15

Sand Sheets on a Beach-Ridge Plain in Thailand: Identification and Dating of Tsunami Deposits in a Far-Field Tropical Setting

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1. Introduction

Surveys of recent tsunamis, especially the 2004 Indian Ocean tsunami, demonstrate that tsunami deposits are different from place to place and that tsunami geology is very complex. This complexity has increased the challenges of identifying and interpreting of past tsunamis in many parts of the world as no set of criteria are suitable in all locations. In this chapter we present a case study of tsunami deposits, both modern and ancient, from Thailand. We discuss further complications and challenges associated with identifying and dating paleotsunami events in this tropical setting that include post-depositional change, the absence of marine microfossils and lack of appropriate materials for dating. Preservation potential of 2004 tsunami deposit in Thailand will also be considered.

2004 Sumatra-Andaman earthquake and associated tsunami seemed unprecedented as there was no written or instrumental record of great earthquakes (M > 8) in this region. No event comparable to the 2004 tsunami is recorded in known historical sources from the Indian Ocean region (Dominey-Howes et al., 2007). Surviving historical accounts in Thailand, mainly from European visitors and Indian and Chinese traders to the Siam Kingdom (Thailand) via Takola- or later known as Takau Pa, a major trading southern coastal town, also lack identified accounts of a large tsunami affecting the Thailand Andaman Coast. Accordingly, prior to the 2004 tsunami, Thailand had almost no awareness of tsunami hazards, let alone any warning system or mitigation measures in place. This situation contributed to the loss of life in Thailand during the 2004 tsunami.

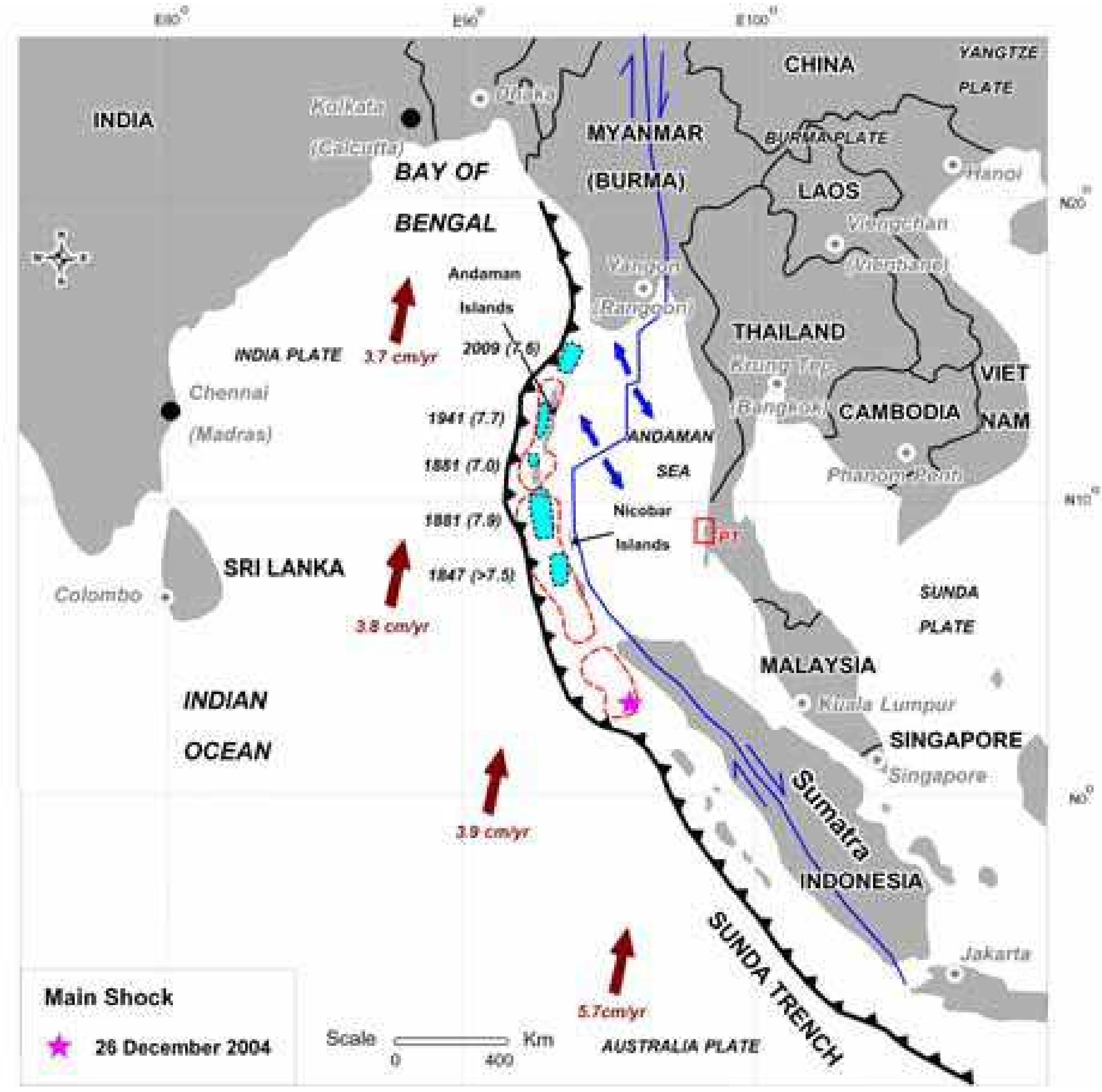

Fig. 1. Setting and rupture areas of large and giant earthquakes in the Sumatra-Andaman area. Star is 26 December 2004 earthquake epicenter. Red dash defines the 2004 rupture area (from Chlieh et al., 2007). Plate convergence rates are from Chlieh et al. (2007). The areas in light blue are rupture areas of historical earthquakes (from Ortiz & Bilham, 2003; Bilham et al. 2005). PT is Phra Thong Island.

It had been thought that subduction zones capable of producing great earthquakes are those with young subducting plates and fast subduction rates (Ruff & Kanomari, 1980). But after the 2004 Sumatra-Andaman earthquake, which occurred where old plates have modest subduction rates, Stein & Okal (2007) have shown that plate ages and subduction rate do not fully predict earthquake magnitudes on subduction zones.

Earthquake magnitude and recurrence interval are important information needed for hazard mitigation. Estimation of earthquake size and tsunami recurrence intervals can be obtained from geophysical studies alone or in combination with paleoseismological studies. Current geophysical estimates of great earthquake recurrence intervals along the Sunda Trench are 140-420 yr (Chlieh et al., 2007) and 200-1000 yr (Stein & Okal, 2007). The large variation in the range is due to the complex and poorly understood tectonic setting of this subduction zone (Stein & Okal, 2007).

A history of past earthquakes and resultant tsunamis can be extended into the prehistoric past by means of geology. Paleoseismological records can be derived from ages and heights of uplifted terraces (e.g. Aung et al. 2008; Rajendran et al., 2008) and ages and level of vertical movement recorded in coral microatolls (e.g. Sieh et al., 2008; Meltzner et al., 2010) above or near the active subduction zone. Paleotsunami deposits are sediments, typically sand-sized but grain size can range up to boulders, moved and left behind by tsunamis (Dawson and Shi, 2000; Bourgeois, 2009). Tsunami deposits can be found both near and far from the tsunami source (Dawson et al., 1988). Paleoseismological and paleotsunami records, if correctly identified and dated, can extend the chronology of earthquake and tsunami of the area for several thousand of years beyond the historic time (e.g. Kelsey et al., 2005).
To improve understanding of the risk from large Indian Ocean tsunamis, there is a need to study tsunami deposits in order to extend the tsunami record in this region. Thailand is situated about 600 km east of the northern Sunda subduction zone-the main and probably the only tsunami source for Thailand. We aim to understand the characteristics of the 2004 tsunami deposits as well as searching for paleotsunami deposits in Thailand. Once identified with confidence, the ages of tsunami deposits is hoped to extend the chronology of large earthquake and associated tsunamis in Thailand. Satake & Atwater (2007) were able to show--using examples of written history in combination with geological study from Chile, Cascadia and Japan-- that earthquake sizes and repeat time along the Pacific Realm subduction zone are varied (non predictable, non characteristic). However, at present, data available on the history and behavior of the Sunda subduction zone is rather scarce. Ages of tsunami deposits from Thailand will help characterize the long-term behavior of the Sunda subduction zone and provide recurrence estimates that can be used to support future tsunami mitigation and risk assessment of the country.

Importance of paleotsunami study of this region

The historical record of large earthquakes and tsunamis in the Indian Ocean is rather brief, as written history of Banda Aceh only extends back to c.1530 AD (Reid, 2005). Long-term behavior of this subduction zone is still obscure; hence risk from tsunami of this region is poorly understood. Earthquake source characteristics, size and recurrence are also not comprehend. Prior to 2004, historical records of large earthquakes in the northern Sunda subduction zone contained no earthquakes bigger than Mw 8 (Fig.1); M 7.5-7.9 (1847, north of Little Nicobar), 7.0 and 7.9 (1881, Car Nicobar) and 7.7 (1941, Middle Andaman) (Ortiz & Bilham 2003). On 10 August 2009 there was an earthquake of magnitude 7.6 with an epicenter reported to be just north of 1941 rupture area.

2. Previous works

Background research in paleotsunami study

Paleotsunami studies involve identification, mapping, and correlation and dating of tsunami deposits (Bourgeois & Minoura, 1997). Paleotsunami deposits are often identified in low-energy coastal environments, such as tidal marsh, back-barrier marshes and coastal lakes.
Most publications on paleotsunami studies during the past two decades are from temperate zones such as the north Atlantic (Bondevik et al., 1997; Bondevik et al., 2003; Dawson et al., 1988), the circum-Pacific shores of the Americas and Asia (Atwater & Moore, 1992; Atwater et al., 2005; Bourgeois et al., 2006; Cisternas et al., 2005; Fiedorowicz & Peterson, 2002; Kelsey et al., 2005; Minoura & Nakata, 1994; Nanayama et al., 2003; Tuttle et al., 2004) and New

Zealand (Chague-Goff et al.,2000; Goff et al., 2001; Goff et al., 1998; Grauert et al., 2001). In many cases tsunami studies occur in conjunction with other evidence for large earthquakes such as the study of coastal geological evidence of past tsunamis and associated post seismic uplift in Japan by Sawai et al. (2009b).

Publications describing historic tsunami deposits from the tropics include the 1883 Krakatau tsunami (Simkin & Fiske, 1983), 1992 East Java tsunami (Shi et al., 1995), 1998 Papua New Guinea tsunami (McSaveney et al., 2000; Gelfenbaum & Jaffe, 2003), and 2006 West Java tsunami (Shi et al., 1995).

2004 Sumatra-Andaman tsunami deposits were examined around the Indian Ocean coasts by many groups of scientist (e.g. Goff et al., 2006; Jaffe et al., 2006; Moore et al., 2006; Paris et al., 2010; Singarasubramanian et al., 2006, etc.). In Thailand, 2004 tsunami deposits were investigated by Choowong et al. (2007); (2008a); (2008b); Fujino et al. (2008); Hawke et al. (2007); Hori et al., (2007) and Sawai et al. (2009a) among others. Preliminary results of paleotsunami study in Thailand are reported by Fujino et al. (2008; 2009) and Jankaew et al. (2008). The 2004 tsunami height at several locations along Thailand Andaman coast was surveyed by Tsuji et al. (2006).

Following the 2004 Sumatra-Andaman tsunami there were a few publications detailing paleotsunami study in this area, including Fujino et al., (2009); Jankaew et al., (2008); Monecke et al. (2008); Rajendran et al., (2006). Jankaew et al., (2008) reported at least three sand layers, which are likely to have been deposited by the predecessors of the 2004 tsunami. Using radiocarbon dating, the youngest sand layer (sand layer B) postdates AD 1300-1450. This age overlaps with the age of the tsunami sand layer from Meulaboh, Sumatra by Monecke et al. (2008) and may be correlative to the age of a shell bed deposit of 500 years found in a cave near Ao Nang, southeast of Phuket reported by Harper (2005). The ages of the two lower paleo-sand layers (sand layers C and D in Jankaew et al., 2008) are not well constrained but ages of non-abraded shells in tidal flat sediments underlying these sand layers suggested that both layers were deposited after 2,500-2,800 years ago (Jankaew et al., 2008).

3. Methods

We have been searching for evidence of past tsunamis in the Thai coastal areas inundated by the 2004 tsunami. Sites investigated include Kamala Beach and Le Pang Bay of Phuket Province, Thap Lamu, Pakarang Cape, Ban Nam Khem tidal inlet, Kho Khao Island and Phra Thong Island of Phang Nga Province (Fig. 2). We cored and dug small pits and trenches on the coastal low-lying area including tidal flat, back beach lagoon and mangrove fringed tidal inlet.

Moist environments such as beach ridge swales and coastal lakes preserve tsunami deposits in other environments (e.g. Pinegina et al., 2003; Kelsey et al., 2005) and in Thailand the equivalent environments are beach ridge swales and mangrove swamps.

In our fieldwork we learned that the 2004 tsunami deposits are not well preserved in mangrove environment, mainly because of burrowing by crabs. The 2004 tsunami sands are already being muddled up by these organisms causing low or no tendency of these sands being preserved as a paleotsunami deposit for future observation. Preservation potential of previous tsunamis along the Andaman coast of Thailand is further jeopardized by the extensive placer tin mining, coastal developments and other human disturbance of the area. Thus far, only on nearly undisturbed beach-ridge plains at Phra Thong Island has it been possible to find numerous sites for preserving geological records of pre-historic tsunamis in Thailand.

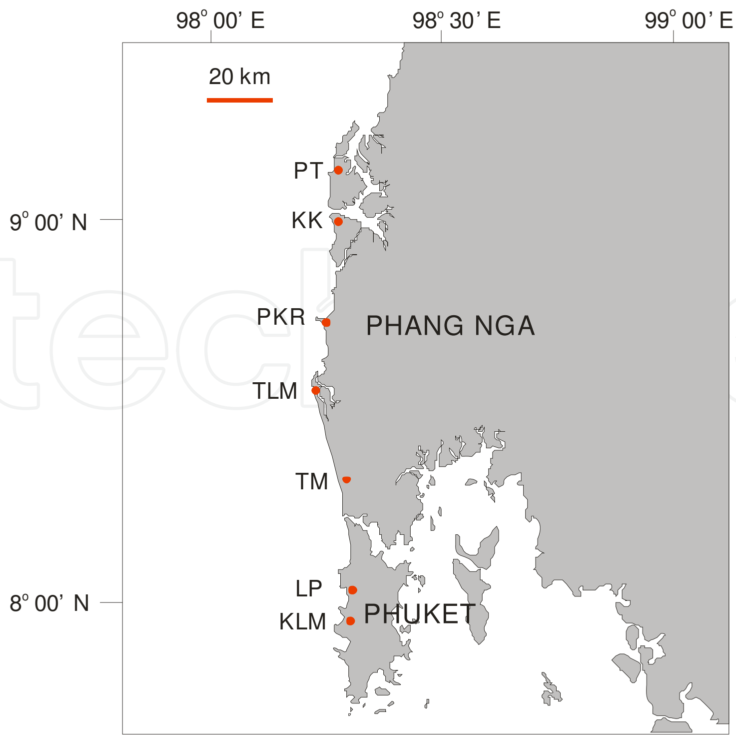

Fig. 2. Map shows locations along the Andaman Coast of Thailand that we have investigated. KLM= Kamala Beach, LP = Le Pang Bay, TM = Tai Maung, TLM = Tap Lamu, PKR = Pakarang Cape, KK = Kho Khao Island, PT = Phra Thong Island

4. Setting of Phra Thong Island

Phra Thong Island is located about 125 km north of Phuket. The island is about 10 km wide and 15 km long, facing the Andaman Sea without any obstruction. It is completely cut off from the mainland by tidal channels. There is no running river on the island except some small tidal channels. Due to its location of just north of the Equator, Phra Thong's exposure to tropical cyclones is probably limited to typhoons that have been weakened by crossing the Thai-Malay Peninsula (Murty & Flather, 1994) for example the case of Typhoon Gay in 1989.. Indian Ocean cyclones that originate near the Equator typically moved west- and northwestward towards India, Bangladesh and Myanmar.

Phra Thong is subjected to inundation by tsunamis due to its relatively flat terrain and its exposure to transoceanic tsunamis from the Northern Sunda Trench. The western half of the island comprises series of beach ridges and swales, extending over 2 km inland. The beach-ridge series is believed to have been formed by prograding beach as a result of the receding sea level following a early-mid Holocene sea level highstand. However, currently there is little information on the numerical ages of these ridges. The eastern half of the island is covered with mangroves which extend from the tidal channels. Tidal range average in this area is about 1.8 meters, with a maximum of 2.7 meters.

Phra Thong History

The name Koh Phra Thong (Phra Thong Island) appeared for the first time in Chotmaihet (account or report) of a visit to Malaya peninsula by King Rama V during 16-22 April 1890 but there was no mention if there was settlement on Phra Thong during that time. It was believed that the first settlement on Phra Thong was by sea gypsies. During 1797-1853, Chinese workers migrated to Phra Thong due to the expansion of tin mining in Southern Thailand.

Phra Thong, as with other places along the Andaman Coast of Thailand but to a lesser degree, was subject to tin-mining and other human disturbance. The settlement and tin mining activity on Phra Thong has existed since before 1909 as described in the Chotmaihet of Southern Thai visit by King Rama VI in 1909. The earliest period of tin mining is on Koh Chad, eastern part of Phra Thong, where concession was granted by the government. The three main sites of tin mining are Koh Chad, Tung Oon Nua and Koh Ra. On the beach-ridge plain of Phra Thong, evidence left by small-scale tin-mining can still be seen (Figs. 3-4) and easily spotted on the satellite images and on the ground by the steep-walled ponds, typically dug into the swales, next to large piles of spoil sand. Tin mining in the beach-ridge plains could only be done in the dry season as during the rainy season (April-November) the swales of the island's beach-ridge plain are submerged. After 1972, mining suffered because the easily mined tin was diminishing and more importantly, the price of tin was dropping making it unprofitable to mine.

At Phra Thong Island, we studied stratigraphy and sediment characteristics from shallow pits and trenches, avoiding the tin mining areas. Maximum depth of the pits dug at a given location is often defined by the ground water level and the stratigraphy. Ground water level at Phra Thong is relatively high even in the dry season, so most of the pits are less than 1m deep.

Fig. 3. Pond dug by tin miners to use as a source of water for placer mining. It has steep slopes compared to a natural swale. The pond is also accompanied by spoil piles of sand.

Fig. 4. Pile of sand, about 1.5 meter high, left behind after separation from tin. The less vegetation covering the tops of these spoil piles made them vulnerable to transport by the 2004 tsunami. Next to the sand pile there is a man-made pond.

Fig. 5. Google Earth image showing locations of pits (small dots) and trench (large dot) investigated for 2004 and paleotsunami sand sheets as described in this chapter.

Tsunami sediments were collected from pits and trench walls for grain size analysis, at 0.5 cm intervals. Grain size analysis was conducted using 1.5-metre long settling tube, and grain size distribution data at 0.1 phi interval was obtained. Organic materials at or near the contact between tsunami deposits and underlying soils, where present, were collected for 14C dating. Non-abraded shells contained in the tidal flat sand at the base of the swale, where present, were also collected for 14C dating. More recently, we have been collecting OSL samples of the sand sheets and bounding beach ridges. The OSL beach-ridge ages will be used to test their geomorphic superposition and provide age bracketing for the tsunami sand sheet. Fig.5 shows locations of shallow pits along the 2-km transect from the shoreline (NW) to the end of 2004 sedimentation (SE). We studied sedimentary characteristics of 2004 and paleotsunami sand layers along this transect. Moreover, we also described a section further north of a transect in Fig.12.

5. Results

Thickness of deposits of the 2004 tsunami and its predecessors varies across the beach-ridge plain and is primarily controlled by local topography. Thickness tends to be greatest in a low-lying swale (as much as 30 cm), whereas in ridges and higher ground it tends to be thinner (few cm, 10 cm at most). Thicker, and sometimes coarser, deposits in topographic lows is a response of the flow to the deeper water depth, which slows the flow and drive deposition (Apotsos et al., 2009). In the case of Phra Thong, thickness is increased if the swale is a path for back flow, which is often channelized and can eroded sediments from landward location as shown in Fig 6. 2004 deposit in these locations are almost 30 cm thick. The deposit contains up to 4 fining-upward sequences. The lowest fining-upward sequence was probably deposited out of the first wave. On top of this sequence there is a continuous dark gray fine silt-clay layer which was probably deposited when the tsunami flow was still and between the two main waves. Above this silty clay layer there are 2-3 fining upward sequences, which were possibly deposited from back flow of the first or second waves. Sets of cross bedding in these upper sequences indicate a flow direction towards the sea (Fig. 6).

On high ground, with less vegetation cover, the 2004 tsunami deposit lies above the sand ridge sediment with faint soil in between (Fig. 7). It is still possible to identify the 2004 tsunami deposits in the high ground 5 years after the event, but allowing more time differentiating it from the sand ridge below will be problematic. At places, distinguishing the 2004 tsunami laid sand and the underlying ridge sand was already difficult due to the lack of organic soil formation on top of the ridge sand. On the high ground right next to the swale, after tsunami dumped majority of sediments in the swale, 2004 sediments compose mainly of silt which fell out of suspension. The tsunami flow then picked up more sediments from the ridge area along its flow path. As a result, grain size of 2004 tsunami on high ground is composed mainly of silt in contrast to sand and silt in the swale deposit.

Topographic profile across the transect in Fig 5. is shown in Fig. 12. The thicknesses of the 2004 deposit at different locations are also shown.

Among more than 200 hand-dug pits, at least 4 paleotsunamis sand layers have been found on Phra Thong Island. These deposits are in the fresh-water swales between beach ridges. The marshy swales of Phra Thong Island serve as an excellent recorder for the tsunami sand layers because they contain peaty soil that gives contrast in colour and grain size to the tsunami sediments, and which protects tsunami deposits by building up on top of them. The fresh water of these swales excludes crabs that would otherwise destroy the sand layers by mixing them with the peat.

Fig. 6. Thick 2004 deposit of almost 30cm is found at the landward location of swale Z in Fig.5. This location is a landward side of the swale, which is in the main direction of the tsunami back flow. Pre-2004 sand layer is also present at this location, though when compared with the 2004 it is very thin (2-3cm) and discontinuous.

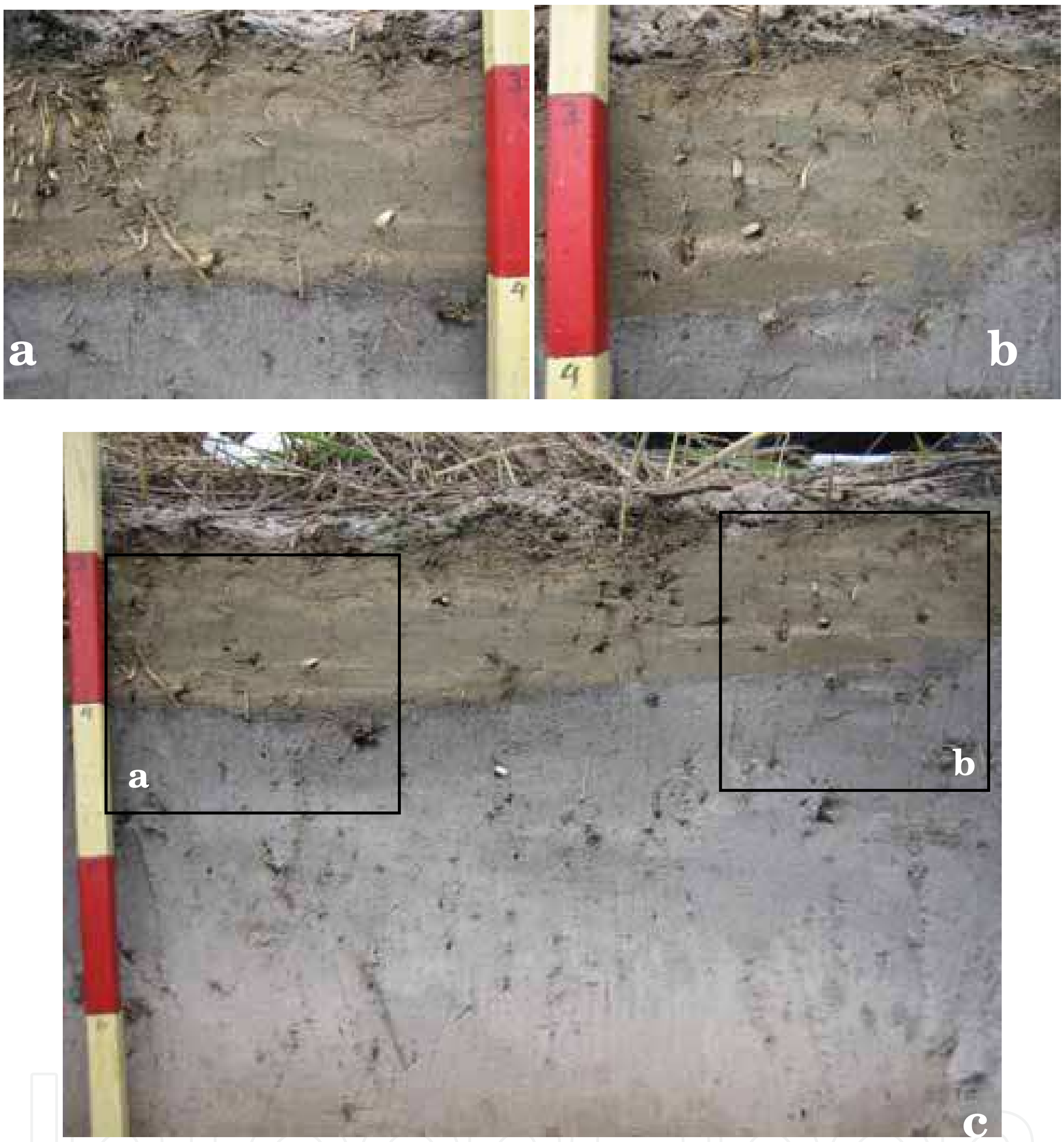

Fig. 7. Thick deposit of 2004 tsunami sediments on the sand ridge with only thin faint organic soil between them.

5.1 Sedimentary characteristics of Phra Thong Tsunami deposit

Apart from variation in thickness of the deposit, internal characteristics of 2004 deposit on Phra Thong also varies greatly from one place to another. Often the deposits show no internal structure layering. Typically the deposits appear as a massive bed or faintly normally graded. In locations close to the sea, some deposits coarsened upward. Examples of sediment grain size and composition described below are from swale Y (see Fig. 5).

a. 2004 Tsunami Deposit

2004 tsunami sediments range in grain size from coarse sand to coarse silt, with distinctive bimodal distribution with first mode in fine-sized range (2 phi), and second and highest mode in very fine-size range (phi 3.3) (Fig. 8A). The coarser sediments are composed of coarser sands from beach berm and possibly from offshore area, and angular shell fragments and large forams and other macrofossils (Fig 9, top row), whereas the finer sediments are possibly from the subtidal zone. 2004 sediment composes about 85% of clear to white quartz grains, 8% of shell fragments and micro fossils, 4% of muscovite and 3% of heavy minerals, mostly small grains of tins. Although typically 2004 tsunami deposits at Phra Thong appear as a massive bed or faintly normally graded, detailed grain size analysis shows that they can contain 2-3 fining-upward sequences (Fig. 10). Mean grain size of the 2004 tsunami is slightly bigger than that of paleotsunami sand (sand B).

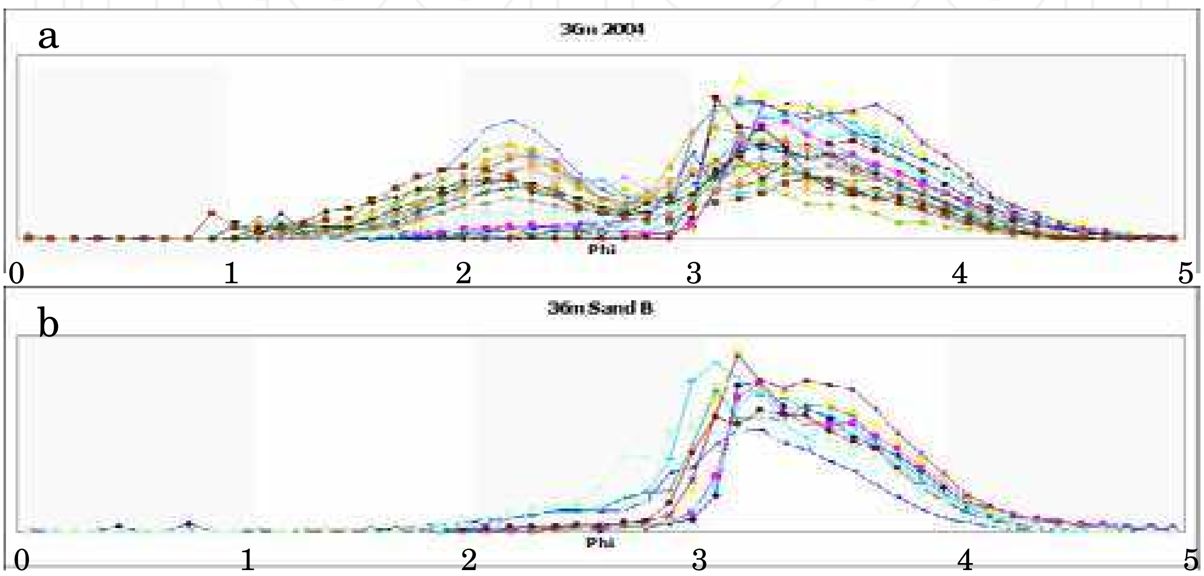

Fig. 8. Sediment grain size distributions of (a) 2004 tsunami deposit compared with (b) sand layer B. Each line represent sample of 0.5 cm interval.

Fig. 9. Photograph of sediments of 2004 tsunami (top row) compare with paleotsunami sand layer B (bottom row). The scale bar, bottom right, is 1 mm.

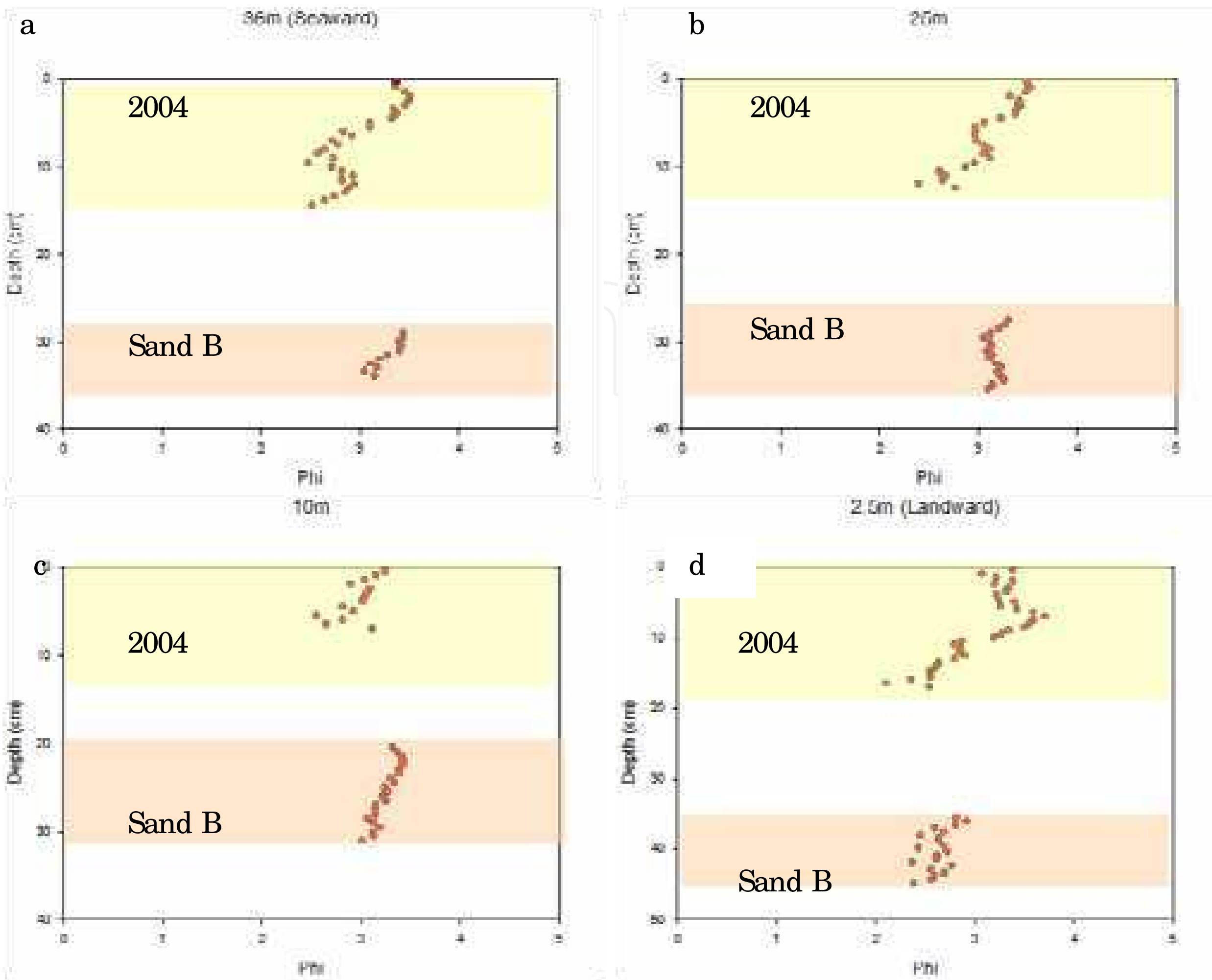

Fig. 10. Plots of mean grain size of 2004 tsunami deposit compared with paleotsunami deposit (sand B) at different locations along the same swale. Each data point represents a sample at 0.5 cm intervals. Thicknesses of 2004 and sand B are varied along the swale's width. 2004 tsunami layer contains 2-3 fining-upward sequences while sand B deposit contains 2 fining-upward sequences. Mean grain size of the 2004 tsunami is slightly larger than that of sand B.

b. Paleotsunami Sand Layers

Paleotsunami deposits at Phra Thong Island are composed of grains ranging in size from coarse sand to coarse silt, with bimodal distribution with small first mode in fine-sized range (2.3 phi), and second and highest mode in very fine-size range (phi 3.2) (Fig. 8B). Sediment of sand B composes about 91% of clear to white quartz grains, 7% of muscovite and 2% of heavy minerals, mostly small grains of tin. The shell fragments and microfossils are absent in the paleosand layer. The cause of the absence will be discussed further below. Phra Thong paleotsunami deposits appear as a massive bed or faintly normally graded, more so than the 2004 deposits, but mean grain size at 0.5 cm thickness intervals show that they contain up to two fining-upward sequences (Fig. 10).

5.2 Complications and challenges in studying Phra Thong Paleotsunami deposits

5.2.1 Identification

Challenges in studying paleotsunami deposits world-wide include positive identification, and dating and correlation of events (Bourgeois & Minoura, 1997). Tsunami deposits are different from place to place depending on the sediment source, nearshore bathymetry, coastal topography and tsunami intensity. Tsunami deposits are only found in locations inundated by the tsunami that were favorable to their deposition and preservation, and coastal conditions at the time of deposition may be different than current conditions. At Phra Thong, paleotsunami deposits are found in fresh water swales between beach ridges. Identification of these deposits is based on their sedimentary character and stratigraphic context.

Marine and brackish diatom and foraminifera contained in tsunami deposits help in identifying the marine origin of the sediments, and in many cases can discriminate between tsunami and storm deposits. They are especially helpful in paleoseismology and paleotsunami studies in temperate climates.

Both diatom and foraminifera are abundantly reported in 2004 tsunami deposits (e.g. Hawke et al., 2007, Sawai et al., 2009a). However, diatoms and foraminifera are absent in the paleotsunami deposits at Phra Thong (Jankaew et al., 2008). High underground water temperature in the tropical setting may have caused dissolution of their carbonate and opaline tests. The absence of diatoms and foraminifera in old tsunami deposits in Thailand deprives us of a simple way to confirm that an inferred tsunami deposit was in fact deposited by sea water.

Non-occurrence or non-recognition of tsunami deposits at a given locality does not mean that there was no tsunami inundation in the past (Bourgeois & Minoura, 1997). This is also the case of Phra Thong tsunami deposits as best shown by example in Fig. 11. At this location, the large dot in Fig. 5, there are at least three paleotsunami sand layers present. However, tracing these sand layers across the trench wall of less than 10-metre distance prove that correlating these sand layers are indeed challenging. The second paleo-sand layer is absent abruptly at various locations along the trench wall. The local disturbance of sand layers after deposition, by animals and other means, causes discontinuities in the deposit. This demonstrates the ambiguity of interpreting and correlating paleotsunami deposits based on core data only. The stratigraphy exposed at this trench also attests to the challenge in correlating paleotsunami deposits in the far-field tropical setting without reliable ages.

5.2.2 Dating

14C dating

Sampling of appropriate materials for radiocarbon dating, a more acceptable dating method, can be problematic (Bourgeois & Minoura, 1997). Organic materials that are alive and then killed by the event, as opposed to transported of older or younger materials, are not always present. Radiocarbon dates of organic materials within or directly underneath the tsunami deposits, thus, represent only a maximum possible age for the tsunami event because they may have been reworked by the tsunami. Limiting maximum ages of the tsunami sand deposits in eastern Hokkaido, Japan, were obtained by dating plant materials (e.g. fruits, seeds and leaves) using accelerated mass spectrometry (AMS) radiocarbon method (Sawai et al., 2008; 2009b). Cisternas et al. (2005) also dated entombed stems of herbaceous plants, using AMS radiocarbon methods, to infer the age of tsunami sand layers.

Precise and accurate dates are often difficult to determine using radiocarbon dating (Peters et al., 2007). In Cascadia, for example, a typical error for tsunami deposit ages using radiocarbon techniques is in the order of ±100–200 years, which does not allow discrimination of tsunamis closely spaced in time (Peters et al., 2007). Numerical dating of pre-historic tsunami deposits is also difficult if a time-scale of decades separate between events (Bourgeois & Minoura, 1997).

Tephra layers found in the stratigraphic sections aid in correlation of tsunami sand layers and identifying the relative ages of tsunamis in eastern Hokkaido, Japan (Nanayama et al. 2003; 2007; Sawai et al., 2008; 2009b) and Kamchatka, Russia (Pinegina et al., 2003).

The plant materials and plant rhizome tend to survive better in Quaternary sediments of temperate climates than in those of the tropics. In Thailand, materials suitable for C14 dating are not easy to find due to high bioturbation and biodegradation. From more than 200 pits and trenches that we dug, only a few of the locations contained organic materials suitable for dating. We searched for seeds and fruits in peaty soils between the sand layers, but typically without success.

Our experience with dating detrital leaves formed as lamina within the tsunami sand layer showed that leaf fragments are less reliable (Jankaew et al., 2008). The leaf ages conflict one another and exceed the barks, collected from the base of the sand layer, age. The ages of the paleotsunami sand layers are still unknown, or not well constrained, except the youngest paleo-sand layer, which was inferred to be older than 550-700 years (Jankaew et al., 2008). The challenge in dating these sand layers exists because the organic materials suitable for radiocarbon dating are not always present in the highly-weathered tropical settings.

OSL Dating

Where organic material is not present for radiocarbon dating, optical dating techniques such as optically stimulated luminescence (OSL) are used to date the tsunami deposits, such as in Cascadia by Ollerhead et al. (2001) and Huntley & Clague (1996).

From our preliminary result of OSL dating, both two 2004 tsunami samples exhibited relatively symmetric D_e distributions, suggesting adequate bleaching. Results from multiple grain single-aliquot and single grain samples from the 2004 sand sheet were compared. The multiple grain single-aliquot samples overestimated the age of the 2004 sand sheet by around 100 years (80 ± 10 years and 110 ± 20 years). Single grain analyses showed between 70 to 76 % of near-zero grains with some partially-bleached grains, which, when averaged in the multiple-grain aliquots, generated the older central ages (Prendergast et al., in prep). Examination of the individual equivalent dose estimates in multiple-grain single-aliquots is not an accurate technique for identifying partial bleaching because each aliquot could contain equal proportions of partially bleached quartz (Wallinga, 2002). Using aliquots of single grains overcomes this problem.

In situations where incomplete bleaching is suspected, Olley et al. (1999; 2004a, b) suggest that the lowest equivalent dose will provide the best estimate of burial age. We therefore applied a minimum age model (Galbraith et al., 1999) to calculate the ages of the sand sheets at Phra Thong Island. In well-bleached samples and in those where bioturbation has caused the intrusion of younger and older grains, a central age model (Galbraith et al., 1999) may provide a more accurate estimate of burial age. This model has been applied to the beach ridges samples.

Preliminary results of optically stimulated luminescence (OSL) age dating of the sand sheets and the beach ridges are presented below (Prendergast et al., in prep).

In addition to tsunami sand sheets, bounding beach ridges; west, middle and east, were also dated. The OSL ages of the beach-ridge sequence will help bracketing the age of the tsunami sand layers deposited in the swales and helping correlating tsunami sand layers across the island. Preliminary results of OSL ages of the ridges prove that the beach ridges young seawards, consistent with their interpretation as a prograding sequence; the east ridge (2560

Fig. 11. Trench wall, about 9 meters long, exposing 2004 tsunami deposit (top light colour layer) and up to three paleotsunami layers. The top two paleotsunami sand layers (light colour) are discontinuous, especially the lower one which disappear laterally. Bioturbation and disturbance by animals are thought to be responsible for the discontinuity of this sand layer. The third paleotsunami sand layer is under the water level and only the top edge can be seen in this fig. Stripe on stick is 10 cm.

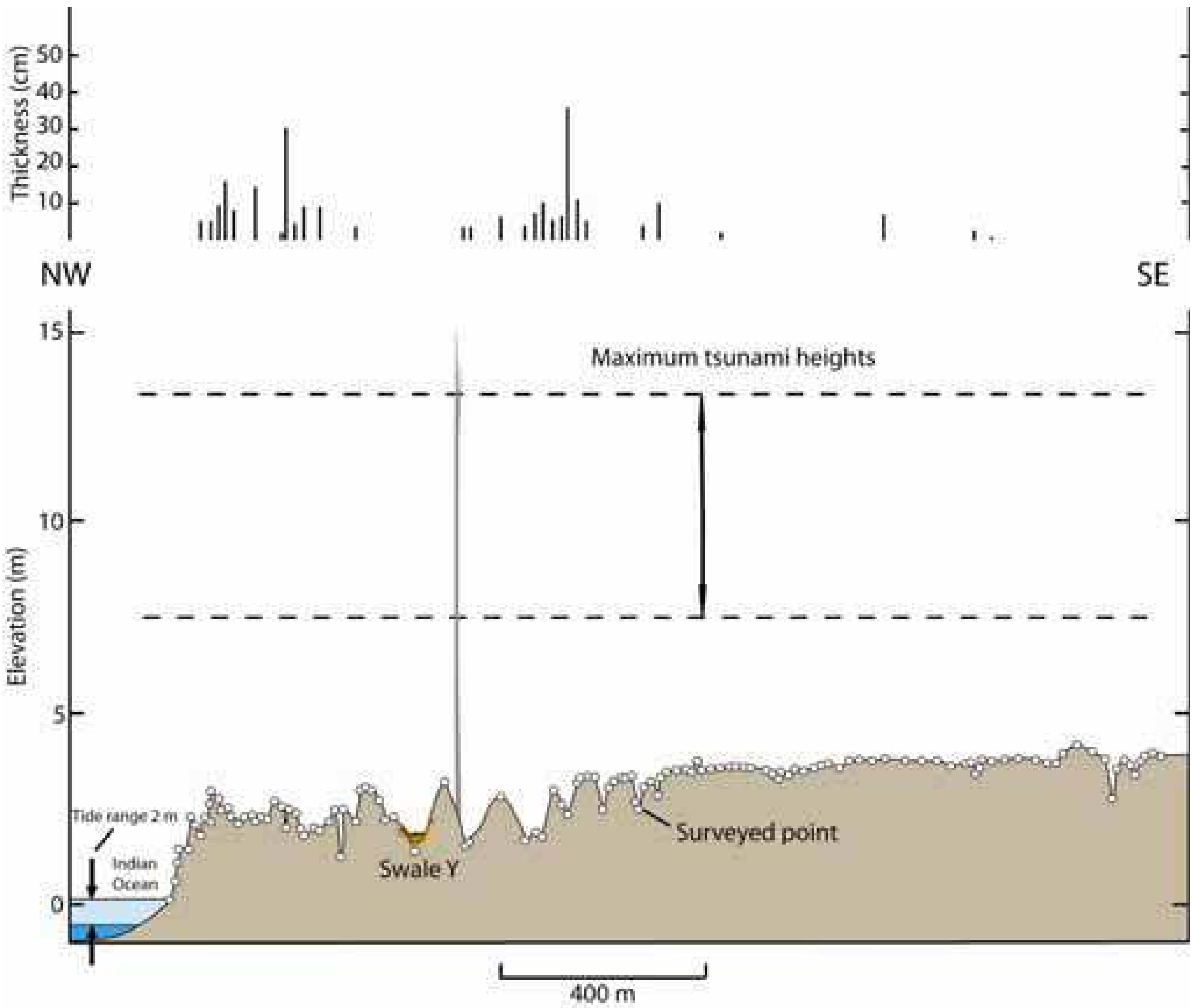

Fig. 12. Topographic profile across the beach-ridge plain (the same transect in Fig. 5). Vertical lines are 2004 tsunami thickness (in centimeter), at different locations along this transect.

± 350 years ago) is older than the middle (2160 ± 280 and 2100 ± 270 years ago) and west ridges (1600± 210 years ago). The nearly identical paired OSL ages from the middle ridge (2160 ± 280 and 2100 ± 270 years) affords confidence in the use of OSL in this environment. Based on the age of the most landward ridge (2560 ± 350 years ago) and its distance from the modern shoreline (500-700 m), the beach ridges prograde at 0.19 – 0.27 m per year by average.

Three tsunami sand layers (B, C and D) have OSL ages of 350 ± 50 - 380 ± 50; 990 ± 130 - 1410 ± 190, and 2100 ± 260 years ago (at 1-sigma precision), while tidal-flat deposit under these sand layers has an OSL age of 2540 ± 340 years ago. The ages are concordant and give the impression that at least three large tsunamis impacted the coast during the Late Holocene, yielding a tsunami recurrence interval of between ~350-1000 years. However, when comparing the OSL ages from beach-ridges, sand sheets and tidal-flat deposit the picture is not clear and the data seem to be conflicting with one another. The problem persists when comparing OSL data of the beach-ridges and sand sheets from this study with 14C ages from previous studies (Jankaew et al., 2008; Monecke et al., 2008; Rajendran et al., 2006,

2008) and uranium-series age (Meltzner et al., 2010). The OSL ages are consistently younger than 14C, uranium-series ages and written records. The complication of OSL ages may lie with the variation of the environmental dose through time.

Other Complications and Challenges

Relative sea level change along the Andaman coast of Thailand in the Holocene is poorly defined. Sea level highstands can enhance the ability of a tsunami to inundate a coast and lowstands can decrease the ability of a tsunami to inundate. Interpretation of tsunami deposits may also be complicated by post-depositional changes in shoreline position. Phra Thong coastline is believed to be prograded after the mid-Holocene highstand. In this case the distance between the present shoreline and the limit of inundation is greater than the inundation distance at the time of the tsunami.

5.2.3 Correlation

On Phra Thong Island it is impossible to trace tsunami deposits from one swale to the next because the sand layers are identifiable only in the low-lying areas, separated by higher topography beach ridges. Furthermore, preservation potential of the sand layers may differ from place to place with physical (micro topography) and biological (bioturbation, human disturbance) factors. An insufficient number of event dated thus far also limits the correlation of these deposits. There are no tephra layers that may help in correlating the sand sheets. Confidence in correlating these deposits relied solely on the deposit ages. Ambiguities s and error in dating also exist.

6. Post depositional change and preservation potential in tropical environment

Phra Thong Island is an excellent site to observe how the 2004 tsunami was preserved. Five years after the Indian Ocean tsunami, black organic rich soil as thick as 5 centimeters has already developed on top of the 2004 tsunami sand layer in the swales (Fig.13), which are submerged under water for most of the year. High precipitation causes a high level of weathering of inorganic material and also aids in the decomposition of organic material that makes up this black organic rich soil. This quick development of soil in areas such as swales and other well protected areas aid in the preservation of 2004 deposits. In comparison, deposit of 2004 tsunami at Pakarang Cape has only a thin veneer of soil developed on top of the 2004 deposits in Fig. 14 which was taken on 11 July 2006. At this location, less than 200m from shore, the 2004 tsunami deposit contain two layers separated by layer of mud and fine-silt about 2.5 centimeters thick. The two layers represent two main waves of the tsunami wave train. Mud and fine silt layer deposited out of suspension from standing water between waves.

On the beach ridges, where there is no or little vegetation cover, top few centimetres of the deposits which is mostly composed of coarse-fine silt were reworked by aeolian and animal and human activities. In the future, should the 2004 deposit at these locations survive and preserve it will lack the very top of the deposit making interpretation of flow property of past tsunami using deposit thickness unsound.

In many places, thickness of 2004 sand layer is much thicker than the paleotsunami sand layer found at the same location (such as in Fig. 6). This could be due to bioturbation or erosion of part of the paleosand layer. Distance of the paleo-shoreline to the site may also be varied through time. The slip distribution of the paleoearthquake might have also generated smaller waves on Phra Thong.

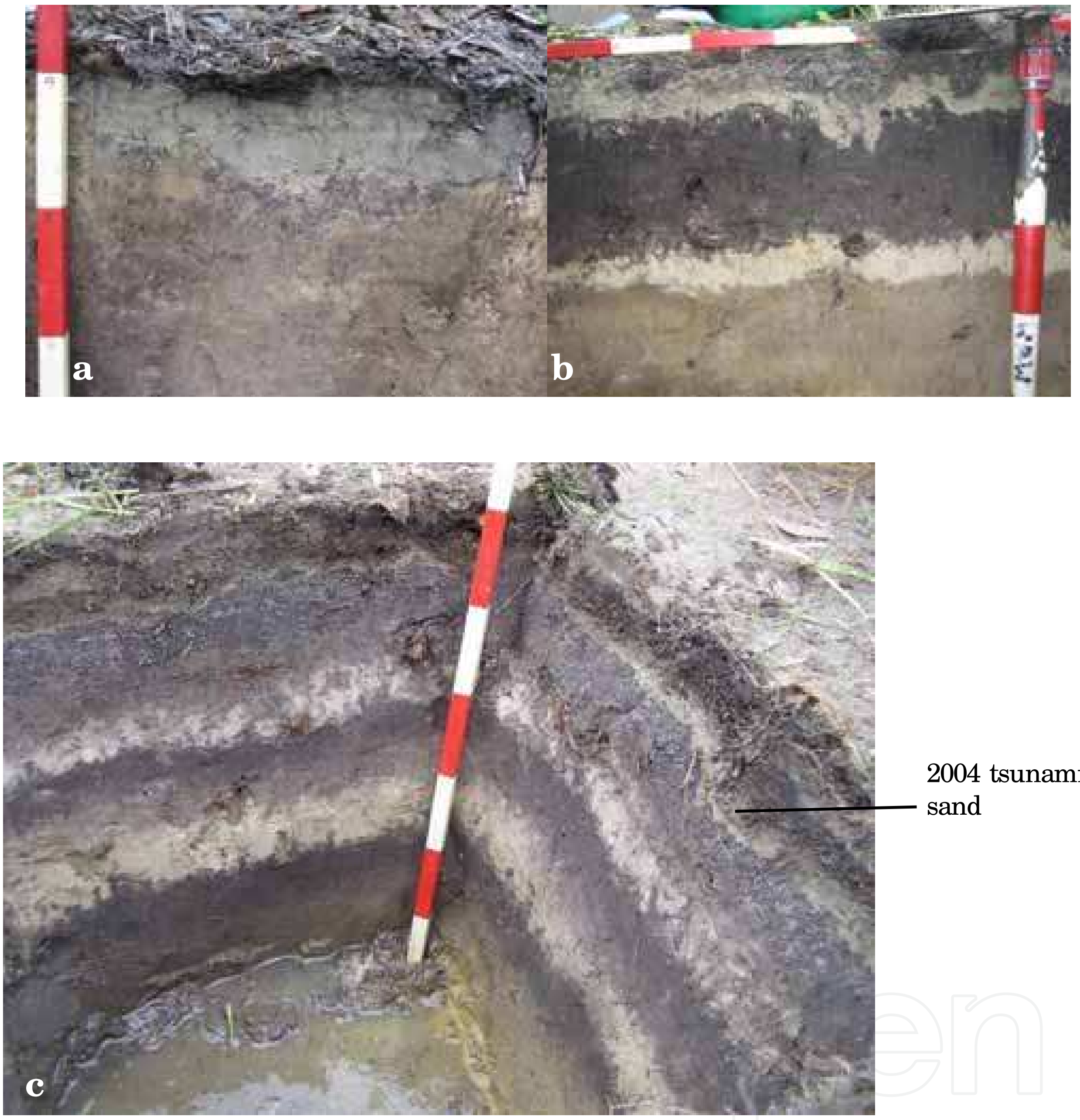

Fig. 13. Thick organic rich soils already developed on top of the 2004 tsunami layer in (a), (b) and (c) (March 2008). One and two paleotsunami sand layers are present in (b) and (c), respectively. Stripe on stick is 10cm.

In certain areas where plant and animal diversity are high, such as the mangroves swamp, the 2004 tsunami deposits suffer from intense bioturbation that has already obliterated much of the deposit (Atwater, 2007). Mangrove crabs eat the tsunami sand and rework the sediment and deposit it at the surface as balls (Fig 15, left). Mud-lobsters, commonly found in tidal fringe mangrove at Phra Thong and other locations such as Tap Lamu, mixed the mangrove sediments with the tsunami sands.

Fig. 14. 27-centemetre thick 2004 tsunami deposit at Blue Village Resort, Pakarang Cape (July 2006). Bluish gray layer consists of mud and silt deposited out of suspension between tsunami wave trains.

Fig. 15. Balls of tsunami sands were created by mangrove crab (a). Mud lobster capable of mixing up sediments, including tsunami sediments, and can build mounds as high as 1 metre (b).

7. Conclusion

Factors such as identifying deposit mechanism and bioturbation make paleoseismology in Thailand difficult. The lack of co-seismic deformation, to indicate an earthquake origin of deposits along the Thai coast caused difficulties in distinguishing and identifying paleotsunami deposits. High levels of vegetation and human disturbance along the western coasts of Thailand further hinder the possibility of finding the deposits of past tsunamis. We found the mangrove environment to be unfavourable for preserving tsunami records. Marshy swales of beach ridge plains, however, can serve as a suitable recorders for tsunami events, as shown on Phra Thong Island.

The 2004 tsunami deposit on Phra Thong varies in thickness, structure and preservation potential. Thickness of the 2004 tsunami deposit at Phra Thong is primarily controlled by local topography and distance inland, with thick deposits in topographic lows and closer to the shore. Internal structure of the 2004 deposits at Phra Thong is different from one location to another. In most cases the deposit shows no internal structure and contains one fining-upward sequence. In thicker deposits, especially in the swales, the deposit is composed of 2-4 fining upward sequences. Preservation potential of the deposit in these swales is higher than other locations because quick soil development offers protection. 2004 tsunami sediments range in grain size from coarse sand to coarse silt. They show prominent bimodal distribution with the larger fraction consisting of beach sand and shell fragments and foraminifera tests.

The fresh-water swales in the beach ridge plain at Phra Thong offer an excellent recorder for tsunami deposits. Up to four paleotsunami sand layers were found on the island thus far. Pre-2004 deposits display up to 2 upward-sequences, but often show just one. Range of grain sizes for paleotsunami sand layers though similar to the 2004 sand, generally they are smaller and do not contain shell fragments and forams. Principal component of both 2004 and paleotsunami sediments are clear quartz, which is ubiquitously present along the Andaman coast of Thailand.

Challenges in studying paleotsunami deposit in tropical settings include identifying the source of the layer, bioturbation, dating and correlation. As foraminifera, shell fragments, and diatom in deposits are dissolved, identification of the marine origin of sand layers becomes more difficult. High bioturbation and disturbance of sand layer after deposition is also a main problem in this environment, leading to difficulty in correlating these sand layers across the area. Dating of these deposits by means of 14C and OSL is also problematic as the high rate of biodegradation in this environment destroyed most, if not all, suitable materials for 14C dating. OSL dating of the tsunami sediments is also doubtful, and is not concordant with ages obtained by other means. OSL ages are found to be younger, when compare with 14C ages. This concordance may be caused by high bioturbation rates or variation of the environmental dose rate through time in this environment.

8. Future research

Priorities in the future study of paleotsunami deposits at Phra Thong is establishing chronology of tsunami sand layers and correlation of sand layer across the island using ^{14}C, OSL and other methods. Combining several methods of dating may help overcome the problem of dating in the tropical environment. But careful interpretation of these ages is of utmost important in inferring the tsunami event age. Future work on other Indian Ocean shores will further provide a more detailed regional picture of the recurrence of great and giant subduction zone earthquakes and tsunami. The magnitude of the tsunamis responsible for the tsunami sand layers at Phra Thong can be assessed using numerical models with help from tsunami deposits to evaluate model results. Because of its relatively flat terrain, Phra Thong offers a suitable site to study velocity and depth of flow from properties of the deposits. Future research also includes establishing evolution of beach ridge-swale series at Phra Thong Island and with more ages of the sand ridges we hope to construct the Holocene relative sea-level curve for the Andaman Coast of Thailand. Hydraulic interpretation of 2004 and past tsunamis from deposits will also be carried out. Data from tsunami deposits-thickness and grain size distribution- can be used in sediment transport models (Jaffe &

Gelfenbaum, 2002; Jaffe & Gelfenbaum, 2007) to derive estimates of flow velocity and water depth (Peters et al., 2007). Estimates of flow velocity and tsunami flow depth are important to building design and in planning evacuation route.

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