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Original Research

Depositional Effects of 2004 Tsunami and Hypothetical Paleotsunami Near Thap Lamu Navy Base in Phang Nga Province, Thailand

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Abstract

On December 26th, 2004, a tsunami hit the Andaman Sea coast of Thailand, leaving bimodal tsunami deposits in the coastal zone. Granite boulders and sandy tsunami deposits were investigated near Thap Lamu Navy Base in Phang Nga Province, Thailand. Boulders (< 2.5m^3) were mostly scattered close to a tidal inlet on a flat plain elevated 1-2m above the high tide water level, reaching up to 140m inland. Most boulders had oyster shell remnants over their surface, which suggests that they were dragged from the nearby shore. The tsunami also brought a sheet of medium to coarse grained sand, with thickness ranging from a few mm up to 37cm. The distribution of deposits was mainly controlled by the existing topography. Another group of granite boulders was found between 150 and 300m from the coastline, at elevations of 2m and more. Their size reached 5.5m^3. This second group of boulders may have been transported by an ancient tsunami.

Keywords: tsunami deposits, boulders, paleotsunami, Andaman Sea, Thailand

Introduction

The Andaman Sea coastline of Thailand is a region where tsunamis are not well known. There is no historical record of tsunamis in Thailand and thus it is quite difficult to assess their frequency without some means of extending the historical record. This data is necessary for an estimation of tsunami risk hazard. Until now, the only recorded event is the Indian Ocean tsunami on December 26th, 2004. During this event, the Andaman Sea coast was heavily affected and a layer of deposits was left covering most of the tsunami-inundated coastal zone. Afterward, the depositional effects of the tsunami on land were reported from various places in the region [1-9]. Generally, the 2004 tsunami deposits are quite heterogeneous. The majority of deposits are composed of sand, with some boulders derived from coral reefs [4, 7] and small floating boulders in bimodal tsunami deposits [8] being observed. A detailed study of modern (i.e. the 2004 tsunami) deposits is necessary to enable better understanding of tsunami wave behavior on land. Also, this study can be used as a reference to gain knowledge of how paleotsunami deposits may look in the region. As shown in numerical simulations by Løvholt et al. [10], an earthquake of magnitude 8.5, causing a tsuna-

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mi with a runup height up to 3m, is likely to occur within the next 50-100 years. Bigger tsunamis may be present when longer intervals are taken into account. It is extremely important to verify these types of simulations with geological records from the past.

In this study, tsunami products were documented in detail, including modern sandy tsunami deposits and granite boulders left in the area near Thap Lamu Navy Base in Phang Nga Province, Thailand. Although granite boulders were described for the first time in Thailand, they are commonly related to tsunami deposition events worldwide [11-13] and their preservation potential may be higher than that of sandy deposits. Moreover, the present paper shows evidence of other boulders being found in the same area. These were potentially transported by a hypothetical ancient tsunami. Most of the Southern Thailand coast has been heavily disturbed by onshore and offshore placer mining activities. Thus, it is difficult to find proof of former tsunamis by means of sand deposits. In this situation, boulder deposits may be very helpful to expand the state of knowledge on tsunami frequency along the Andaman Sea coastline.

Two major objectives of the presented paper include:

- presentation of documents from the 2004 tsunami deposits, consisting of sandy material and boulders, as a potential reference in the search for a paleotsunami record;
- analysis of a set of older boulder deposits from the same area, in context with their hypothetical tsunami-related origin.

Study Area

Sand and boulder deposits from the 2004 tsunami were observed near a small bay in the area between Khao Lak, about 9km north of the bay, and Thap Lamu, about 4km south of the bay (Fig. 1). The assessed area covers approximately 1km^2 and is bordered by a granite ridge from the north and east, a mixed rocky/sandy coastline to the west, and a river-tidal channel to the south. Bedrock outcrops of Mesozoic granite make up topographical elevations in this area, while depressions are filled with Quaternary deposits [14]. The coastline was strongly eroded during the 2004 tsunami, as reported by local eyewitnesses (Fig. 1). The runup height of the tsunami was on the order of 7m.

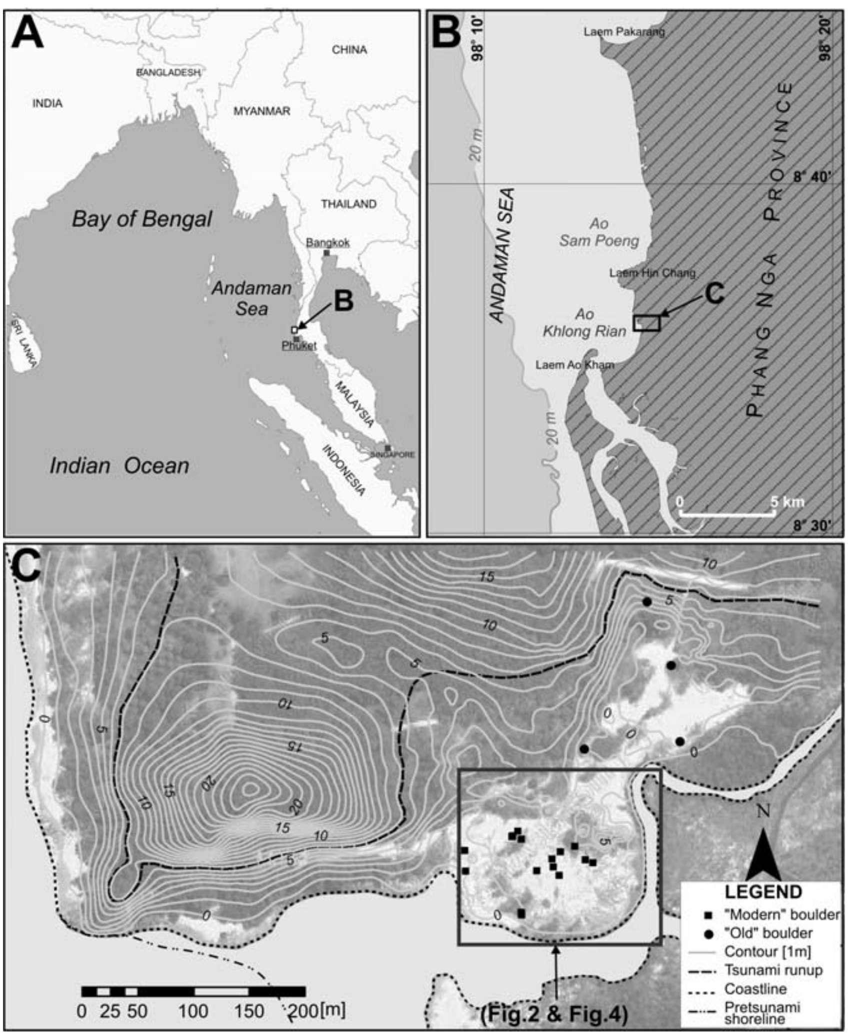

Fig. 1. Study area within the Andaman Sea region and Phang Nga Province. The lower map shows results of a topographic survey, including the distribution of boulders, as well as the tsunami inundation limit. Topographical data is based on a survey performed by the authors. "Modern" boulders refer to 2004 tsunami deposits and "old" boulders refer to pre-2004 deposits.

Materials and Methods

Field investigations were carried out in February 2007 and February 2008. Topographical mapping was performed with theodolite. Measurements were referenced to local sea level datum, which was determined using the predicted high tide level (h.t.l.) and the actual position of high water on the day of the survey. During the survey, all of the boulders, both those deposited by the 2004 tsunami and older materials, were localized, measured and described. Sandy tsunami deposits were sampled in a grid (Fig. 2). During sampling, observations were made regarding tsunami deposit thicknesses, lower contacts and structures. Forty-seven samples were also taken from the bulk tsunami layer and four were taken from pre-tsunami soil. To determine the grain size distribution, sediment samples were dried and sieved into thirteen 0.5 phi intervals. Conversion of micrometers into phi values is based on the following relationship:

$$\text{phi } (\Phi) = -\log_2 D$$

...where D equals the size in millimeters. Analysis of grain size statistics (e.g., mean and sorting) was performed according to the Folk and Ward [15] graphical methods using Gradistat software [16].

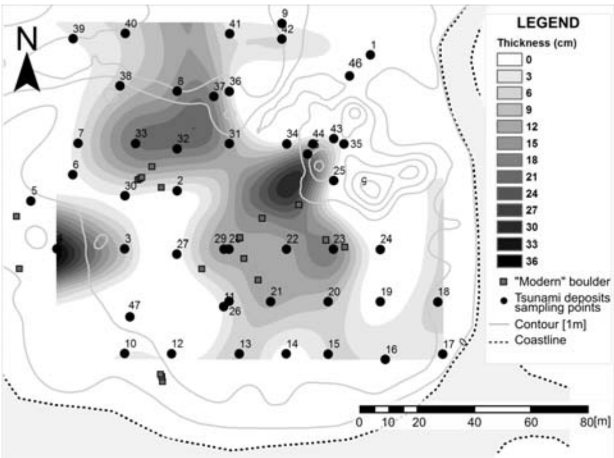

Fig. 2. Tsunami sand deposit thickness map, with sampling point locations and 2004 tsunami boulder deposits noted.

Results

Topographical Survey Results

The detailed topographic map, generated at a scale of 1:1000 (Fig. 1), demonstrates the relative flatness of the studied area (1-2m above h.t.l.). Prominent bedrock outcrops in the middle portion were found to rise up to 5m above h.t.l. and a small escarpment running approximately in the NW–to-SE direction reached 3m above h.t.l. These obstacles were flooded by the tsunami wave; however, almost no deposits were found on their landward side.

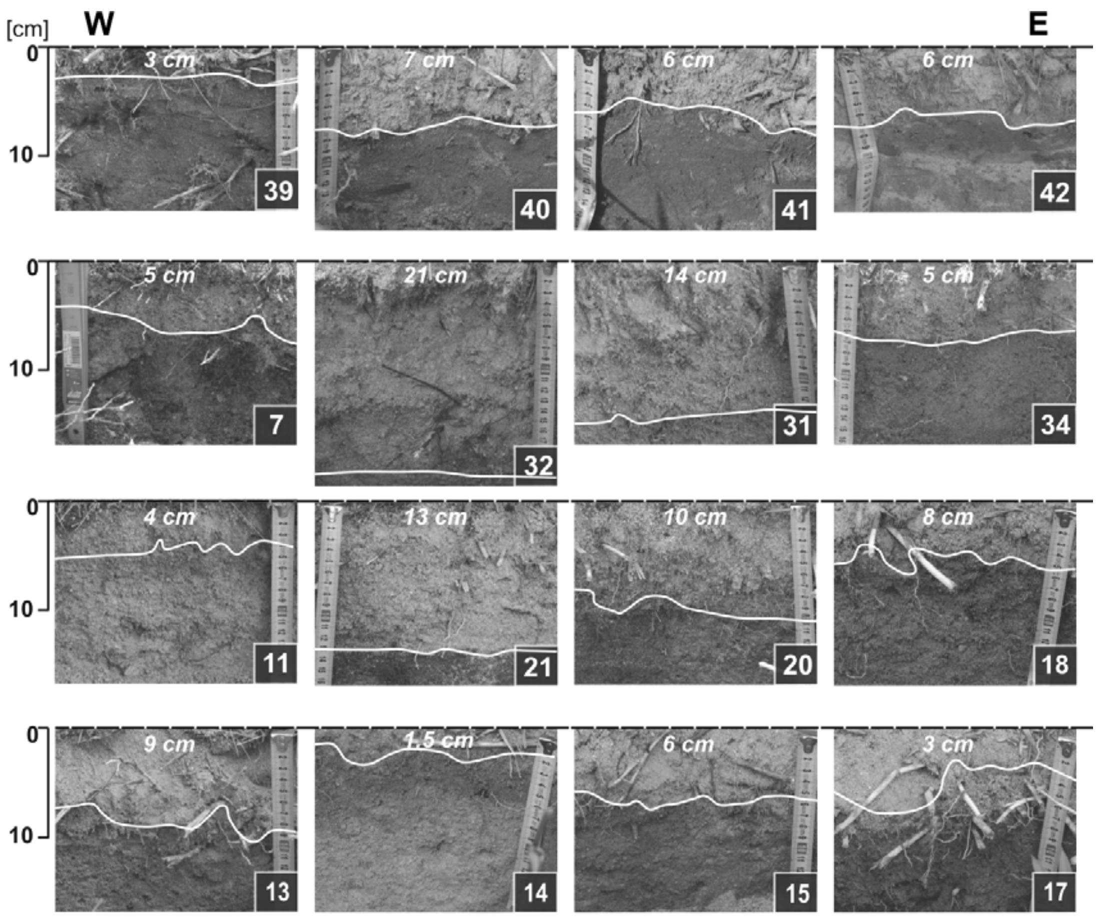

Fig. 3. Examples of sandy tsunami deposits. Numbers refer to sampling points in Fig. 2. Note the sharp contact with pre-tsunami soil.

Table 1. Size, weight, distance from shoreline and specific boulder features in the studied area. “M” represents boulders transported by the 2004 tsunami; “B” represents boulders transported before the 2004 tsunami.

Boulder	Length (cm)	Width (cm)	Height (cm)	Volume (m^3)	[1]Weight (ton)	[2]Distance (m)	Oyster shell	Broken
M1	117	47	96	0.53	1.45	45	y	y
M2	158	93	70	1.03	2.83	30	y	y
M3	110	90	70	0.69	1.91	66	y	y
M4	162	103	106	1.77	4.86	80	y	y
M5	54	75	88	0.36	0.98	81	n	y
M6	190	130	93	2.30	6.32	82	y	y
M7	148	118	94	1.64	4.51	88	y	y
M8	97	60	55	0.32	0.88	80	y	y
M9	78	40	27	0.08	0.23	80	y	y
M10	65	33	12	0.03	0.07	80	y	y
M11	64	25	15	0.02	0.07	106	y	y
M12	113	58	30	0.20	0.54	104	y	y
M13	80	80	60	0.38	1.06	103	y	y
M14	35	17	11	0.01	0.02	86	y	y
M15	120	100	80	0.96	2.64	113	n	y
M16	120	110	80	1.06	2.90	125	y	y
M17	130	100	80	1,04	2,86	132	n	y
M18	80	60	30	0.14	0.40	140	y	y
B1	130	118	95	1.46	4.01	230	n	n
B2	220	140	180	5.54	15.25	295	n	n
B3	130	96	47	0.59	1.61	315	n	n
B4	70	40	50	0.14	0.39	265	n	n
B5	75	70	55	0.29	0.79	300	n	n
B6	220	145	110	3.51	9.65	300	n	n

[1]Weight was estimated using an average granite density of 2750 kg/m^3.
[2]Distance from the shoreline refers to the direction from which the tsunami wave came (from west).

2004 Tsunami Sand Deposits

Approximately one half of the area flooded by the tsunami is covered with a deposited sand sheet. This layer has a thickness ranging from a few mm to 37cm, with 9.1cm being the average thickness for 47 measurements. The thickness map of the 2004 tsunami deposits shows a clear pattern. The thickest layer is located on the SW side of the escarpment and bedrock outcrop (Fig. 2).

Internal structure of the sand layer was usually masked by post-depositional changes, mostly related to plant growth and mixing owing to root development (Fig. 3). However, the lower boundary was, in all cases, sharp and readily visible. In places having a greater thickness, an upward fining trend was still observed.

Grain size analysis revealed that samples consisted mostly of medium to coarse grain sand, were moderately to poorly sorted, and were very fine to very coarse skewed. The spatial pattern of the mean, sorting and skewness (Fig. 4) reveals a trend that is similar to that observed for tsunami deposit thicknesses (Fig. 2). Southwest of the small escarpment and bedrock outcrop, deposits consisted of fine to medium grained sand. These were moderately to poorly sorted and symmetrical to coarse skewed. In the remaining area, sand was usually coarse grained, poorly sorted and fine skewed.

Four pre-tsunami soil samples demonstrated similar distributions when compared to the 2004 tsunami deposits. These were composed of medium to very coarse sand, were poorly sorted and their skewness varied from very fine to coarse skewed.

2004 Tsunami Boulder Deposits

Eighteen granite boulders, which were transported by the 2004 tsunami wave, were found scattered on a flat plain between 30 and 140m from the shoreline (Figs. 1, 2 and 5; Table 1). Almost half of them were lined up in a row about 80m from the coastline. Their sizes varied from 0.005 to 2.3m^3 and their average weight was found to be 2.14 tons, with a maximum weight of 6.32 tons (Table 1). Boulders found closer to the shoreline were more elongated than those transported further inland. All boulders were broken and possessed some readily visible, fresh, unweathered surfaces (Fig. 5A). Most of the boulders had a rim of oyster shells attached to them, often in a vertical position (Fig. 5A and B). These shells prove the boulders' origin at the modern coastline and their overturning during transport.

Pre-2004 Tsunami Boulder Deposits

Several granite boulders, having no traces of recent transport, were found between 230 and 300m from the modern coastline (Figs. 1 and 5; Table 1). Most of these were settled along a small escarpment (Fig. 1). They varied in volume from 0.14 to 5.5m^3. Their average weight was 5.5 tons, with a maximum weight of over 15 tons. These boulders were rounded and their surfaces showed traces of chemical weathering. The bases of the boulders were excavated and they were found to be deposited on abraded and rounded bedrock outcrops.

Discussion

This study proves that tsunami deposits in Thailand may have a bimodal nature, including both sand sheet and boulder features, which have been rarely mentioned before in this region [7, 8]. Although tsunami sand deposits were sampled more than three years after the 2004 tsunami, they were still preserved. However, post-depositional processes masked their sedimentary structure. As shown by Szczuciński et al. [8, 17], no major changes in deposit thickness were observed in several cm-thick layers after the first rainy season. Thus, we assume that the documented distribution is similar to that which resulted from the tsunami, except for the most inland areas where no deposits were found. Most likely, the more inland zone was originally covered with a thin layer of tsunami deposits, which was later removed. Szczuciński et al. [17] also mentioned that, after the first rainy season, coarse sand tsunami deposits were depleted into finer fractions owing to washing, thus causing overall deposits to become coarser. This must be taken into account when using the present data as a source for further research (e.g., for sedimentation modeling).

The distribution of sand deposits, as well as changes in their grain size distribution, reveals a pattern that is probably controlled by local topography. In this distribution, the thickest, finest and most highly sorted deposits were left in front of a small escarpment and basement outcrop. Similar situations when using topography-controlled deposition were also observed in other places [6, 8]. Obstacles could cause a reduction in the tsunami current velocity and thus enhance deposition.

Boulders transported by the 2004 tsunami were probably moved from the shoreline, which is composed of similar rounded boulders with horizontal oyster shell rims at water level. Therefore, during tsunami flooding the boulders were not submerged and the coast was reached first by the tsunami wave trough. Boulders were also already

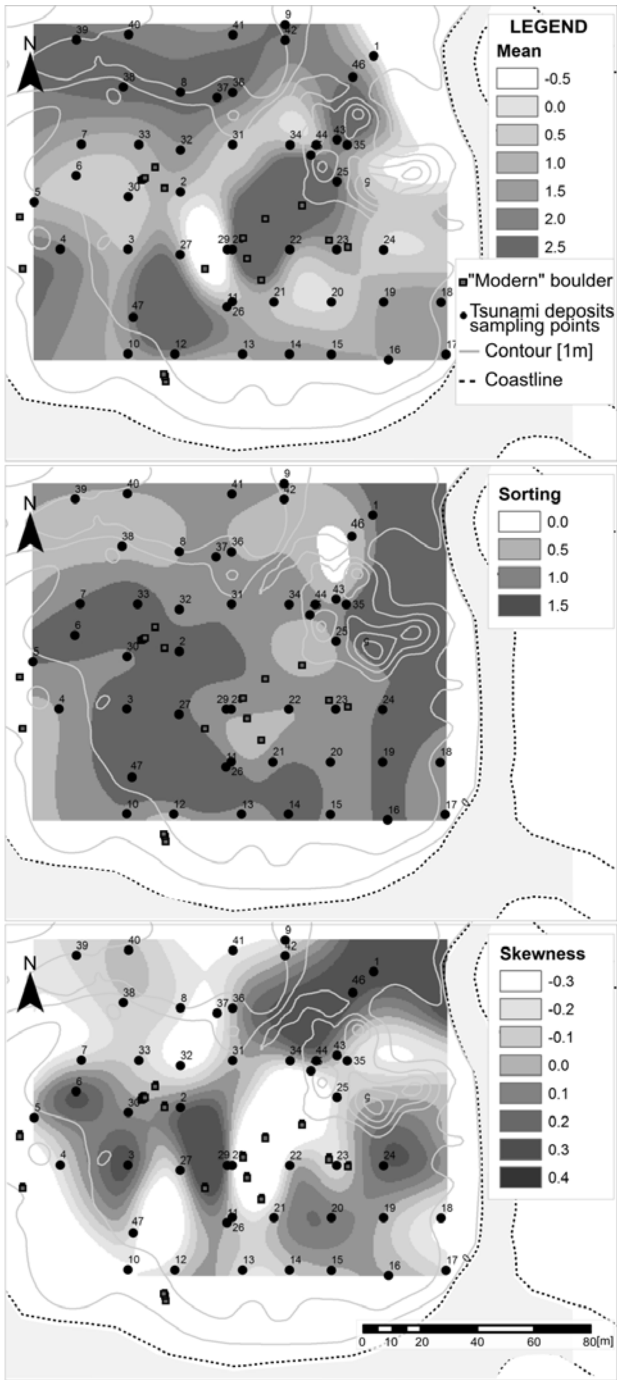

Fig. 4. Mean, sorting and skewness calculated from tsunami sand deposit grain size distributions.

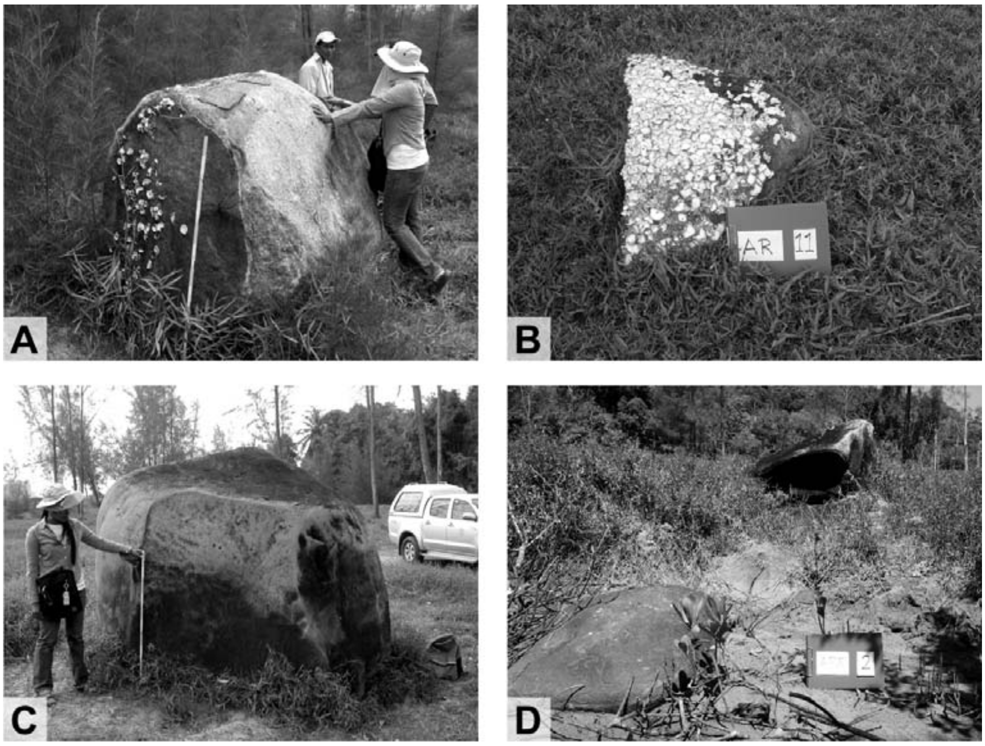

Fig. 5. Examples of 2004 tsunami (A, B) and pre-2004 (C, D) boulders. Note the freshly broken surfaces and rim of oyster shells on 2004 tsunami boulders.

detached and rounded. The tsunami wave, apart from moving them almost 200m inland, also caused crushing during transport, resulting in fresh, unweathered surfaces. To evaluate the minimum velocity necessary to move the largest boulders, formulae developed by Nott [18] were applied. The calculated velocity is approximately 2.2m/s. This is well within the range of observed velocities for the tsunami wave during runup, which were estimated to be 2 and 5m/s based on survivor videos [19]. Boulders, similar to sandy deposits, were not transported over topographical obstacles, indicating that the tsunami energy had decreased upon reaching them.

Until now, there was no well documented proof in the sedimentary record of previous tsunamis in Thailand. In part, this is due to large-scale tin mining, which caused sediment mixing along most of the coastal plain [8]. Thus, boulder deposits could potentially provide a better preserved historical tsunami record. Pre-2004 tsunami boulders found within the study area were considered in this context. The boulders' location and positioning suggest that they were transported to their present positions from the seaward side. The lack of carbonate shells on these boulders is not surprising, as chemical weathering of carbonates on acid rocks is relatively fast in this climate. Several hypotheses exist regarding their genesis. If they were transported in an environment similar to the modern coastline, it would be necessary to have a tsunami or storm event even more powerful than the 2004 tsunami. This requirement is also supported by the size of the biggest boulder. Using the formula proposed by Nott [18], the minimum water velocity to move this boulder is about 6m/s. On the other hand, the boulders could also have been transported for much shorter distances during the Holocene sea level highstand, when sea levels were a few meters higher than at present [20]. However, a more detailed study of the local coastal evolution is necessary to solve this problem.

The results presented here do not support earlier opinions concerning a very limited number of 2004 tsunami boulder deposits along the coast of Thailand and other countries [7]. Boulders, although not very common, were found in several places, including on Sumatra [21]. The limited amount of boulder deposits is probably due in part to coastline types containing a small amount of boulders that are suitable for transport.

Conclusions

The results of this study lead to several preliminary conclusions:

- the 2004 Indian Ocean tsunami caused a simultaneous deposition of both sand and boulder deposits on land, when both materials were available for erosion and transport;
- the distribution and grain size of sand deposits was, to a large extent, controlled by local relief, with small elevations and scarps enhancing deposition;
- the tsunami transported boulders with a maximum weight of about 6 tons up to 140m inland. The minimum necessary water velocity was about 2.2m/s;
- several pre-2004 tsunami boulders found in the region may have been transported in the past by catastrophic flooding that was larger than the 2004 tsunami or occurred during the mid-Holocene, during which time sea levels were higher.

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