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ORIGINAL PAPER

Evidence of probable paleotsunami deposits on Kho Khao Island, Phang Nga Province, Thailand

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Abstract The 2004 tsunami deposits and probable paleotsunami deposits were studied at the southern Kho Khao Island, on Andaman Sea coast of Thailand. The 2004 tsunami laid down about 8 cm of fining upward medium sand and locally about 40 cm of massive coarse sand with common mud clasts. The sediments were characterized by the presence of marine foraminiferal assemblage; however, already after 5 years many of carbonate foraminiferal tests were partly or completely dissolved. The probable paleotsunami deposits form layer about 1 m thick. It consists of massive very coarse sand with common big shells and mud clasts. Its composition suggests a marine origin and the presence of mud clasts, and similarity to the 2004 tsunami deposits suggests that the layer was left by paleotsunami, which took place probably during the late Holocene, even though two shells within the layer gave ^{14}C ages of 40,000 years or more.

Keywords Paleotsunami deposits · Indian Ocean tsunami deposits · Post-depositional changes · Coastal zone · Thailand

1 Introduction

One of the coasts severely impacted by the Indian Ocean tsunami on 26 December 2004 was the Andaman Sea coast of Thailand, where about 20,300 ha of land were flooded with seawater (UNEP 2005). The occurrence of the tsunami was unprecedented and raised a

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question on tsunami hazard assessment for this coast. In principle, to provide such an assessment it is required to have knowledge of probable tsunami sources, their likelihood of occurrence and characteristics of tsunami from those sources at different places along the coast. Data of earlier tsunamis present an invaluable help in quantification of these factors. Since there are no historical accounts about any former tsunamis on the Andaman Sea coast, it is necessary to base tsunami hazard assessment for the region on sedimentary record of past tsunamis (paleotsunamis) and on modelling studies.

Because tsunami deposits may be represented by various sediment types, which range from mud to boulders (e.g., Dawson and Shi 2000; Goff et al. 2001; Scheffers and Kelletat 2003; Bourgeois 2009); they may also be similar to other deposits, for instance storm deposits (e.g., Morton et al. 2007; Switzer and Jones 2008) and may be altered by post-depositional changes (e.g., Nichol and Kench 2008; Szczuciński 2011), in consequence their explicit identification is often difficult. The extensive studies on 2004 onshore tsunami deposits in the Andaman Sea coastal zone of Thailand revealed that they are incredibly variable in regard to extent, thickness, grain size (mud to boulders), internal structures, composition, and preservation potential. However, detail analyses allowed to discriminate the 2004 tsunami deposits from other coastal sediments using sedimentological (e.g. Szczuciński et al. 2006; Choowong et al. 2007 2008a, b; Goto et al. 2007, 2008; Hori et al. 2007; Kelletat et al. 2007; Fujino et al. 2008; Matsumoto et al. 2008), micropaleontological, (Hawkes et al. 2007; Kokociński et al. 2009; Sawai et al. 2009), geochemical (e.g. Szczuciński et al. 2005, 2007; Kozak et al. 2008), and mineralogical (Jagodziński et al. 2009) characteristics. These sediment properties may serve in quest for older tsunami deposits.

Several research groups started to search for paleotsunami record on the Andaman Sea coast of Thailand within a few months after the tsunami. However, due to similarity of tsunami deposits to other coastal sediments, intensive post-depositional changes, lack of lagoons or coastal lakes usually serving as good sedimentary archives, and as a result of extensive placer mining of the coastal plain, initial quests for paleotsunami record failed (Szczuciński et al. 2006; Tuttle et al. 2007) or faced problems during identification and age determination of the paleotsunami events (Jankaew et al. 2008; Fujino et al. 2009; Yawsangratt et al. 2009). Soon, however, compelling evidence for paleotsunamis was found on northern part of Phra Thong Island (Fig. 1, north from Kho Khao Island). Jankaew et al. (2008) traced several sand sheets younger than 2.5–2.8 ka. The most recent of the inferred paleotsunamis was found to be slightly younger than AD 1300–1450. These findings were anticipated by Fujino et al. (2009), who reported at least two sand sheets interpreted as record of paleotsunamis, which occurred respectively more than 700 and more than 100 years ago. A bedded shell deposit interpreted as an event layer of similar age (beginning of the fifteenth century) as the youngest sand sheet on Phra Thong Island was reported by Harper (2005) from Krabi province (over 100 km southward). In addition, from a region nearby Thap Lamu navy base (Fig. 1), boulders possibly deposited by a paleotsunami of unknown age were described by Yawsangratt et al. (2009). Next to Thap Lamu also, possible traces of mid-Holocene tsunami were found in mangrove environment by Rhodes et al. (in review). Recently, Brückner et al. (2010) reported likely evidence of two paleotsunami events from Ban Bang Sak (Fig. 1), where the younger was dated to AD 1300–1400, and of older events from Pakarang Cape (Fig. 1) and located several tens of km southward Phang Nga Bay.

Apart from the limited geological record, the tsunami recurrence period assessment for the Andaman coast of Thailand was made by Løvholt et al. (2006) on a basis of an analysis of the plate tectonic situation, earthquake history, and numerical modelling. They estimated that it would take at least 300–400 years to accumulate the energy that was released

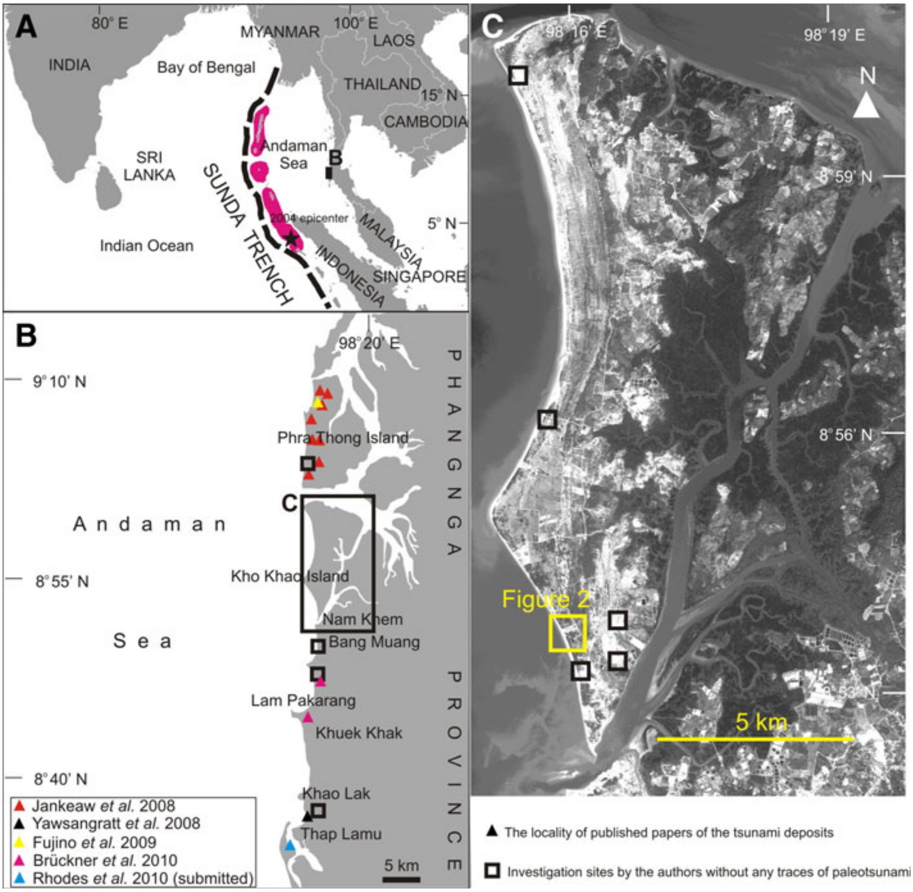

Fig. 1 Study area. **a** Location of study area within Indian Ocean. In *pink* are marked major rupture areas during the 2004 Sumatra–Andaman earthquake after Subarya et al. (2006). **b** The most severely impacted part of Andaman Sea coast of Thailand in Phang Nga Province with marked sites with documented published paleotsunami deposits (in number) and sites investigated by the authors in search for paleotsunami. **c** Satellite image of Kho Khao Island with marked sites investigated by the authors for paleotsunami

during the December 2004 earthquake. They also estimated that tsunamis with a runup height of 1.5–2 m and a recurrence of 50–100 years are possible; however, as discussed by Szczuciński (2011), the sedimentary record of those smaller tsunamis would be of very low preservation potential. Meltzner et al. (2010) found evidence for uplift of northern Simeulue Island, near the south end of the 2004 rupture, and inferred big earthquakes in the 1390s and around 1450. One of those earthquakes likely accounts for Jankaew's et al. (2008) unit B, the penultimate sand sheet at Ko Phra Thong.

The objective of the present study is to extend the paleotsunami record on the Andaman Sea coast of Thailand. It documents 2004 tsunami deposits, their post-depositional changes and likely paleotsunami deposits found on the southern part of Kho Khao Island. The ultimate aim of the study is to improve tsunami hazard assessment for the studied coast.

2 Study site

Kho Khao Island is located in Phang Nga Province, Thailand (Fig. 1), which was heavily affected by the 2004 tsunami. The region is in tropical climate zone with seasonal heavy rains during southwestern monsoons. The study site is located in the coastal zone of the southern part of the island, next to Kho Khao Island Beach Resort (Figs. 1, 2). The area is built mainly from a series of beach ridges formed during sea level fall following the middle Holocene sea level highstand (Sinsakul 1992). The inundation distance and maximum runup height of the 2004 tsunami for the study site measured at the resort were 540 and 7.7 m, respectively (Szczuciński et al. 2006). The tsunami left a layer of sandy deposits less than 0.5 m thick with variable sediment composition and structures (Jagodziński et al. 2009, Szczuciński et al. in review).

From the west, the investigated area is bordered by beach and beach berm, which are cut by a channel serving as stream bed and tidal channel (Fig. 2). Further landward is a low laying, periodically flooded area ("lagoon"), which was covered by thick (40 cm on average) 2004 tsunami deposits containing characteristic mud clasts several cm wide that had been eroded from the mud layer below (KK6 on Fig. 3). Eastward is an elevated terrace (about 3 m above mean sea level), covered with dense old forest. On this terrace, most of the investigated pits were dug. Though the terrace is not continuous because it was partly removed during old tin mining activities, the remnants of the latter are still well visible in landscape and in characteristic deposits, which are left after separation of cassiterite rich fraction.

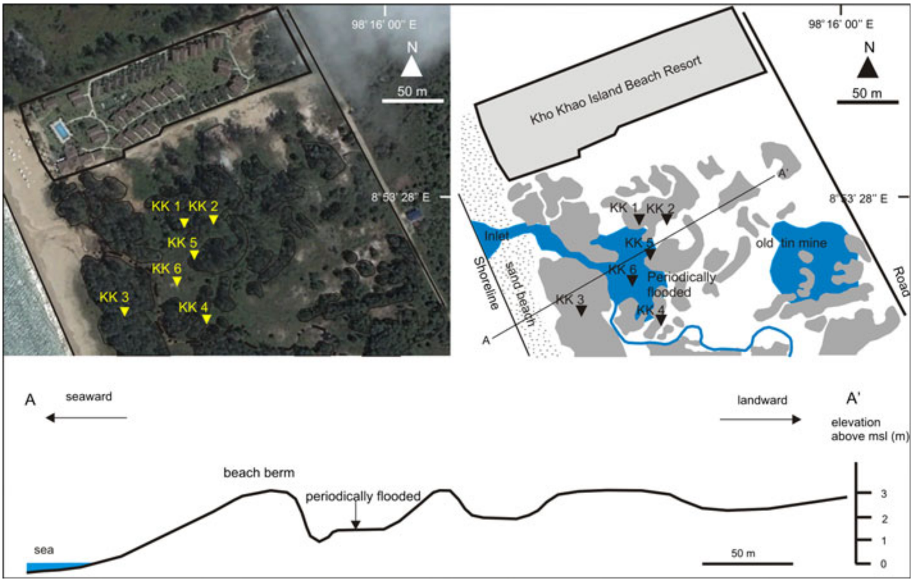

Fig. 2 Study site with marked locations of investigated pits (KK1–KK6), major landforms, and topographical profile

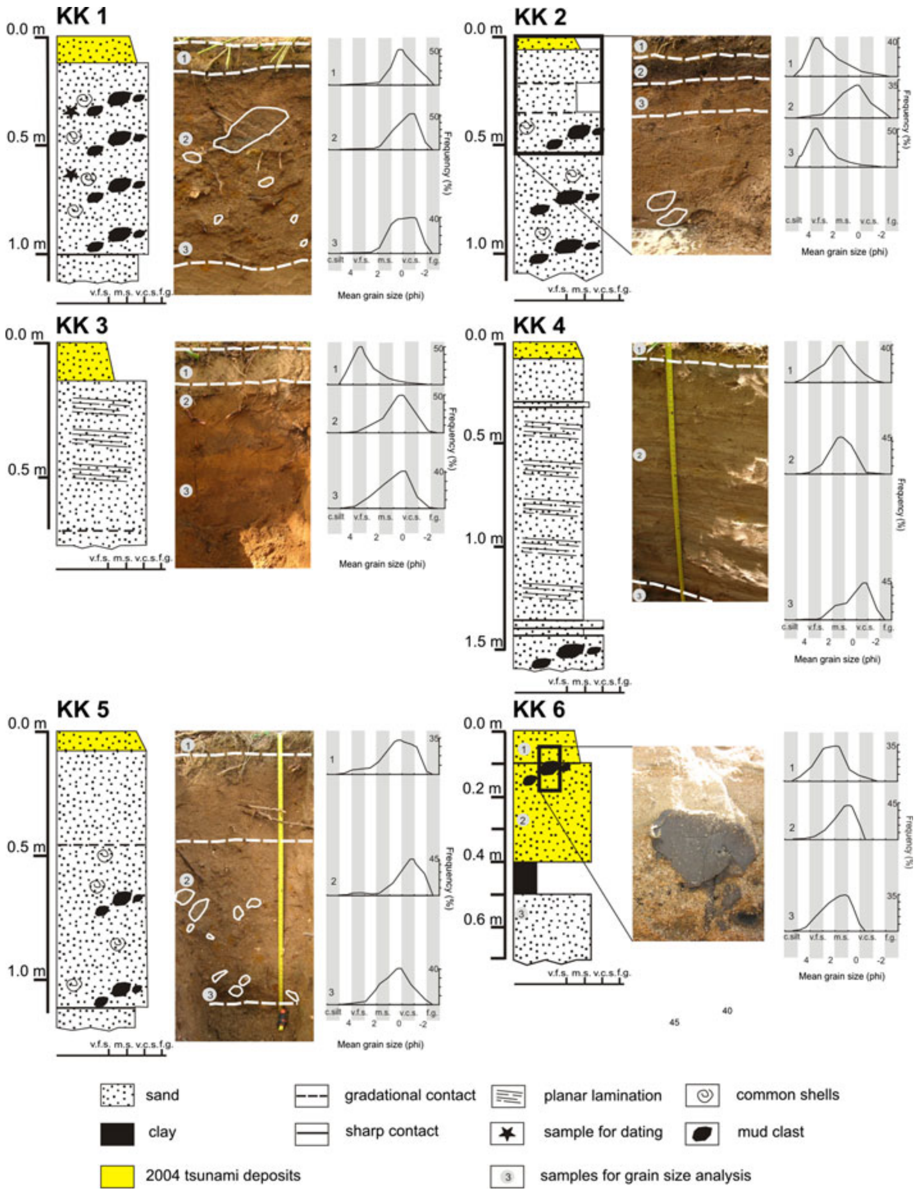

Fig. 3 Sedimentary logs and grain size distributions of the analysed samples (see Fig. 2 for pit locations)

3 Materials and methods

In search for paleotsunami record, the authors conducted surveys in 2005, 2007, 2008, and 2009, in various sites of coastal zone in Phang Nga Province (Fig. 1; Table 1). At each of the sites, several 1–2-m-deep pits down to groundwater table were excavated; however, apart from documentation presented in this paper, no evidence of paleotsunami was found. Common problem was to find the studied sequences to be disturbed by tin mining or land reclamation.

Table 1 List of the sites investigated in search for paleotsunami (as marked on Fig. 1) with short information on location and dominating sediments

Site	Coordinates	Description
Present study, southern Kho Khao Island	8°53.4′N 98°15.8′E	6 pits
S Phra Thong Island	9°3.8′N 98°15.4′E	2 pits; multilayered sandy sediments
N Kho Khao Island	9°0.2′N 98°15.6′E	2 pits; multilayered sandy sediments covered with 2004 tsunami deposits, traces of land reclamation
Middle Kho Khao Island	8°56.2′N 98°15.7′E	1 pit; massive sand with paleosoil covered by 2004 tsunami deposits
Thung Tuk, SE Kho Khao Island	8°53.3′N 98°16.8′E	3 pits and drilling at archeological site, where a city and harbour flourished in ninth and tenth century AD; multilayered sand
Nearby Thung Tuk, SE Kho Khao Island	8°53.9′N 98°16.7′E	1 pit; brown sand on pure quartz sand below; mining area
Southern Kho Khao Island	8°53.1′N 98°15.9′E	1 pit; massive sand with paleosoil covered by 2004 tsunami deposits
Ban Bang Muang	8°49.9′N 98°16.1′E	1 pit; multilayered sandy sediments covered with 2004 tsunami deposits
Ban Bang Sak	8°47.4′N 98°15.7′E	4 pits; multilayered sandy sediments covered with 2004 tsunami deposits, traces of mining activity
Thap Lamu	8°36.1′N 98°14.7′E	7 pits; massive sand with paleosoil covered by 2004 tsunami deposits and multilayered sandy sediments on mangrove remnants; traces of land reclamation; next to the boulders described by Yawsangratt et al. (2009)

At each site, pits were dug down to groundwater level, usually approximately 2 m deep. In case of sites with several pits, the coordinates are provided for the central part of the studied area

The present study is based on survey of 2004 tsunami deposits in February 2005 (KK6) and on investigation into five pits dug in July 2009 (KK1–KK5). The sediments in excavated pits were described, photographed, and sampled (both 2004 tsunami deposits and the older sediments). Eighteen samples were analysed for grain size distribution through dry sieving on a set of 13, 0.5 phi interval sieves. Ten samples (5 from 2004 tsunami deposits and 5 from hypothetical paleotsunami deposits) were investigated for analysis of foraminiferal assemblages under optical microscope and SEM. The dating of two carbonate shells from hypothetical paleotsunami deposits was performed by high-precision ^{14}C measurements using accelerator mass spectrometry (AMS) in the Poznań Radiocarbon Laboratory.

4 Results

4.1 Sediments

4.1.1 2004 tsunami deposits

In all the investigated pits, the uppermost sediments were from the 2004 tsunami. Apart from the KK6 pit, they were relatively uniform, with thickness being on average from 8 to

12 cm thickness (Fig. 3), although within a single pit the changes were usually in range of 1–15 cm. They were composed mostly of medium- to very coarse-grained sand, moderately to poorly sorted, with grain size fining upward. The layer had a sharp uneven lower contact with the remnants of former soil. In all the cases, development of new soil, with up to 3-cm-thick surface organic reach layer, was observed. After 5 years, the 2004 tsunami deposits were already disturbed by post-depositional changes, including mixing by growing roots, rodents, and insects.

The KK6 pit (documented in 2005) was dug, in contrast to the other pits, in low-lying, periodically flooded area (Fig. 2). The 2004 tsunami deposits were found to be 40 cm thick and were covering black stiff mud layer with still preserved bent grass in living position (Fig. 3). The lower 30 cm were composed of massive very coarse sand with shells and with mud clasts in its upper part (Fig. 3). The mud clasts were of the same colour and composition as the underlying sediments. Their maximum diameter was about 20 cm. The upper 10 cm of the tsunami deposits was composed of medium sand fining upward.

4.1.2 Older sediments

The deposits predating 2004 tsunami were generally composed from medium to very coarse sand. In pits KK3 and large part of KK4, the most of the sediments consisted of partly laminated sand capped with the remnants of pre-2004 soil. However, in case of KK1, KK2, KK5, and the lowermost part of KK4, an approximately 1-m-thick layer of very coarse massive sand with common big shells of nearshore snails and bivalves (with *Turritella* spp. and *Anadara* spp. the most frequent) and scattered rounded, slightly elongated, black, brownish, or yellowish mud clasts with maximum diameter in a range of 4–30 cm was found (Fig. 3). The layer was continuous at least for 150 m. The lower contact with underlying well sorted medium to coarse sand was sharp. The grain size was generally the same among the sites (very coarse sand), except of the most landward site (KK2), where also finer fractions were intercalated. At KK2 site also the number of mud clasts was the lowest and the size the smallest. The upper part of the layer was a part of pre-2004 tsunami soil (except of KK4); it is depleted in shells and mud clasts and was changed by the former soil and groundwater related processes, including redox changes exemplified in changes in colour of the sand as well as mud clasts.

4.2 Foraminifera

Foraminifera were found only in samples taken from 2004 tsunami deposits. No foraminiferal tests were encountered in the older sediments.

In all five samples from the 2004 tsunami layers, only benthic foraminifera were present (Table 2; Fig. 4). The assemblages are of rather low diversity and they are strongly dominated by calcareous forms. Only two specimens of agglutinating *Quinqueloculina agglutinata* were found in sample from KK1 pit. A great majority of foraminiferal test are

Table 2 The results of the AMS 14C dating

Pit	Depth below ground surface (cm)	Lab no.	AMS ^{14}C age	Dated material
KK1	60	Poz-33353	>43000 BP	*Anadara* spp.
KK1	29	Poz-33354	45000 ± 4000 BP	*Turritella* spp.

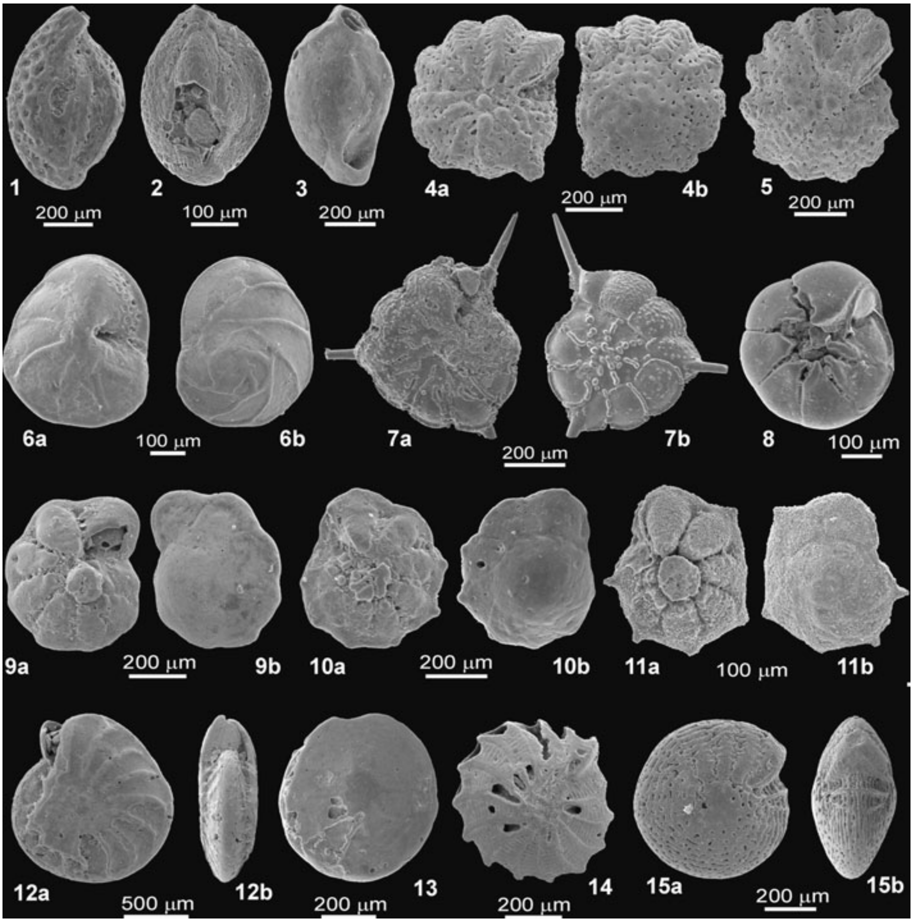

Fig. 4 SEM images of foraminifera from 2004 tsunami deposits. **1**. *Quinqueloculina pseudoreticulata* Parr 1941, KK4; **2**. *Quinqueloculina seminulum* (Linn 1758), KK3; **3**. *Quinqueloculina* sp. KK1; **4**, **5**. *Pararotalia stellata* (de Férussac 1827), KK1, KK4; **6**. *Eponides repandus* (Fitchell and Moll 1798), KK1; **7**. *Asterorotalia pulchella* (d'Orbigny 1839), KK2; **8**. *Ammonia tepida* (Cushman 1926), KK3; **9**. *Ammonia parkinsoniana* (d'Orbigny 1839), KK1; **10**, **11**. *Ammonia* cf. *parkinsoniana*, KK1, KK2; **12**, **13**. *Amphistegina* spp., KK5, KK4; **14**. *Elphidium* sp., KK4; **15**. *Elphidium craticulatum* (Fitchell and Moll 1798), KK2

poorly preserved. They bear signs of chemical and/or mechanic weathering (Fig. 4). For this reason, it was impossible to assign between 10.6 and 62.4% of specimens into particular genus. They were placed into "unrecognized" category.

The most abundant (up to 56%) is *Ammonia* spp., greatly dominated by *Ammonia parkinsoniana* and similar forms (Fig. 4. 9–11) and *Pararotalia stellata* (Fig. 4. 4–5). The later, being quite robust, constitutes up to one-third of total assemblage in samples KK1 and KK4. They are both considered to be typical for inner shelf (Hawkes et al. 2007). Less numerous are *Quinqueloculina* (2.6–7.2%), *Amphistegina* (5.5–14.3%), and *Elphidium* (2.1–6.3%), the last being dominated by *Elphidium crispum* and *Elphidium craticulatum*. Other taxa include *Eponides*, *Asterorotalia*, and a few species of miliolid foraminifera.

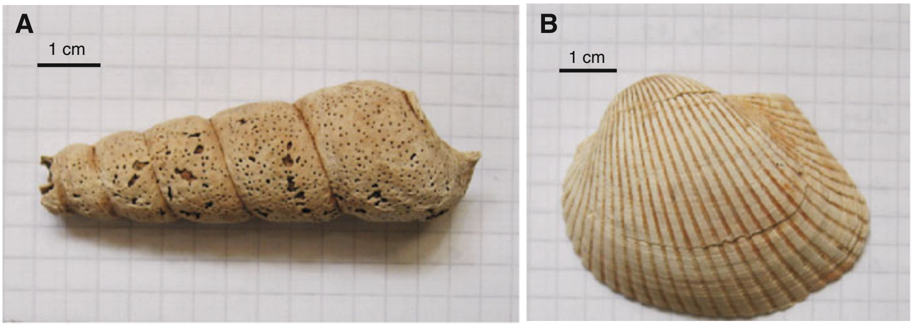

Fig. 5 Samples selected for radiocarbon dating from KK 1 (**a**) at depth 29 cm *Turritella* spp. (**b**) at depth 60 cm *Anadara* spp.

Table 3 Foraminiferal abundances in percentages of total assemblage in samples from 2004 tsunami deposits

	Sample				
	KK1	KK2	KK3	KK4	KK5
Quinqueloculina spp.	7.2	3.0	7.2	3.8	2.6
Pararotalia stellata	33.9	14.0	11.6	34.4	9.5
Ammonia spp.	24.6	53.8	56.0	2.5	7.4
Amphistegina spp.	5.5	6.8	7.7	5.6	14.3
Elphidium spp.	4.2	2.7	5.8	6.3	2.1
Others	5.5	0.8	1.0	0.6	1.6
Unrecognizable	19.1	18.9	10.6	46.9	62.4
Total # of specimens	236	264	207	160	189

The foraminiferal assemblages seem to be modified by post-depositional processes already 5 years after the tsunami. Samples KK4 and KK5, which show the highest percentages of unrecognizable foraminifera (Table 2), are devoid of minute specimens, which is expressed in low *Ammonia parkinsoniana* percentages.

4.3 ^{14}C ages

Two relatively large shells (Fig. 5) of nearshore snail (*Turritella* spp.) and bivalve (*Anadara* spp.) were collected from KK1 pit, respectively, at depth 29 and 60 cm, from a hypothetical paleotsunami layer, and dated with AMS ^{14}C technique. The obtained ages of over 40 ka BP (Table 3) are very close to the border of the method application, so the dates can be treated as minimum values only.

5 Discussion

The presented results showed that in coastal sediments of southern Kho Khao Island exist a layer of pre-2004 tsunami sediments, which is characterized by several features typical for high energy and abrupt event. Moreover, many of the characteristics are shared with 2004 tsunami deposits at the same site. Summarizing, the discussed event layer was found in pits on the landward side of a periodically flooded area (lagoon), they have a significant thickness (up to 1 m), they are laterally continuous (for at least 100 m), they are composed of very coarse sand with several cm big shells (but no minor shells or foraminifera) and they contain large mud clasts. Unfortunately it was not possible to trace the layer further landward because of former mining.

The striking similarity with 2004 tsunami sediments found nearby (KK6), in both cases there is a thick layer of massive very coarse sand, rich in mud clasts, suggests us to consider a paleotsunami origin for the event layer. Storms are not frequent in the area (see Jankaew et al. 2008 for discussion, Brand 2009). There were several tropical cyclones recorded during the twentieth century passing next to the study area (Brand 2009). However, despite their record can be traced in the middle continental shelf deposits (Szczuciński 2010), they have not been registered to cause significant water level changes on the eastern coast of Andaman Sea due to their westward oriented tracks (Brand 2009). Moreover, the documented layer reveals several characteristics, which are suggested by several authors to be absent in onshore storm deposits, for instance large mud clasts (see Kortekaas and Dawson 2007; Morton et al. 2007). Mud clasts of smaller sizes have been found on Andaman Sea coast also in 2004 tsunami deposits from other sites (e.g. Szczuciński et al. 2006, in review; Choowong et al. 2008a). On the other hand, they have not been found in the storm deposits forming beach ridges. Presence of shells suggests rather marine origin of the sediments. The lack of smaller shells and foraminifera is attributed to post-depositional dissolution. As was presented above foraminifera from 2004 tsunami deposits sampled after 5 years were already not well preserved, were partly dissolved and smaller foraminifera tests were probably already lost. The dissolution of carbonates was also well visible on the preserved bigger shells (Fig. 5).

If the discussed sediment are due to paleotsunami event then a question arise, when did it took place. The only suitable material for dating was the shells in the sediment layer. The obtained ages of more than 40 ka is a maximum age and it is not likely to represent the age of the event. About 40 ka BP the sea level was approximately 80 m lower in the region (Hanebuth and Stattegger 2004), moreover at that time the study site did not exist, since the coastal part of Kho Khao Island is built of beach ridges formed after the mid-Holocene sea level highstand (Sinsakul 1992). So the dated shells had to be redeposited from older sediments and the hypothetical paleotsunami event had to take place probably in the late Holocene, when the outer beach ridge was already formed and the lagoon already existed, so mud could be deposited and later on eroded. The existing record of paleotsunamis from the region reveals that about 600 years ago a tsunami took place (Harper 2005, Jankaew et al. 2008), which left sediments in some places thicker than 2004 tsunami. The thickness and the grain size of the tsunami deposits depend primary on the available sediment for erosion and transport and then on the tsunami forces. However, as was found in the case of 2004 tsunami on Andaman Sea coast, there is a positive correlation between tsunami runup height and the thickness of resultant deposits (Szczuciński et al. in review). The reported hypothetical paleotsunami deposits are thicker than the corresponding 2004 tsunami deposits. So, one may speculate if the event deposits documented in this paper origin from the same paleotsunami event as described in the previous works, which could be even larger than 2004 tsunami. Alternatively, the coastline configuration at the time of the paleoevent could be slightly different enhancing deposition of such a thick sediment layer. However, further extensive field and laboratory studies are necessary to confirm the age of the event.

6 Conclusions

The presented results lead to several conclusions:

1. The paleotsunami record on the Andaman Sea coasts is restricted to limited areas, which were not subjected to placer mining and in most places is very difficult to be recognized because of post-depositional changes and similarity to the underlying sediments.
2. The 2004 tsunami deposits after 5 years are still visible in many places, however, are subjected to post-depositional changes related to soil formation and dissolution of carbonates (e.g., foraminiferal tests).
3. In the study site at southern Kho Khao, where 2004 tsunami deposits were characterized by massive very coarse sand rich in mud clasts, similar deposits were found in form of about 1-m-thick layer of very coarse sand rich in big marine shells and mud clasts; its characteristics suggest that it could have been deposited by paleotsunami event, bigger than 2004 tsunami, during the late Holocene; however, precise dating of the event was not possible.

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