Wurmian sea level rise), geologic setting (bottom lithology, earthquakes), coastal and submerged morphology (beach slope, bottom gradient, submerged channels, passes), fluvial flow and regime, sedimentary load.

The fine size terrigenous sediments carried to the sea by a few small rivers and tidal channels is very poor. The offshore sediment source is mainly an organogenic source, containing mainly corals followed by molluscs, bryozoans, forams, and others skeletons.

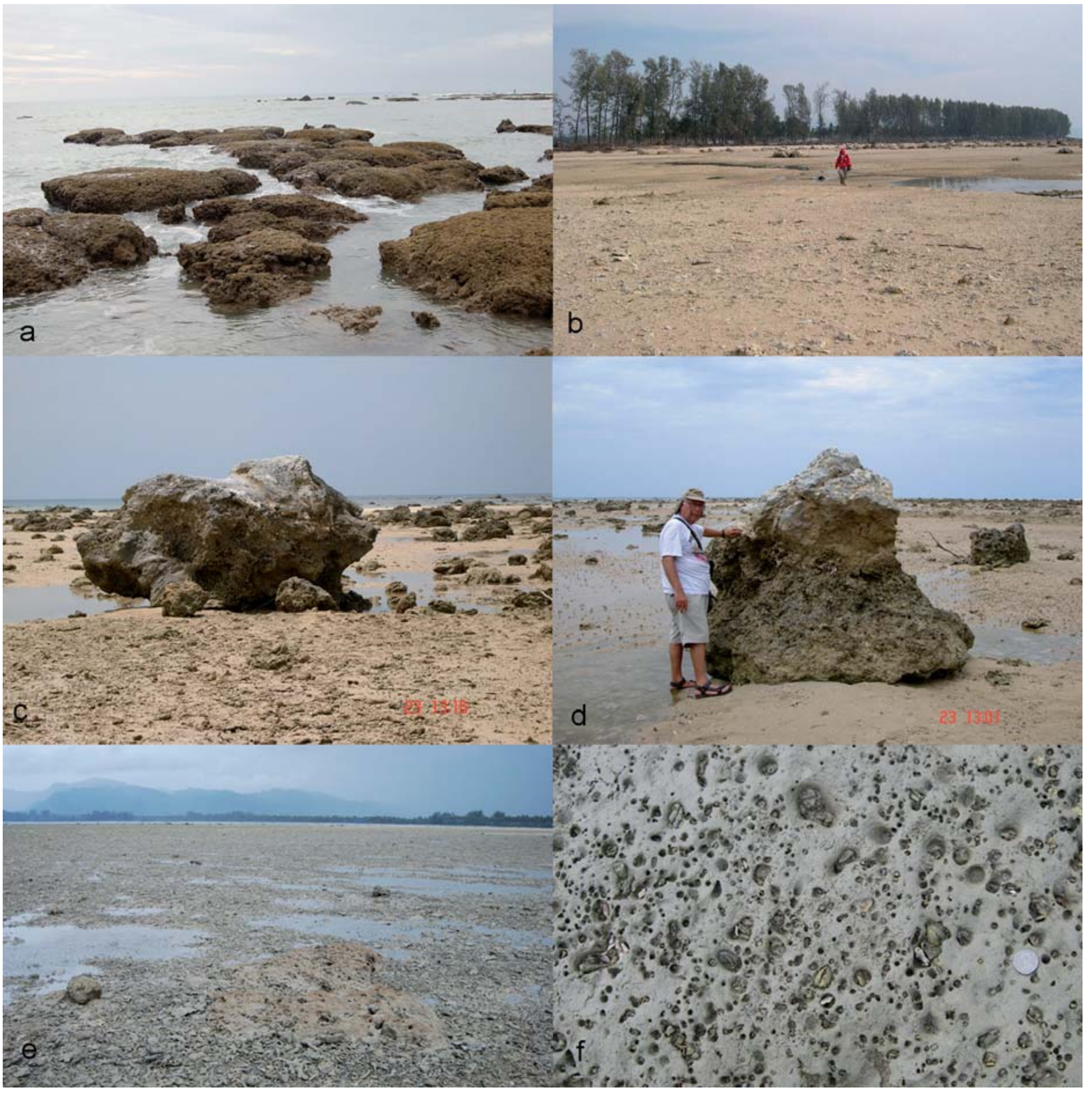

Fig. 4. Laem Pakarang tidal reef flat after the tsunami impact. a) Microatolls and surge channels at the reef tidal flat in December 2006. b) Coral sand and rubble covering the tidal flat in January 2005. c) Mega-block with a tidal notch moved by tsunami from the tidal flat edge in February 2006. d) Porite colony conical block uprooted and moved by tsunami to the tidal flat in February 2006. e) Erosion surface of Holocene tidal flat covered with a patched thin rubble film in March 2008. f) Holocene bioerosion on tidal flat surface; some perforations still contain the lithophagous mollusc bivalve shells.

Fig. 5. Poseidon Resort at Khao Lak in February 2006. Alignment of granite blocks moved by tsunami up to 150 m inland.

Fig. 6. Beachrock slabs moved by tsunami at Ao Po, northern side of Laem Pakarang. The slabs are largely exposed during low tide. March 2008.

The outer deeper strip sands are not consistent with the present local river load, coastal morphology and the littoral transport to the North stopped by the bay caps with deep rocky cliffs. The quartz composition, particle size and roundness, brown colour and the old look of the abraded, fragmented and bioeroded shells and corals point to the deposition of these sediments as residual littoral or beach sands during the post Wurmian Holocene sea level rise.

Fig. 7. Vortex formed at sea, northwest of Laem Hin Chang, by 26 December 2004 tsunami. Picture from eyewitness personal video at approximately 10:26 a.m.

Along the coastal marine bottoms of Phang Nga province, the local and northern rivers and tidal channels are likely a natural source of mud, but sediment loading is increased by land and offshore tin mining started in 1970 [21] and before [22]. The Andaman marine current is generally controlled by the tropical monsoonal regime and by coastal morphology, flows to the south and southwest (Fig. 3B) from June to February [23, 24] caused the loading of mud from the coast. Most parts of the suspension river mud and the re-suspension by waves and storms during the southwest monsoon season should be dispersed far away at the Andaman continental shelf. Nevertheless, a large amount of mud, after trespassing the rocky shoal line through the numerous submerged channels is trapped just after in a relatively quiet zone off bounded by the open sea Andaman current (Fig. 3B).

At the north of Laem Pakarang, the greater mud quantity is probably coming from northern Khlong Pak Ko that is trapped inside the bay between Laem Hua Krang Noi and Laem Pakarang.

Mud trapped inside Ban Bang Niang bay comes mainly from the short canals nearby. The rocky bottom morphology

Fig. 8. Two coral sand-rubble bars along the southern side of Laem Pakarang, at low tide. The smaller one (a), not in the map, is located 300 m southeast of the bigger one (b).

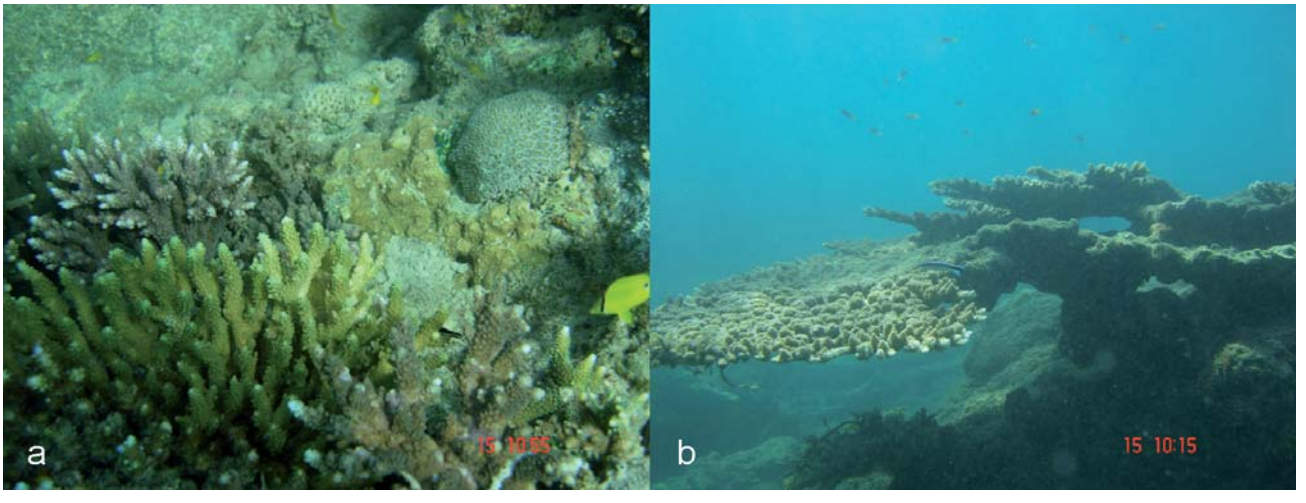

Fig. 9.a-b. Fragile Acroporidae living coral colonies along the Laem Ao Kham western slope (-5m) not damaged by 26 December 2004 tsunami.

and current through the submerged channel off the coast of Ban Thung Wa Nok are likely decisive factors of the two areas of muddy sediment distribution. South of Laem Hin Chang, the mud comes mainly from Khlong Khao Lak and the Khlong Kao, but probably and partially transports from the southern Khlong Thung Maphrao.

The two unusual black anoxic pure mud patches northwest of Laem Hin Chang (Fig. 2) are supposed to be temporary. The origin of these shallow water open sea face exceptional mud accumulations is two persistent big vortexes by the 26 December 2004 tsunami (Figs. 3B, 7) and by the relevant suspension.

A large amount of marine sand with a low percentage of pebbles, shells and forams was eroded by tsunami waves from the coastal bottoms, not deeper than 5-6 m, and from the beach, and then quickly deposited on land with generally 2 layers 0-30cm thick [4]. A large amount of white coral sand and rubble, however, was deposited on Pakarang tidal flat (Fig. 4b) and on the Ao Po bay after destroying and passing over the cape. This coral sand and rubble was later moved and pushed back to the coast by the return flow; along the coast, and then possibly moved to the north by the littoral drift. Now the Pakarang tidal reef flat, nearly free of sand and coral rubble, shows many areas of the former erosional surface riddled with endobiont organism perforations (Fig. 4e, f). Moreover, around Pakarang 4 evolving sand-rubble bars are presently formed. The larger and longer bar is formed by the northern sediments moved by the littoral drift, in the same place were the Pakarang terminal stretch was swept away by the tsunami. The other three bars are likely formed by the present wave refractions (Fig. 8).

The hundreds of blocks on the Pakarang tidal flat were definitely moved by the tsunami wave, not only proven by eyewitnesses but particularly by positions and biogenic encrustations. All the blocks are made up of coral reef fragments with irregular globular, pyramidal and conical shapes (Fig. 4d), with as much as three meters major axis, and up to more than 40 tons calculated weight [7]). The base of the pyramid- or cone-shaped blocks are flat, wave-eroded and sifted with bivalves and other *Lithophagous* perforations. Three irregular globular large-sized blocks have the upper side with a very smooth and not encrusted tidal notch (Fig. 4c). They are 100m away from the reef edge and lie on one tilted side and on the bottom floor, incompatible with the present tidal levels.

Block distribution on the tidal flat contains many small blocks and rare, large blocks in the Pakarang tidal flat southern area, south of the west point bar. The large blocks make up the majority in the central area up to the cape. There are no blocks in the outer area near the tidal flat edge, but instead the larger amount of blocks occurs in the middle and proximal area, with some scattered megablocks near the coastline. Some scattered blocks also lie in the northeast side of the newly formed spit of Pakarang.

Furthermore, the organogenic crusts observed on some block surfaces during a survey in 2006 were relatively well preserved and clear, even if they were observed more than one year after the event. They are constituted by encrusting invertebrates, i.e. corals, bivalves, gastropods, polychaete serpulids, bryozoans and also by calcareous algae. As a whole, the ecological meaning of such association is not compatible with the present position (within the tidal flat) of the encrusted blocks, since all species are typical of infralittoral hard-bottoms, which are regularly submerged or only exceptionally interested by emersion episodes. Furthermore, the distribution pattern of encrusting organisms is not compatible with the present laying of the block above the sea floor. In fact, they are clearly tilted from the sub-horizontal distribution of settlement.

We believe that this distribution pattern was caused not only by tsunami wave speed, energy and height increase due to coastal morphology, but also because the reef edge blocks uprooting and their distal deposition was made only by the first big tsunami wave. A similar mechanism involves the biggest cobbles and boulders deposited more inland in the backshore during the storm weather on the beach.

Indeed, the second and the third tsunami wave trains, during their move inland, would presumably encounter a certain resistance due to the backwash of the preceding first and second waves. In addition, they would be fairly transported owing to the general turbulence produced during the tsunami event. A mechanism like this substantially reduced wave energy and potential transport inland of the wave events following the first one.

Relationship between Run-Up and Coastal Morphology

In the Khao Lak area, the good relationship between the observed run-up height with submerged bathymetry, geomorphology and slope inclination of the coastal area is clear. Run-up height values from 4 to 21m were observed in the studied area. [10, 13] The maximum run-up value was observed at Ban Bang Sak bay, which the gentlest sloped (0.20%), and the minimum one was detected at the Laem Ao Kham peninsula cliff, where slope inclination is 1.23% (Fig. 3). At the Ao Kham cliff vertical wall, vegetation growing higher than 4m above sea level was not impacted. No moved blocks and no broken corals were observed during the diving visual survey on bottoms deeper than 4m. On the reef tidal flat, any signatures of tsunami impact were also recognized. The surface was covered by a thin and patched film of coral rubble and only one small block with 70cm major axis was found.

At the cut end cape of Laem Pakarang, a run-up of 16m height was observed. The run-up was 6-7m just north and south of the cape. The surrounding bottom morphology and lithology can explain the difference. When the tsunami front wave coming from the east reached the reef shoal off Pakarang, a first refraction around it possibly formed two wave fronts. These two fronts went ahead to the Pakarang tidal reef edge, reaching two small coves just west where the cape ended. Here a second refraction happened, causing the further wave to rise up. The load of sand and blocks occurring after the wave run about 500m and then swept away the former Laem Pakarang spit point.

On the northern side of Pakarang, the run-up was lower (6m) because after refraction around the northern side of the reef tidal flat, going SE the new front wave collided with spit overwash coming from the west. At the southern side of Pakarang, instead of the refraction around the southern side reef tidal flat, the wave interfered with another one that was refracted by the southernmost shoal.

The submerged morphology and the various refractions of the wave can also explain the wave-enhanced energy, block uprooting, movement and settlement on the Pakarang tidal flat.

The run-up height values from Pakarang to Ao Khlong Rian were between 8-10m, because the area exhibited at almost the same slope inclination of 0.30% in average. Moreover, the front wave was likely fragmented and refracted many times, leading to the speed and energy wave reduced almost unvaryingly by the submerged long line of granite shoals.

Conclusions

As we can infer from eyewitness accounts and from the sediment distribution map of the study area, erosion occurred at tsunami wave base at 5-6m depth, where the morphology dipping of bottom topography was less than 0.5%. This situation caused, moreover, the beaches, small canals and tide channel mouths to be strongly eroded. The Pakarang terminal stretch was swept away and a large amount of reef blocks, coral rubble and sand on the tidal flat was poured.

During the diving surveys, excepting the collapsed coral blocks along the Pakarang reef slope, no morphology, erosion sign or tilted blocks on the bottom floor were clearly seen. At Laem Ao Kham reef slope, the horned living coral colonies were undamaged from 4m depth down slope (Fig. 9). At the Pakarang coral rubble rich on horned coral fragments likely came from the Holocene former reef. However, at present only incrusting coral colonies live along the reef slope.

Two years after the tsunami event, the Khao Lak beaches are almost fully recovered by natural processes and the equilibrium profile also returned almost to a normal situation as recorded before the event. The post-tsunami beach sediment comes mainly from the offshore bottom sediments. Only the widened cut banks along the tidal channels in land may need several decades to return [18]. Around Pakarang, new sand-rubble bars are forming and a new spit is growing where the former spit was located.

Our new detailed coastal bathymetry and morphology map is of significant to better understanding of two tsunami parameters, i.e. 1) the energy wave enhanced and 2) run-up. Our results also help to explain the behaviour of tsunami run-up in relation to the change of bathymetry along the Khao Lak coastline. As these two tsunami wave parameters are the most important key to evaluating coastal impact, we suggest that a new detailed bathymetry and morphology mapping survey all along the Thai Andaman coastal strip is necessary to build a more realistic coastal hazard map for the mitigation of future tsunami events.

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