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Grain-Size and Thin Section Characteristics of Tsunami Sediments from Thai-Andaman Coast, Thailand

Wagner Jean-Frank[1] and Srisutam Chanchai[2]
[1]Department of Geology, University of Trier, 54286 Trier,
[2]Soil Investigation Section, Office of Topographical and Geotechnical Surveys, Royal Irrigation Dept., 10300 Bangkok,
[1]Germany
[2]Thailand

1. Introduction

The 2004 Indian Ocean tsunami killed more than 300,000 people and damaged the infrastructures, properties and environments of many coastal and island nations of the Indian Ocean, principally Indonesia, Sri Lanka, Thailand, India, The Maldives and the African Coast. In Thailand, the coastal provinces of Ranong, Phang Nga, Phuket, Krabi, Trang and Satun on the Andaman coast at latitude 5° to 11°N, longitude 98° to 102°E (Fig. 1) suffered 1–10 m run-up heights (Japanese Survey Team 2006). Phang Nga was the worst affected province attacked by 4–10 m high run-ups. Tsunamis cause seawater to flood onto land, creating distinctive horizontally widespread sandy deposits. Tsunami sediments from Japan are the typical sediments discussed for the historical tsunami events and the geological evidence (e.g., Minoura et al., 1996; Fujiwara et al., 2000; Sawai, 2002; Fujino et al., 2006).

Tsunami waves transport sandy sediments from offshore areas and the beach and deposit sediments on the inundated land surface. Tsunami deposits are very characteristic for tsunami affected areas. A local tsunami chronology can be determined by using geological methods to identify and characterize recent and ancient tsunami events in coastal sediment sequences (Dawson et al., 1996; Dawson, 2007; Dawson & Stewart, 2007). Sediment characteristics from general coastal processes, storms, ancient and recent tsunamis have been reported from many parts of the world for distinguishing deposit types, geomorphological effects and sedimentation processes (e.g. Dawson et al., 1991; Dawson, 1994; Nanayama et al., 2000; Shi & Smith, 2003; Gelfenbaum & Jaffe, 2003; Anthony & Hequette, 2007; Morton et al., 2007; Kortekaas & Dawson, 2007). Tsunami deposits are provisionally distinguished in the field on the basis of anomalous sand horizontals, fining-upward and fining-landward, coupled with organic-rich, fragmented backwash sediment (e.g. Dawson et al., 1991; Shi et al., 1995; Gelfenbaum & Jaffe, 2003; Smith et al., 2004; Srisutam & Wagner, 2009; Srisutam & Wagner, 2010a). Typically, tsunami sediments comprise medium to fine sand with small amounts of fine silt and clay (e.g. Dawson & Shi,

2000; Smith et al., 2004) . Detailed analysis of the grain-size distributions of tsunami deposits in vertical and horizontal directions reveal both landward and upward fining sedimentation sheets (Srisutam & Wagner, 2009; Srisutam & Wagner 2010a).

Grain-size and various parameters derived from the statistical analysis of the grain-size distribution, such as sorting, reflect the energy gradients responsible for transportation and deposition of sand bodies and are therefore important in reconstructing the geological environment (Friedman, 1962). Smith et al. (2007), Srisutam & Wagner (2009) and Srisutam & Wagner (2010a) identified the sedimentation sequences by grain-size distribution curve analyses. Hindson & Andrade (1999) proposed that the break points in a plot of standard deviation with depth of the tsunami deposit mark a break in turbulence associated with a transition to a lower or higher Reynolds number run-up.

Although a sedimentary signature for onshore tsunami deposits has been defined (e.g. Nelson et al., 1996; Dawson & Shi, 2000; Whelan & Kelletat, 2003), the particular hydrodynamic behavior of the long-period surge associated with tsunamigenic flooding is still under debate. In many tsunami studies, scientists have used data on tsunami run-up (e.g. number of tsunami run-ups, run-up height) to calibrate numerical models for undersea fault-generated and submarine landslide-generated tsunami (Dawson et al., 1991). In almost all cases, the number of tsunami run-ups have been based on eyewitness reports of the tsunami flood.

This chapter presents the composition and physical properties of tsunami sediments from Thai-Andaman Coast, Thailand.

2. Study area

Tsunami-affected areas at the Thai-Andaman coast (Fig. 1, western coast of southern Thailand) were investigated in 7 transects at 5 different locations.

Study locations are:

1. Ao Kheuy beach (Phang Nga province), the reference coordinate is 9.30°N, 98.38°E. Two transects have been examined.
2. Khuk Khak beach (Phang Nga province), the reference coordinate is 8.69°N, 98.23°E. Two transects have been examined.
3. Bang Thao beach (Phuket province), the reference coordinate is 7.99°N, 98.29°E. One transect has been examined.
4. Kamala beach (Phuket province), the reference coordinate is 7.96°N, 98.26°E. One transect has been examined.
5. Ao Krabi (Krabi province), the reference coordinate is 7.96°N, 98.95°E. One transect has been examined.

The geomorphological features of the study areas are described as open coastal zone except Ao Krabi (estuary zone). The pre-existing sediments are coastal deposits and agricultural soils.

The tsunami inundation distance (200-2000m) and the run-up height (0.80-10m) are different for the 5 areas due to a different geomorphology of the coastal area (steep or mild slope), bathymetry of the seawater body, orientation of approaching waves, interference with tides, etc. (Table 1).

The selected locations are also different in the shape of coastline. For Ao Kheuy beach, Khuk Khak beach and Ao Krabi the shape is a long straight coastline and for Bang Thao beach and Kamala beach a circular bay. The selected locations were affected by direct and indirect (diffracted and/or dissipated) tsunami waves as well.
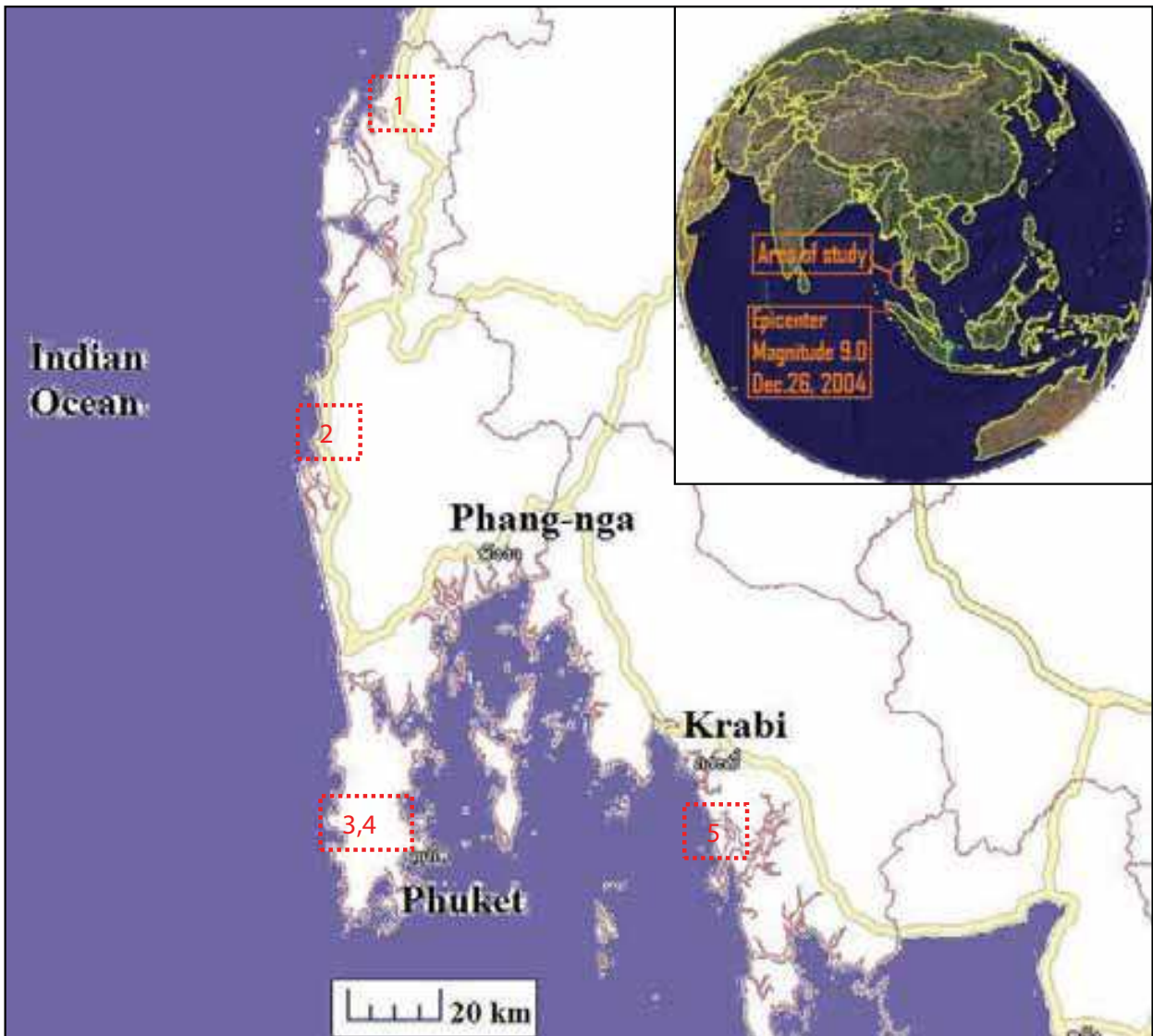
Fig. 1. Location map of southern Thailand. Areas in red dashed line rectangles are the study areas: (1) Ao Kheuy beach; (2) Khuk Khak beach; (3) Bang Thao beach; (4) Kamala beach; (5) Ao Krabi.

3. Methods

The depositional characteristics of tsunami sediments were evaluated from grain-size distribution curves, analyzed by wet-sieving and from micro-morphological features from thin sections, respectively.

Topographical profile investigations, tsunami deposit thickness measurements and sediment sample collections were made in the study areas from August to October 2007, more than two and a half year after the December 2004 Indian Ocean tsunami event. Topographical profiles were established by the combination of an automatic level measurement and Thai topographical maps.

Sediment samples were collected from four sub-locations which are offshore (S1), swash zone (S2), berm/dune (S3) and tsunami deposits plus underlying soil/sediment (S4). S1 samples have been drilled from a boat about 300 to 500 m from coastline (Fig. 2; only at

Bang Thao beach and Ao Krabi), S2 samples (swash zone, Fig. 3a) have been sampled at coastline. S3 samples (dune, Fig. 3b) and S4 samples (tsunami deposit, Fig. 4) have been collected in test pits at a distance between 20 to 40m and in trenches 50 to 300 m from coastline, respectively.

The S1, S2 and S3 samples have been analyzed in 1- to 5-cm intervals. The S4 samples were separated into a tsunami layer (S4d) and the pre-existing soil (S4p) (Fig. 4) and analyzed in 1-cm intervals.

In total 41 samples from offshore (S1), 33 from swash zone (S2), 54 from berm/dune (S3) and 123 samples from tsunami sediments resp. soil (S4) have been collected and analyzed.

In addition undisturbed samples of tsunami sediment from Khuk Khak beach were collected in 3 inches diameter PVC tubes in December 2006 for studying the micro-morphological features in thin sections (Fig.5).

The number of tsunami run-ups and run-up heights were obtained from eyewitness reports and local people's observations.

Province	Location	Latitude (°N)	Longitude (°E)	Run-up height (m)	Direction of approach (degrees)	Max. inundation distance (m)	Offshore slope
Phang-Nga	Ao Kheuy beach	9.30	98.38	4-6	80 **	800	1:100
	Khuk Khak beach	8.69	98.23	8-10	85 **	2,000	1:600
	Khao Lak *	8.68*	98.24*	8.59*	85 **	1,800 ***	1:600
Phuket	Bang Thao beach *	8.00*	98.30 *	3.76 *	85 **	1,500 ***	1:50
	Bang Thao beach	7.99	98.29	4-6	85 **	1,500 ***	1:50
	Kamala beach	7.96	98.26	4-6	85 **	1,000	1:75
	Kamala Beach *	7.95*	98.28*	4.85 *	85 **	1,000	1:75
	Kamala Beach *	7.95*	98.28*	5.29 *	85 **	1,000	1:75
	Leam Him	7.94*	98.40*	0.72 *	-	-	-
Krabi	Ao Krabi	7.96	98.95	0.8-1.2	40 **	200	1:100

*   HARADA, K. (http://www.drs.dpri.kyoto-u.ac.jp/sumatra/thailand/phuket_survey_e.html)
**   Estimated from Titov et al.; 2005
***   Chulalongkorn Tsunami Research Team, 2005

Table 1. Survey results of the 2004 Indian Ocean tsunami at the Thai Andaman coast.
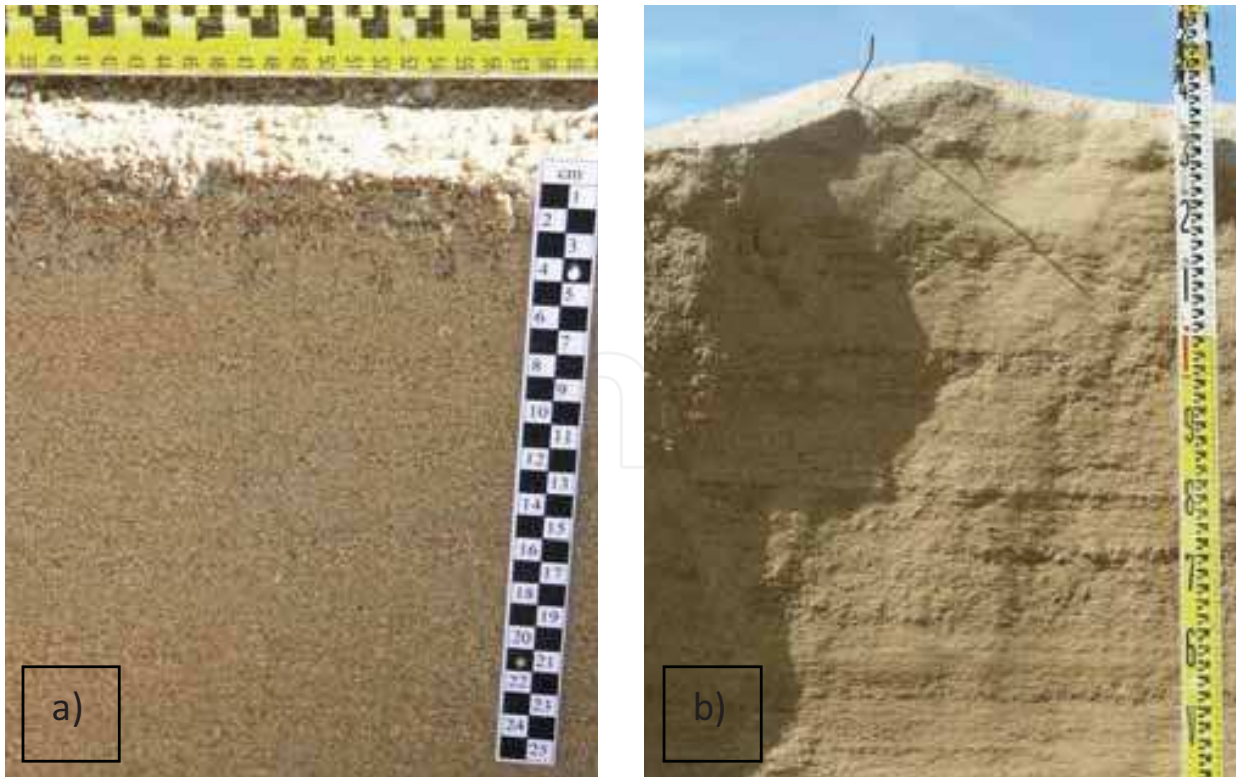
Fig. 2. Offshore sampling

Fig. 3. Coastal deposits at Khuk Khak beach, transect 1; a) Test Pit P0 (swash zone); b) Test
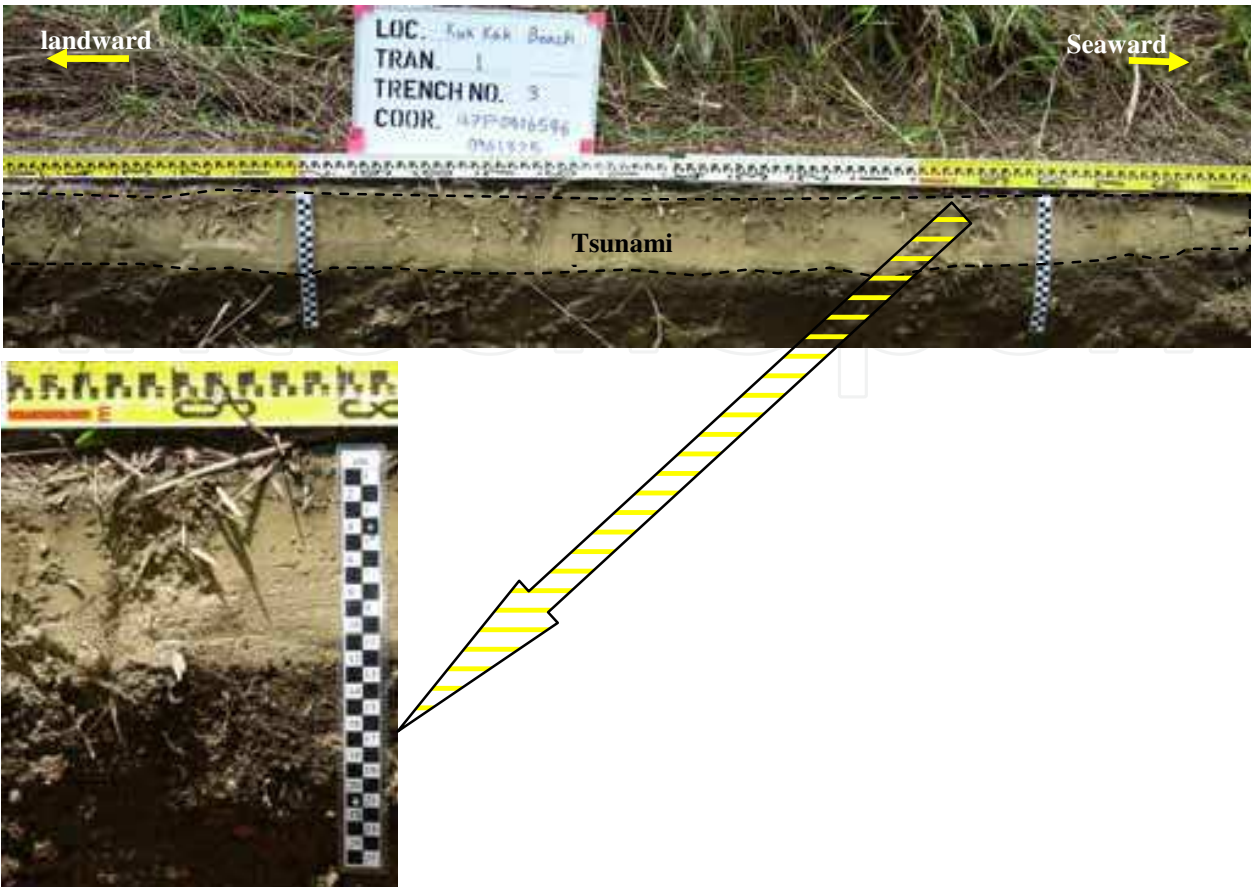Pit P5 (dune)

Fig. 4. Tsunami sediments in a sampling trench at Khuk Khak beach

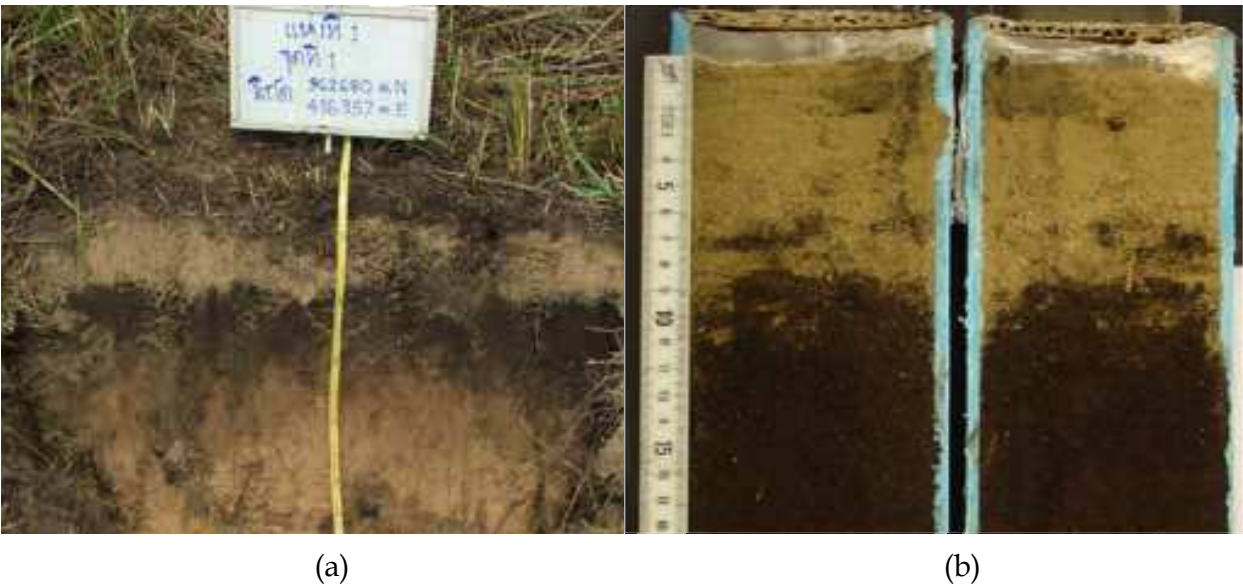   (a)   (b)

Fig. 5. (a) Tsunami deposit rests on the pre-existing soil; (b) an opened drilling core sample
for the preparation of thin sections (from Srisutam & Wagner, 2010c).

3.1 Grain size analysis

Collected samples were analyzed for grain-size distribution by the wet-sieve method. Mean grain-size, standard deviation, skewness and kurtosis were calculated on the basis of the percentile statistics of Folk & Ward (1957). The characteristics of coastal non-tsunami deposits and tsunami sediments could be studied and compared by using grain-size analysis results. The tsunami sediment and tsunami run-up characteristics were evaluated from (1) grain-size distribution curves, (2) percent content of sediment fractions, (3) plotting of mean grain-size with standard deviation and (4) plotting of mean grain-size, standard deviation, skewness and kurtosis with depth.

The different run-up sequences in the tsunami deposit are evaluated from particle size and plot of standard deviation with depth. The sediment transportation pattern is analyzed by a sediment trend analysis (STA) following McLaren et al. (2007).

3.2 Sample preparation for thin sections

Samples for thin-sectioning are collected by coredrilling with a PVC tube. As the samples are cohesionless sands, the pushing of thing-walled aluminum boxes into the core of soft sediment similar to that made by Francus (1998) could not be used. Therefore the whole section of sample core is left to dry at air first. Then it is impregnated by a low-viscosity epoxy resin (Fig. 6). When the core has hardened, slices for the preparation of thin sections are cut from the depth 0-16 cm, providing an undisturbed vertical slice of the tsunami sediment and the sediment/soil interface.

Fig. 6. Impregnation of the soft core sediment to get a hardened sample for the preparation of a thin section (from Srisutam & Wagner, 2010c)

4. Results

4.1 Grain size analyses
4.1.1 Tsunami sediment layer

Tsunami deposits are not observed at swash zone, berm/dune and the ending of water inundation. The locations where the recent tsunami sediment layer can be found is about

50–200 m inland from coastline. We observe three zones within the tsunami affected areas: (1) a zone of erosion extending from the shore inland, (2) a broad zone of tsunami deposition landward of the erosion zone and (3) a narrow zone with neither deposition nor erosion near the limit of inundation (Fig.7). Tsunami sediments consist of a distinct sediment layer of gray sand with shell fragments resting on a pre-existing soil with a sharp, often erosional contact including eroded clasts. These observations resemble to the results of recent tsunami field investigations from literature (Gelfenbaum & Jaffe, 2003, Jaffe et al., 2003, Jaffe & Gelfenbaum, 2007). Fig. 8 displays example photos of the 2004 Indian Ocean tsunami sediments overlying the pre-existing soil at the Thai Andaman coast. Table 2 gives tsunami sediment thicknesses at study areas which vary from 2 to 22 cm. The thickness variations may depend on coastal morphology and local topography as discussed by Gelfenbaum & Jaffe (2003).
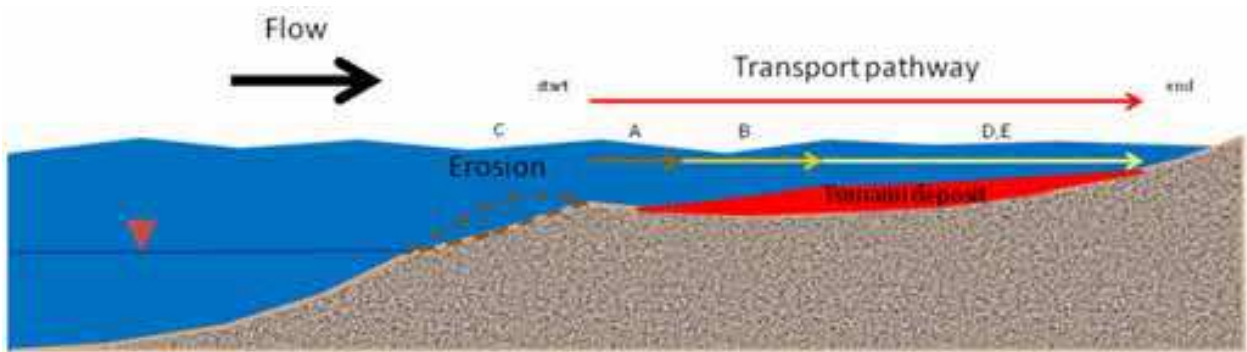

Fig. 7. Schematic of tsunami sediment transportation pattern during the tsunami run-up (following McLaren et al., 2007). A detailed description is given by Srisutam & Wagner (2010a)

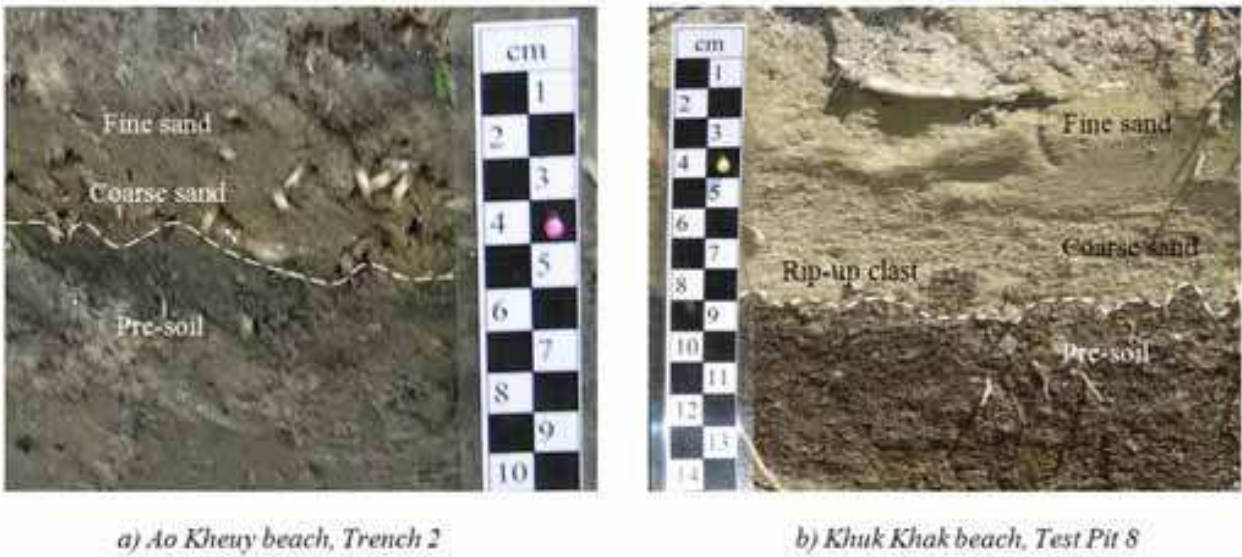a) Ao Kheuy beach, Trench 2   b) Khuk Khak beach, Test Pit 8

Fig. 8. Tsunami deposits overlying a pre-existing agricultural soil with a bottom layer of coarse sand containing rip-up soil clasts and an upper layer of fine sand (from Srisutam & Wagner, 2010c)

4.1.2 Comparison of tsunami sediment characteristics with coastal non-tsunami sediment characteristics

The grain-size distribution curves from the four sub-environment deposits which were a) offshore deposits, b) swash zone deposits, c) berm/dune deposits and d) tsunami deposits did vary concerning average grain size, sorting and modality respectively. Representative grain-size distribution curves of the deposits from the different littoral environments are shown in Fig. 9. A low degree of variability in the shape of the distribution curves was observed for the offshore sediments. The fine sandy deposits were mainly uni-modal and well to moderately sorted. The swash zone samples did consist of coarse to fine sand, poorly to moderately sorted with a bi-modal character. Also coarse to fine sand but better sorted (well to moderately) and with a uni-modal distribution were found in the berm/dune deposits. The characteristics of the particle size distribution in tsunami sediments change progressively from a poorly-sorted multi-modal distribution in the bottom layer to a better sorted distribution within the upper sequences.

Deposit mean grain-sizes from all study areas of the Thai Andaman coast are plotted against their standard deviations (sorting values) in Fig. 10. The plot shows the trend of scatter for each sub-location. The scatter in Fig. 10 demonstrates that the S1 deposit is a fine to very fine sand, poorly to moderately well sorted; the S2 deposit is a coarse to fine sand, poorly to well sorted; the S3 deposit is a medium to fine sand, moderately to well sorted; the S4d deposit is coarse to very fine sand, poorly to moderately well sorted; and the S4p deposit is coarse to fine sand, poorly to moderately sorted. The plot of the mean grain-size of tsunami sediment versus sorting indicates that tsunami deposits (S4d) are a mixture of offshore sediments, swash zone deposits and berm/dune deposits as well. Generally tsunami sediments are not characterized by a typical grain size distribution and their grain size distribution depends strongly on the coastal morphology. E.g. for a coastal area where the offshore slope is mild such as at Khuk Khak beach, the major origin of tsunami sediment is the offshore area. But also large quantities of beach sediments were eroded as Fig.11 does show.

Locations	Tsunami sediment's thickness (cm)	Coastal morphology
1. Ao Kheuy beach	4-10	~1:100 offshore slope, ~1:150 coastal slope, short inundation zone (~250 m inland) which is limited by hill.
2. Khuk Khak beach	2-15	~1:600 offshore slope, coastal plain, long inundation zone (~2 km inland), there are natural and manmade structures (pond and road) in direction of run-up flow.
3. Bang Thao beach	7-20	~1:75 offshore slope, coastal plain, long inundation zone (~1 km inland), there are manmade structures (road) in direction of run-up flow.
4. Kamala beach	2-22	
5. Ao Krabi	3-9	~1:100 offshore slope, coastal plain, short inundation zone (~200 m inland) which is limited by road.

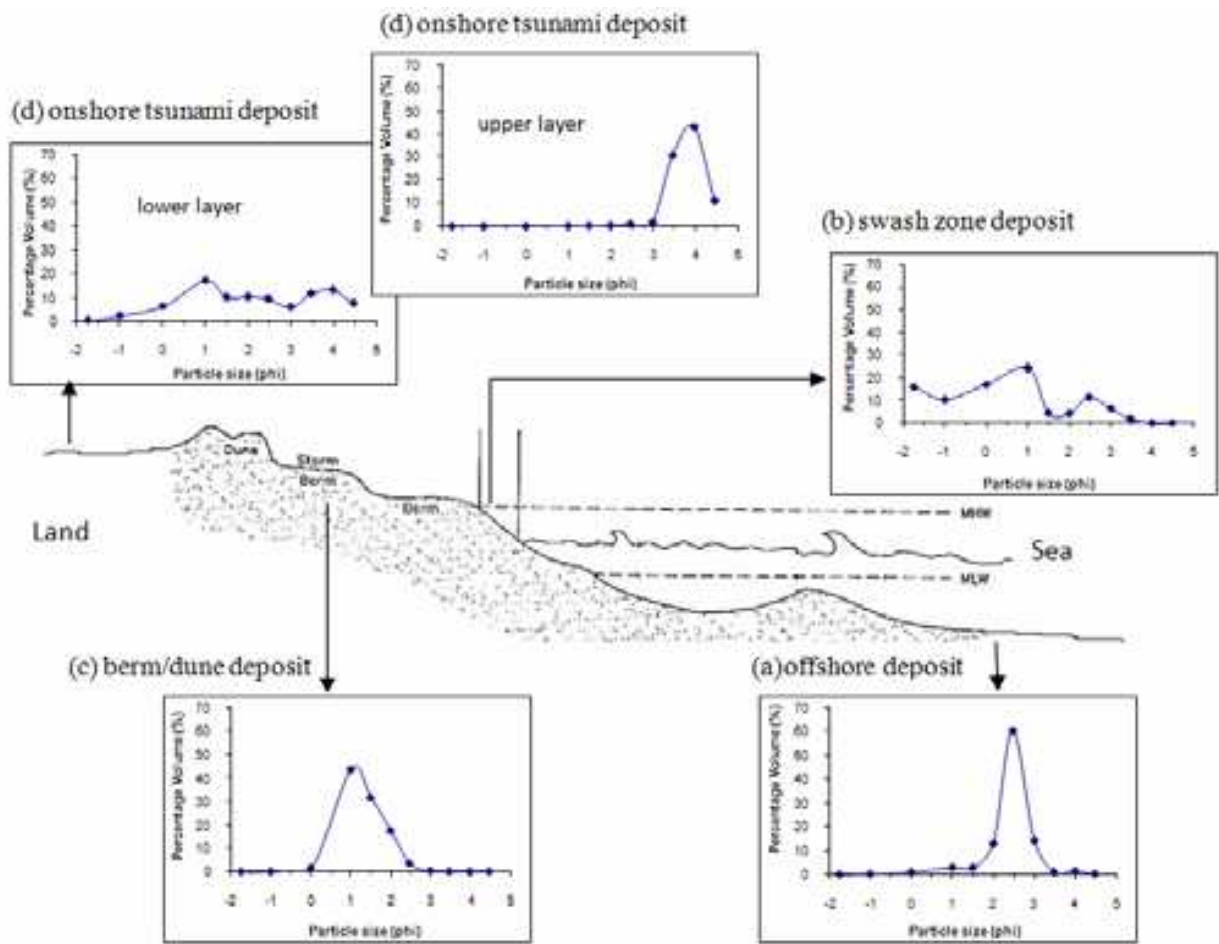Table 2. Tsunami sediment thickness from field surveys at the Thai-Andaman coast

Fig. 9. Representative grain-size distribution curves of littoral deposits from the four sub-environments at the Thai Andaman coast (from Srisutam & Wagner, 2010a)
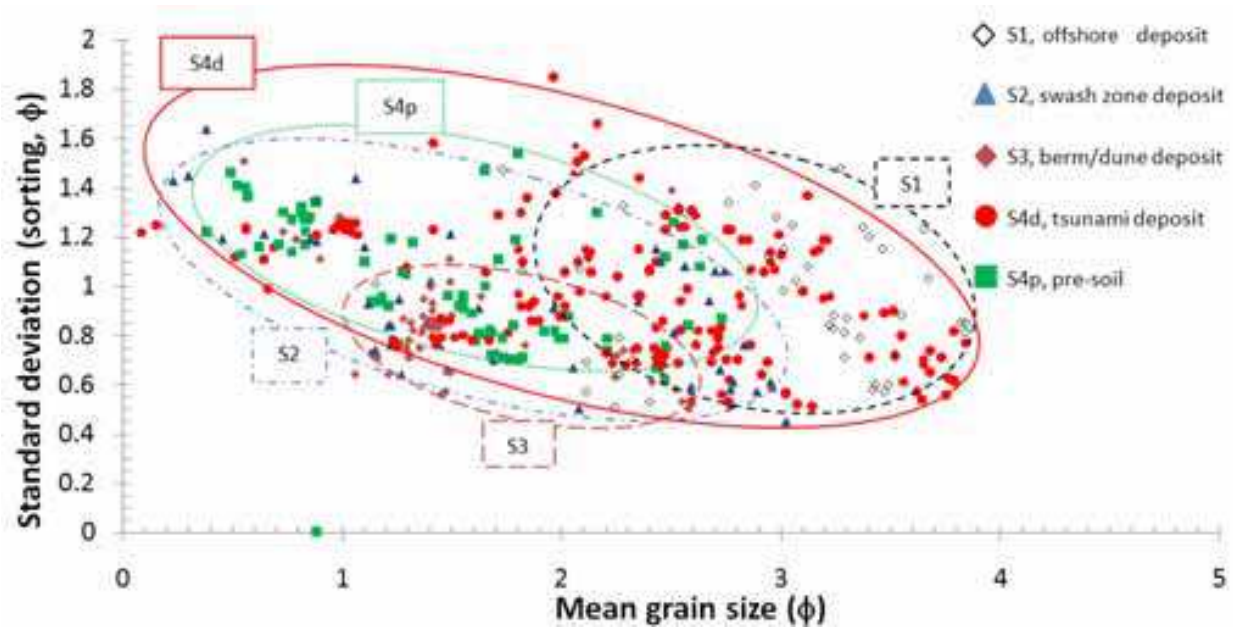

Fig. 10. Mean grain-size of tsunami sediment samples and non-tsunami deposits versus standard deviation (sorting) (from Srisutam & Wagner, 2010a)

Fig. 11. Coastal erosion caused by the 2004 Indian Ocean Tsunami (Pakarang Cape, about 4 km north of Khuk Khak beach)

4.1.3 Vertical grain size variations in the tsunami layer

The vertical development of tsunami sediment textures are shown in Fig.12 and Fig.13.

At Ao Kheuy and Khuk Khak beach mean grain-size fines generally upward and landward. There appears high vertical variability of mean grain-size at the beginning of the deposition zone. Shi et al. (1995) did propose that during periods when tsunamis inundate the coastal zone, provided an adequate sediment supply, sedimentation rates are so high that tsunami sediment is frequently composed of several populations of particles in different size ranges. As a result, the interaction of turbulence, rapid sedimentation and the characteristics of the transported material play a large part in dictating the characteristics of the particular tsunami deposit (Dawson et al., 1996). The set of individual fining upward sequences in the tsunami sediment suggests that tsunami waves inundated the study areas more than once. The coarse-grained sediments are supplied during a tsunami run-up wave. The overlying fine grained sediments with lower settling velocities probably have accumulated when run-up flows decelerate or stand still before the subsequent backflows (Hori et al., 2007).

Fig. 14 shows an example of some more textural parameters of the tsunami sediment at Khuk Khak beach. Sorting values may be used to determine the wave period. The sediment main layer with a higher variation of sorted value suggests that the sediment may be created by a shorter wave period. The value of skewness exhibits a large magnitude change over relatively short vertical intervals. The high value of skewness corresponds to a grain-size distribution with a modal peak corresponding to medium-grain sands and the corresponding tail to a distribution composed of finer-grain sediments. By contrast, low skewness values correspond to grain size distributions in which there is a significant coarse-tail element (Dawson et al., 1996). The kurtosis value generally refers to the degree in which the grain size distribution exhibits marked peakedness. High kurtosis values correspond to

grain size distributions which are characteristically unimodal and which possess a peaked distribution. Conversely, low kurtosis values correspond to flatter grain-size distributions. From these data we conclude that at the Thai Andaman coast, tsunamis are associated with rapid changes in the energy regime so that periods of high water turbulence (tsunami run-up at the beginning of the inundation) are followed by a still-water condition (pre-backwash phase) and, in turn followed by increased turbulence (backwash). The grain-size distributions of examples shown in Fig.12-14 demonstrates a distinctive change from a multi-modal sediment distribution to a uni-modal one as it was observed in previous publications (e.g., Flores event, Shi et al., 1995; Grand banks tsunami, Moore et al., 2007).

4.1.4 Identification of tsunami wave run-ups
The changing of slope in the plots of standard deviation with depth can be used to identify the boundaries of tsunami sediment layers (number of run-up sequences). The break points of slope in the plots of standard deviation with depth mark a break in turbulence associated with a transition to a lower or higher Reynolds number run-up. This may be due to a number of factors, including a deceleration or reflection of the wave bore, backwash from a
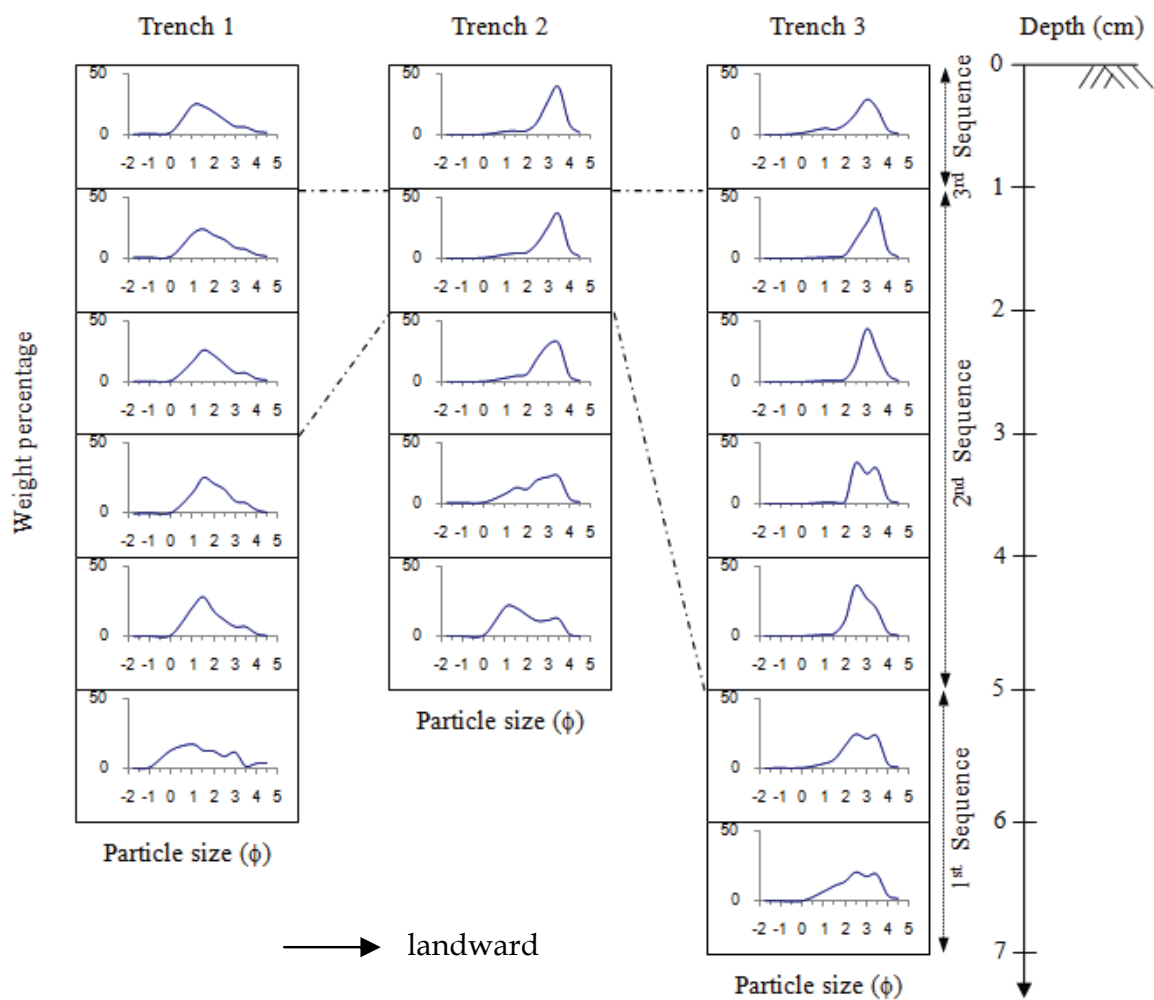

Fig. 12. Particle sizes profile for the tsunami deposit Ao Kheuy beach (from Srisutam & Wagner, 2009)
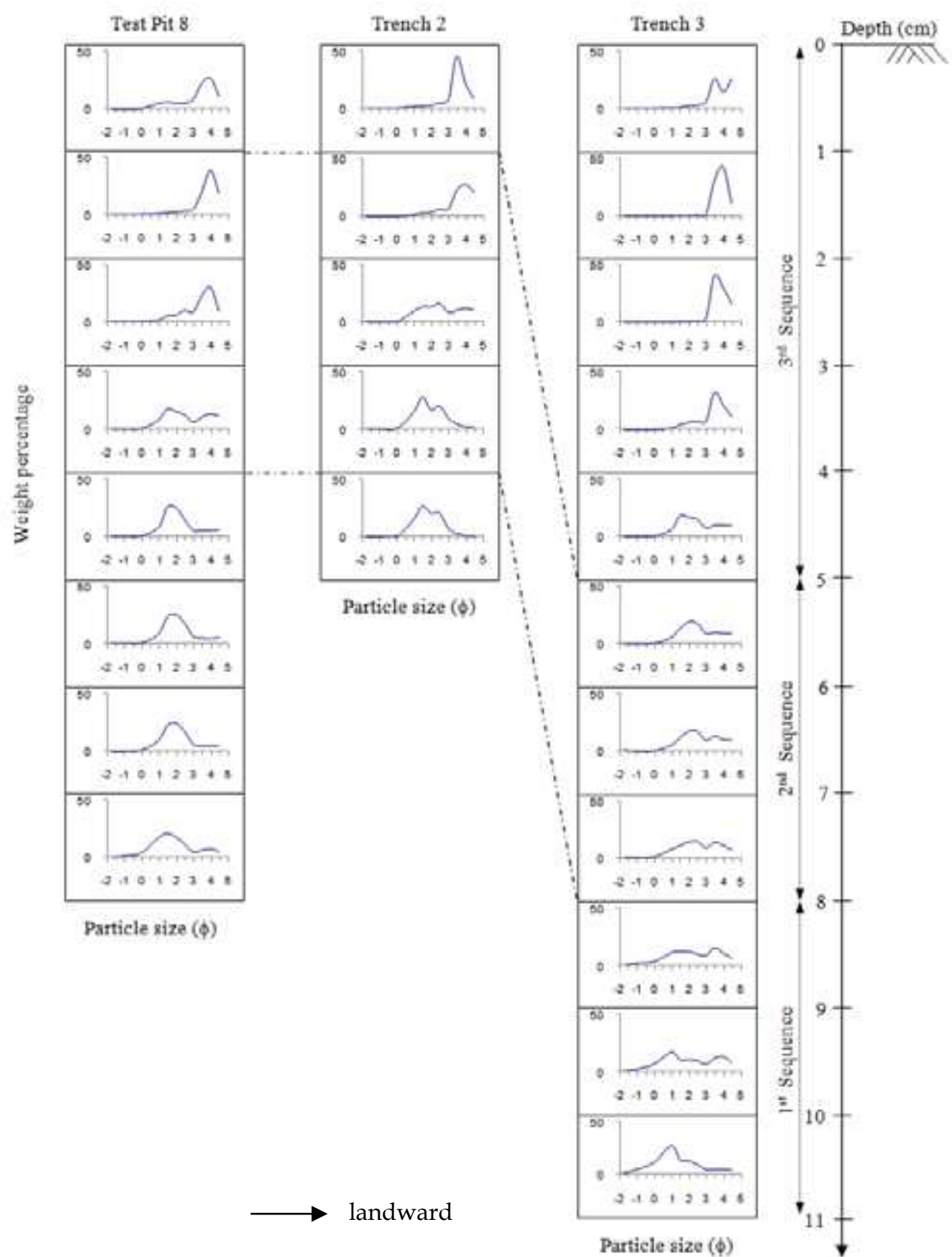
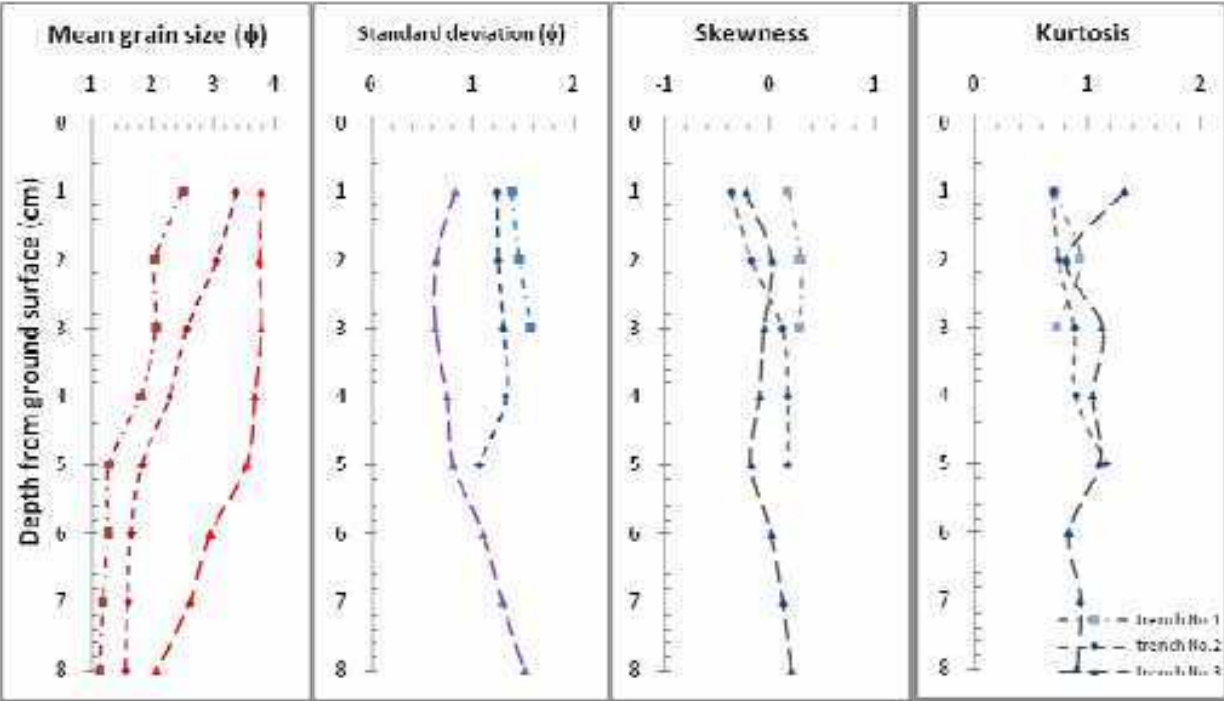Fig. 13. Particle sizes profile for the tsunami deposit deposit at Khuk Khak beach (from Srisutam & Wagner, 2009)

Fig. 14. Plots of tsunami deposits mean grain-size, standard deviation (sorting), skewness and kurtosis versus depth (Khuk Khak beach, Transect 2)

a) Ao Kheuy beach, Trench 2

b) Khuk Khak beach, Test Pit 8

Legend: ⇨ = Run-up; ⇦ = Backwash or drawdown
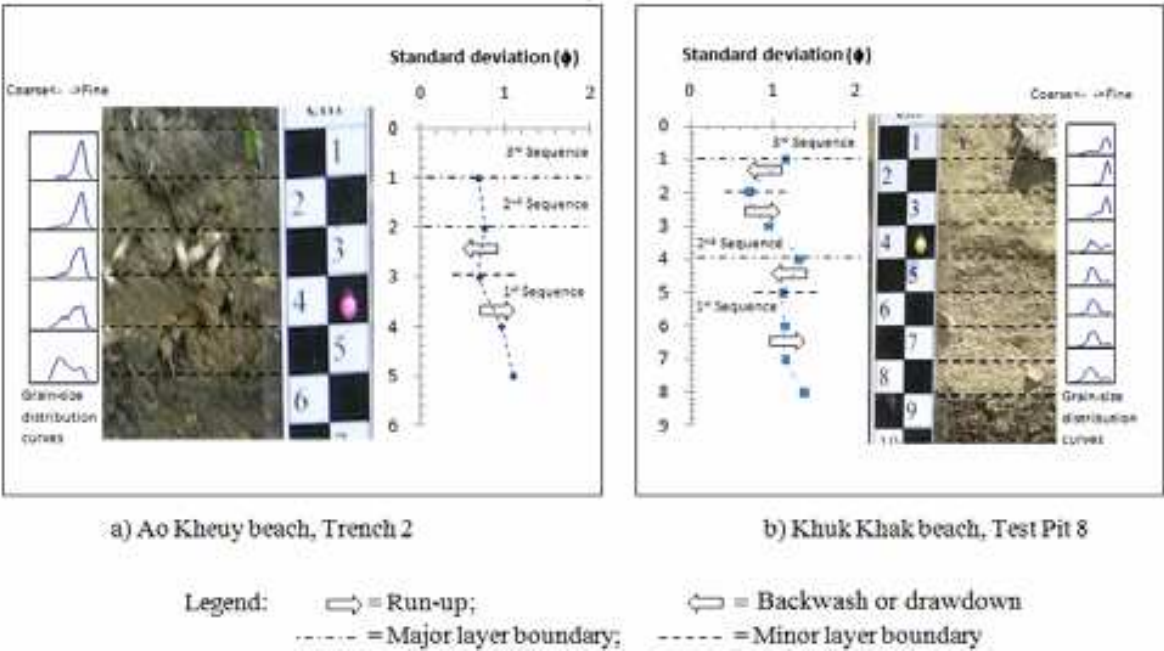----- = Major layer boundary; ----- = Minor layer boundary

Fig. 15. Plot of standard deviation versus depth for identification of run-up sequences (from Srisutam & Wagner, 2009)

previous wave or another incoming wave running over an already flooded surface (Hindson & Andrade, 1999).

To identify the tsunami run-up layers at Thai Andaman coast, plots of standard deviation with depth and grain-size distribution curve for the sediment layer in 1-cm intervals are evaluated (Fig. 15). Three main layers of tsunami sediment (or three tsunami run-ups) could be identified

from the grain size profiles at Thai Andaman coast. It corresponds to the observed run-up numbers from local eyewitnesses. The tsunami flow consists of a run-up and a backwash (return flow or drawdown) during the inundation event (e.g., Morton et al., 2007). In each tsunami sediment layer, there is a break point of standard deviation. It shows that tsunami sediment layer is composed of a deposit from run-up and backwash. Generally, the thickness of the deposit from run-up is higher than from backwash at the study areas.

Fig.16 shows a decrease of the grain-size from the first to the third run-up. A flattening of the curve can also be observed. The distribution curve is much flatter for the first run-up than the following, i.e. an increase in sorting occurs with every new run-up.
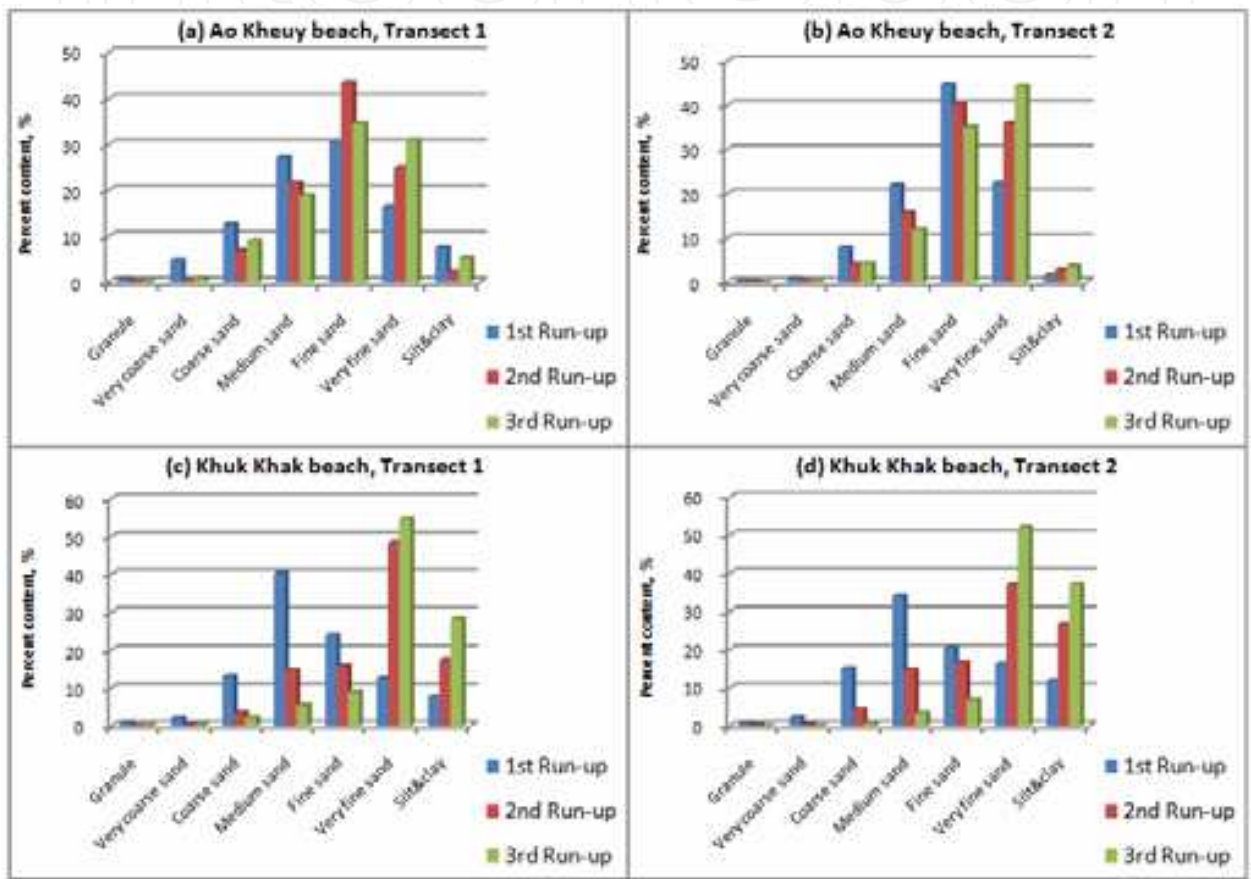

Fig. 16. Mean grain-size classes of run-up sequences (from Srisutam & Wagner, 2010a)

4.1.5 Influence of coastal morphology on tsunami deposits

The offshore slope influences tsunami waves in term of wave build-up (wave amplitude) and wave breaking. A wave breaks closer to the coastline at a steep offshore slope. When the wave breaks, the energy is dissipated, the near shore currents are induced and the mean water level is increased. The onshore slope however influences the velocity and inundation length of tsunami run-ups. At a steep onshore slope, the run-up velocity and inundation length are low and short, respectively. In contrast, the run-up velocity and inundation length are high and long at a mild onshore slope.

Two different offshore slopes are selected to discuss thickness and mean grain-size of the tsunami deposits at different slope inclination. Ao Kheuy beach, transect 1 (Morphology A) and Khuk Khak beach, transect 1 (Morphology B) represent a steep and a mild offshore

slope, respectively. The Wentworth size classes for the mean grain-size of the run-up layers are plotted in Fig.17 and show that for a steep slope the grain-size characteristics are very similar for every run-up sequence. On the contrary, a mild slope leads to a distinctly coarser deposit from the first run-up.

Further tsunami deposit characteristics for different slope inclinations are described in detail in Table 3.
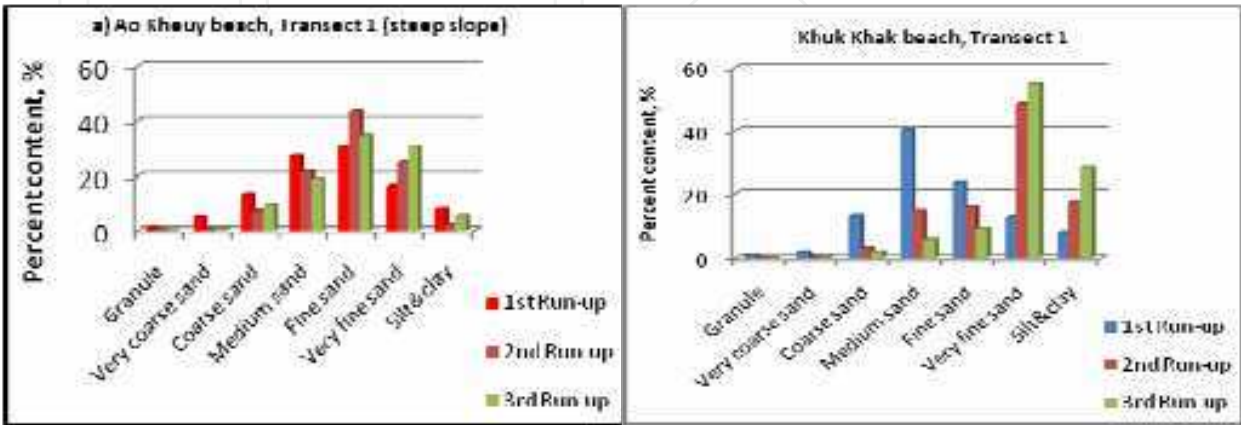

Fig. 17. Mean grain-size distribution charts for the deposits created by the tsunami run-ups at a steep (Ao Kheuy beach) and a mild (Khuk Khak beach) offshore slope

Tsunami deposit characteristics	Offshore	
	Steep slope (Ao Kheuy beach)	Mild slope (Khuk Khak beach)
Started point of deposit	About 40 m inland from coastline	About 70 m inland from coastline
Thickness	4-10 cm (inundation ends at hill slope)	2-12 cm (longer inundation and more deposits)
Mean grain-size	Medium to fine sand, the modal of deposit in each major run-up is same (fine sand)	Fine to very fine sand, the 1st run-up deposited coarser sediments (medium sand), the followed run-up deposited finer sediments (very fine sand)
On-land run-up energy	Lower energy, more run-up energy is dissipated by offshore slope	Higher energy, less run-up energy is dissipated by offshore slope

Table 3. Details of tsunami deposit characteristics at the steep and mild offshore slope

4.1.6 Influence of direct or indirect attacking tsunami waves

Two coastal areas (Khuk Khak beach and Ao Krabi) are considered for tsunami deposit characteristics created by direct and indirect tsunami waves. Khuk Khak beach is located at the upper part of the Thai Andaman coast. It was attacked by direct tsunami waves. Ao

Krabi was attacked by indirect tsunami waves which were diffracted and dissipated by Phuket Island. It is located at the lower part of the Thai Andaman coast. Plots of standard deviation with depth and plots of mean grain-size with standard deviation are used to define the characteristics of tsunami deposits created by direct and indirect tsunami waves, which are described in Table 4.

The tsunami deposit characteristics show that the energy at the coastline and onshore of the area attacked by the direct tsunami waves is higher and more variable than at the area attacked by the indirect tsunami waves (higher scatter in the plot of mean grain-size and standard deviation). A wide range of different source sediments is found at the area attacked by direct tsunami waves. The lower layer is mainly built up by nearshore and onshore sediments, the upper deposits comes from offshore sediments. At the area attacked by indirect tsunami waves, nearshore sediments are less found in the lower part of the deposits. More onshore sediments are found in the upper part of the tsunami deposit. These suggest that the tsunami deposits at the area attacked by indirect tsunami waves are mainly transported and deposited by the backwash flow.

Tsunami deposit characteristics	Affected coastal areas	
	Direct tsunami waves (Khuk Khak beach)	Indirect tsunami waves (Ao Krabi)
Mean grain-size	Medium to very fine sand, fining upward	Fine sand, particle size is uniform
Grain sorted	Moderately well sorted to poorly sorted	Well sorted to moderately sorted
Base	Major deposit base are easy to notice	Major deposit base are not easy to notice.
Source of deposits	Offshore, nearshore, and onshore	Nearshore and onshore
Attacked wave	High energy (~8-10 m run-up height)	Low energy (~1 m run-up height)

Table 4. Tsunami deposit characteristics at areas attacked by direct and indirect tsunami waves.

4.2 Thin sections

More details about the tsunami sediment composition can be studied in thin sections (see also Srisutam & Wagner, 2010c). The tsunami sediments (light colored sediments in Fig. 18) are medium to very fine grained. Sub-angular to sub-rounded grains are widely dispersed. There is evidence for grass roots which are the brown materials at the top of the tsunami deposit (0-2 cm). A lot of organic matter (dark colored materials) is also found in the sediment at the bottom of the tsunami deposit (9-12 cm). The tsunami deposit fines upward with three distinguishable sedimentation layers (Fig. 18). The base of each major sediment layer is identified by the changing of grain-size from fine grained to coarse grained upwards. The interfaces of the major sediment sequences are identified at the depths of 3-4 cm (the base of the upper major sediment layer, Fig. 18(d)) and 7-8 cm (the base of the 2nd sequence, Fig. 18(g)). The basis of the tsunami deposit is not seen by a changing in grain
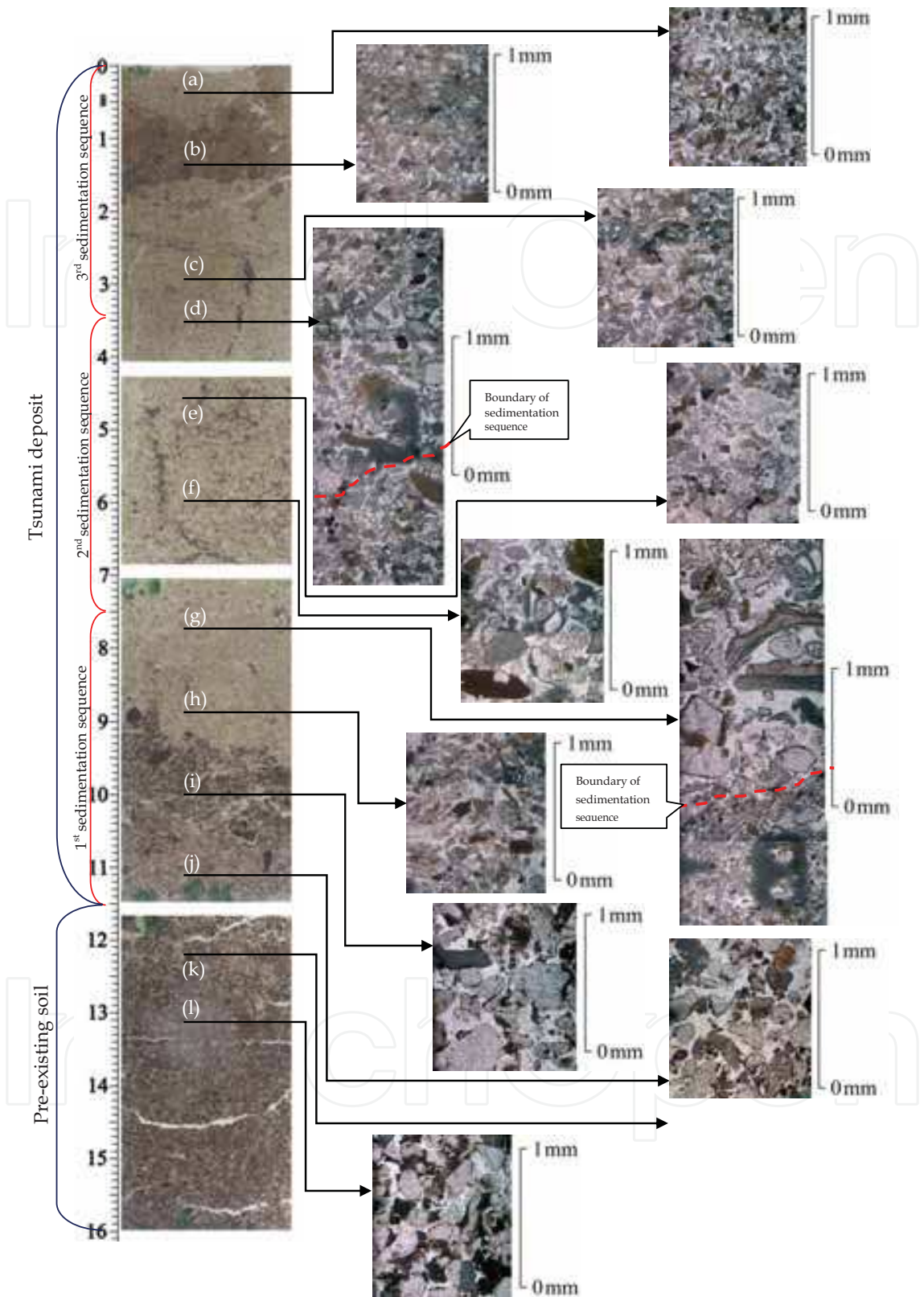
Fig. 18. The pictures of thin sections show details of the sediments in the tsunami deposit. The upper parts (light colored sediments, at the depth of 0-11.5 cm) are the tsunami deposit. The lower part (dark colored sediments) is the pre-existing soil. The sediments fine upward with three run-up sequences (from Srisutam & Wagner, 2010c)

size. It is identified by differences in the roundness of the grains and the content of organic matter. The pre-existing soil is composed of rounded grains and the percentage of organic material in the soil is higher. Therefore, the depth which separates the tsunami deposit from the pre-existing soil is at a depth between 11-12 cm (the base of the 1st major sediment layer, see Fig. 18(j) and Fig. 18(k)). There are three sediment layers or three sedimentation sequences in the tsunami deposit in total. The 1st, 2nd and 3rd sedimentation sequences are at the depth from 7.5-11.5 cm, 3.5-7.5 cm and 0-3.5 cm, respectively.

Shell fragments and shallow water micro-organisms are commonly found in the tsunami deposit as shown in Fig. 19(a). It is possible to observe micro-soil rip-up clasts or micro-sand pockets (a cluster of sediments which are coarser or finer than the surrounding sediment) in each sedimentation sequence (Fig. 19(b)). The most abundant sediment grains are quartz, some muscovite mica and some organic material (Fig. 20).
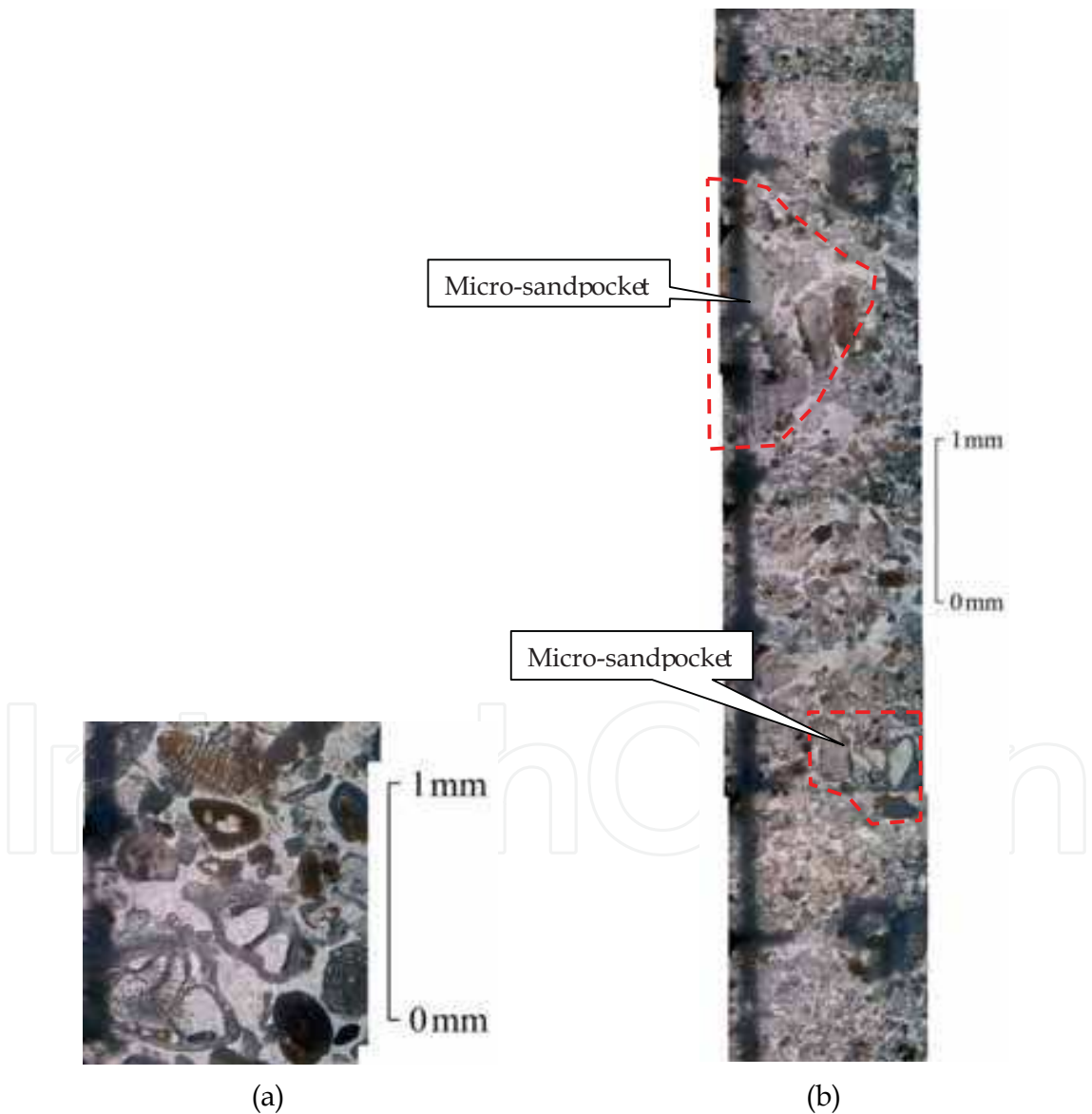

(a)   (b)

Fig. 19. (a) Shell fragment and shallow water micro-organisms in the tsunami deposit (an example from the depth of 6.3-6.4 cm) and (b) example of the micro- sand pockets from the depth 8.5-9.0 cm (from Srisutam & Wagner, 2010c)

(a) Plane-polarized photomicrograph   (b) Cross-polarized photomicrograph
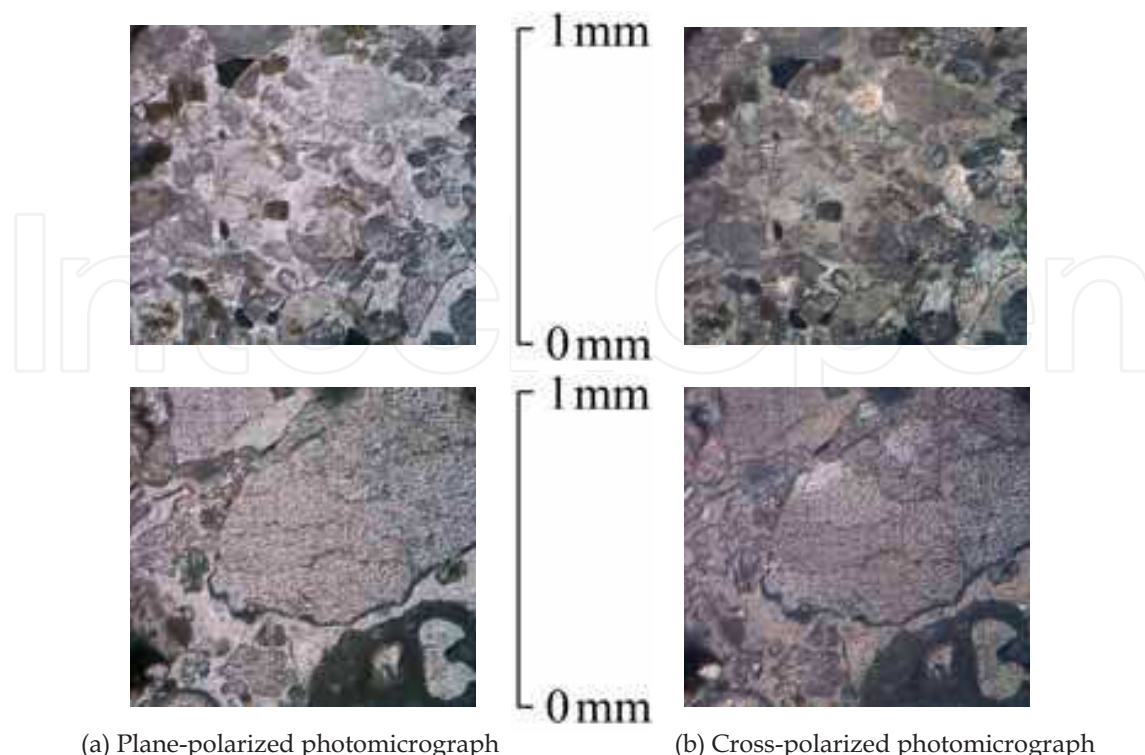
Fig. 20. Polarizing microscope pictures of the tsunami deposit thin sections. The cross-polarized picture better displays the mineralogy of the sediment. The quartz grains are the large grey grains, which are displaying corroded margins. The brightly colored mineral is muscovite mica, in typical lath shaped appearance. The dark colored spots are organic components in the tsunami deposit (from Srisutam & Wagner, 2010c)

5. Discussion

The results of the authors demonstrate that the wet-sieve grain-size analysis as well as thin section analyses can be used to illustrate the characteristics of a tsunami deposit. Both techniques show best the unique characteristics of tsunami sediments which are very similar for both methods. The tsunami deposit is generally composed of multiple fining upward sediment layers. The vertical variations of grain-size parameters from the wet-sieve suggest that there are three major sediment layers in the tsunami deposit which can be interpreted as three run-up/backwash sequences. The same observation was made from the thin sections. Here the interfaces of the major sediment layers were at depths of 3-4 cm, 7-8 cm and 11-12 cm. In the vertical grain-size profiles they were identified at the break points in plot of standard deviation with depth and at the locations of grain-size changing from fine grained to coarse grained. The similar characteristics from both methods can be explained by the previous works of Friedman (1958, 1962) and Johnson (1994). They presented a linear relationship existence for grain-size analysis between the quartile measures of sieving and thin section data. There is very little scatter on either side of the regression line for this relationship and the coefficient of correlation is close to 1.0. The finding that three run-ups or three tsunami waves affected the study area is in accordance with eyewitnesses presented by Szczuciński et al. (2006) and Hori et al. (2007).

In this study, minor details which could not be observed in wet-sieve analysis such as the exact contact between tsunami deposit and the pre-existing soil (the base of the tsunami deposit), the micro-soil rip-up clasts or micro-sand pockets in the major sediment layer and the mineral content could be identified in thin sections. Generally, the contact between tsunami deposit and pre-existing soil can be identified in the field at the boundary where the color of sediments is changing (normally dark to light color of sediments). The thin section shows that the contact of tsunami deposit and pre-existing soil is located lower than the boundary where the color of the sediment changes from dark to light. The sediment lying immediately above the soil/tsunami sediment contact has a darker color than the sediments in the upper part. Sediments at the base of a tsunami deposit are composed of coastal sand (light color), onshore sediments and the dark color may be due to organic matter or resedimentated soil clasts (see Fig. 18(j)). This is a further proof that tsunamis erode and transport pre-existing sediments from coastal and onshore areas to be deposited further inland. This phenomenon does not only occur in the 1st run-up, but also in the 2nd and the 3rd. It is however more easy to be observed in the 1st run-up layer where more micro-soil rip-up clasts or micro-sand pockets can be observed. The clasts and sand pockets may be the result of turbulence associated with a transition to a lower or higher Reynolds flow number.

The mineral content of a tsunami deposit can be evaluated under the polarizing microscope. At the Thai-Andaman Coast the tsunami sediment grains are mainly quartz and some muscovite mica. These minerals are the major minerals found in sand and silt deposits of the coastal area (e.g. Smith et al., 1976; Harris et al., 1989).

6. Conclusions

The following depositional characteristics of tsunami sediments were obtained from field observations, grain-size distributions (Srisutam and Wagner, 2009, 2010a), analyzed by wet-sieving and from micro-morphological features from thin sections (Srisutam & Wagner, 2010c), respectively

- Tsunami sediments overlay the pre-existing soil with a sharp basal erosion surface.
- The tsunami deposit is a multiple-layered sediment. It generally fines upwards and landwards.
- The material of the tsunami layer is eroded sediment from offshore, coastal and onshore areas transported by the tsunami to inland areas.
- The tsunami sediment in this study is very often a moderately to poorly sorted, fine to very fine sand with coarser particles like e.g. shell fragments. Generally tsunami sediments are not characterized by a typical grain size distribution.
- A plot of the mean grain-size of tsunami sediment versus sorting indicates that tsunami deposits are a mixture of offshore sediments, swash zone deposits and berm/dune deposits as well.
- The grain size distribution depends strongly on the coastal morphology.
- At Thai-Andaman Coast three sedimentation sequences could be distinguished in the tsunami deposit which reflects three run-ups or three tsunami waves affecting this area. The interface of each sedimentation sequence can be located at break points in a plot of grain-size standard deviation with depth. The break points are the changing points of grain-sizes from fine to coarse grains upwards and can be observed in the thin sections as well.

- The 1st run-up transported and deposited coarser particles than the following run-ups.
- Shallow water microorganisms, shell fragments and micro soil rip-up clasts or sand pockets can be observed in almost all sediment sequences.
- Micro-morphological features suggest also that the tsunami sediments are deposited by a run-up flow and a drawdown (backwash) flow as well. Mean grain-sizes of the sediments deposited by both flows are not significantly different.
- The wet-sieving and thin section analyses for the characterization of tsunami deposits give significantly similar results concerning grain size distribution. However, the reconstruction of the sedimentological environment from tsunami sediment characteristics is more convenient from the grain size distribution by wet sieving than from thin sections. Thin sections give additional information about micro-morphological features and composition.

The characteristics of tsunami deposits can be used to calculate tsunami run-up height and velocity. From these data risk assessment and coastal development programs can be deduced for tsunami affected areas (Srisutam and Wagner, 2010b).

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The Tsunami Threat - Research and Technology

Edited by Nils-Axel Mörner

Submarine earthquakes, submarine slides and impacts may set large water volumes in motion characterized by very long wavelengths and a very high speed of lateral displacement, when reaching shallower water the wave breaks in over land - often with disastrous effects. This natural phenomenon is known as a tsunami event. By December 26, 2004, an event in the Indian Ocean, this word suddenly became known to the public. The effects were indeed disastrous and 227,898 people were killed. Tsunami events are a natural part of the Earth's geophysical system. There have been numerous events in the past and they will continue to be a threat to humanity; even more so today, when the coastal zone is occupied by so much more human activity and many more people. Therefore, tsunamis pose a very serious threat to humanity. The only way for us to face this threat is by increased knowledge so that we can meet future events by efficient warning systems and aid organizations. This book offers extensive and new information on tsunamis; their origin, history, effects, monitoring, hazards assessment and proposed handling with respect to precaution. Only through knowledge do we know how to behave in a wise manner. This book should be a well of tsunami knowledge for a long time, we hope.

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