เอกสารแนบ

1. ผลงานตีพิมพ์ในวารสารวิชาการระดับนานาชาติ จำนวน 3 บทความ (ระบุคำขอบคุณ สกว และรหัสโครงการ) ดังนี้

1.1 Choowong, M., 2010. Forewarning of M 7.6 earthquake at Andaman Islands: where next? *Current Science*, Vol. 98, No. 8, 1013-1014. ISI Impact Factor (2012) 0.905

1.2 Phantuwongraj, S., and Choowong, M., 2012. Tsunami versus storm deposits from Thailand. *Natural Hazards*, 63 (1), 30-50. ISI Impact Factor (2012) 1.639

1.3 Phantuwongraj, S., Choowong, M., Nanayama, F., Hisada, K., Charusiri, P., Chutakositkanon, V., Pailoplee, S., Chabangbon, A. 2012. Coastal Geomorphic Conditions and Styles of Washover Deposits by NE Monsoon from Southern Thailand. *Geomorphology*, 192, 43-58. ISI Impact Factor (2012) = 2.552

2. บทความในวารสารวิชาการระดับชาติ จำนวน 2 บทความ (ระบุคำขอบคุณ สกว และรหัสโครงการ) ดังนี้

2.1 Lertnork, W., Choowong, M., Thitimakorn, T., 2010. "Geomorphology and Ground Penetrating Radar Profiles of Holocene Coastal Dune, Western Coastal Plain of the Gulf of Thailand". *Bulletin of Earth Sciences of Thailand*, Vol. 3, No. 1, 17-27.

2.2 Nimnate P, Choowong, M. and Chutakositkanon, V., 2013. Characteristics of former beach ridge plains from remote sensing data at Chumphon estuaries, southern Thailand. *Bulletin of Earth Sciences of Thailand*, Vol. 5, No. 1, 39-48

3. บทในหนังสือที่เผยแพร่ระดับนานาชาติ (ระบุคำขอบคุณ สกว และรหัสโครงการ)

3.1 Choowong, M., 2011. "Quaternary", Book Series "Geology of Thailand". In: Ridd, M.F., Barber, A.J., Crow, M.J. (Eds). *Geological Society of London* (Chapter 12), 335-350)

4. มนตรี ชูวงษ์ 2555 เปิดแฟ้มพิบัติภัย หายนะโลกในรอบ 10 ปี บทสัมภาษณ์และบทความ นิตยสารแพรว ฉบับวันที่ 25 พฤษภาคม 2555 หน้า 210-214

Forewarning of *M* 7.6 earthquake at Andaman Islands: where next?

On Monday, 10 August 2009 at 19:55:39 Universal time (UT) (11 August 2:56 a.m., Thailand local time), an earthquake of surface wave magnitude (*M*) 7.6 occurred off the coast of Port Blair, Andaman Islands, India[1]. This quake (depth at 15 km of 13.991°:93.838°E)[2] spawned a regional quake which was felt up to some 600 km west of its epicentre. At Thong Pha Phum, Kanchanaburi, western Thailand, the quake started at 2:57 a.m. and persisted for more than 60 s. This earthquake is located about 200 km north of the pre-2004 rupture areas related to the 1941 earthquake (Figure 1).

According to the prediction made before the 2004 Sumatran earthquake[3], this recent earthquake of *M* 7.6 at the northern Sunda Trench was not the first of its kind[4]. An earthquake with a magnitude up to *M* 8.0 was expected to recur at 157 ± 43 years from the rupture zone of Car Nicobar Islands after 1881 – i.e. between 1995 and 2081 (refs 5 and 6). At southern Sunda Trench, seismological data reveals that the recurrence of the quake at Sumatra with a magnitude $\geq M$ 9.0 may not be earlier than 140 years from 2004 (ref. 7). Though this *M* 7.6 earthquake was about 500 km away from the previously expected recurrent zone[5,6], it confirmed the probable recurrence in the pre-2004 rupture zone according to the seismological and geological predictions. To date, sedimentological evidence also extends tsunami history for the Sunda Trench region. If the youngest sand sheet beneath 2004 tsunami layer found in Thailand[8] and Indonesia[9] is a predecessor of the 2004 Indian Ocean tsunami, the expected recurrence with a similar magnitude of tsunamigenic earthquake at Sumatra is inferred to possibly recur in the next 600 years. These issues challenge the scientists to narrow down the prediction of the recurrence of such a potential mega-tsunamigenic earthquake spatially and temporally along the Sumatra–Andaman subduction zone. However, the possibility of a local tsunamigenic earthquake should also be taken into account.

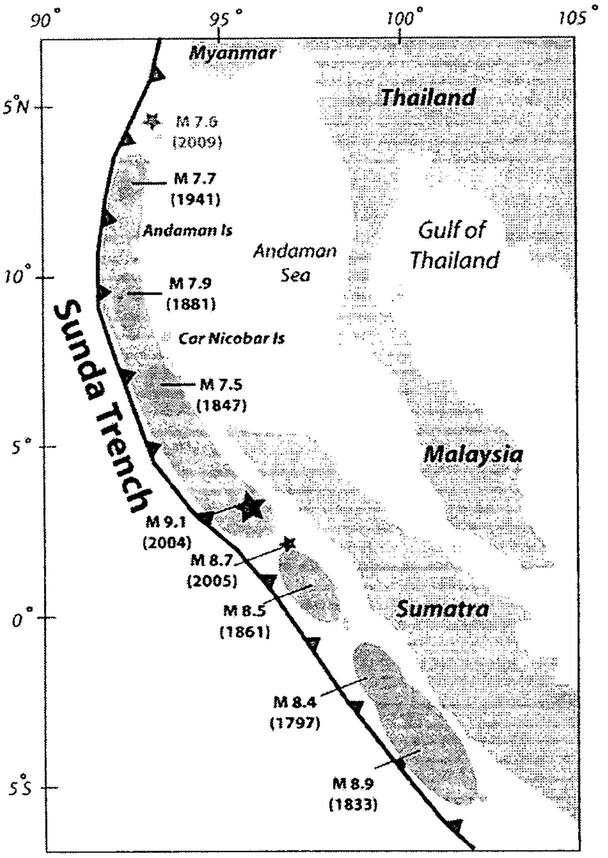

Figure 1. Historical records of submarine earthquakes along Sunda Trench[3–6]. The 2004 ($M = 9.1$) event at Sumatra rupture extended to Andaman Islands (pale brown)[7–9]; green circles indicate rupture zone for each event.

The *M* 7.6 earthquake provides a significant scenario to be construed as an early warning sign of the seismological stress beneath the Sumatra–Andaman subduction zone. It is interesting that the trend of stress around this part of Indian Ocean region may possibly be released northward along the northern Sunda Trench rupture zone (*M* 7.5, *M* 7.9, *M* 7.7, *M* 7.6 in 1847, 1881, 1941 and 2009 respectively). Statistically, the recurrent interval of stress release along the northern Andaman Trench is likely to be at least 60 years. If this trend of stress release is to the north, the possibility of the next earthquake may regionally recur either at the northern part of the Andaman rupture zone or at the western and central parts of Myanmar.

In terms of geological setting, the *M* 7.6 (2009) quake may have generated from a normal fault and not directly connected to the major strike–slip active fault in central Myanmar – the Sagaing Fault (SF; Figure 2)[10]. The north–south SF is more than 1000 km length on land and extends for 100 km to its south through the Andaman Sea and ending its connection with the Sumatra–Andaman subduction zone. The SF branches to the two major strike–slip active faults of the western Thailand – the Mae Ping Fault (MPF) and the Three Pagoda Fault (TPF). It is important to note that, if this trend of stress releases to the north around the northern part of Andaman subduction zone, either the strike–slip SF in Myanmar or the TPF and the MPF in Thailand may further be subjected to local movement. The movement of active faults indicates the maximum earthquake magnitude of *M* 8.5 (refs 10, 11) and *M* 6.3 (ref. 11) to *M* 6.9 (ref. 10) being generated along the SF and TPF fault zones. Thus, all countries around Indian Ocean (especially Thailand and Myanmar) need to be cautious about the next possible earthquake event.

The *M* 7.6 earthquake is primarily categorized as magnitude intensity II–III (ref. 1), but such an earthquake magnitude has rarely been felt by people living in the countries east of the Sumatra–

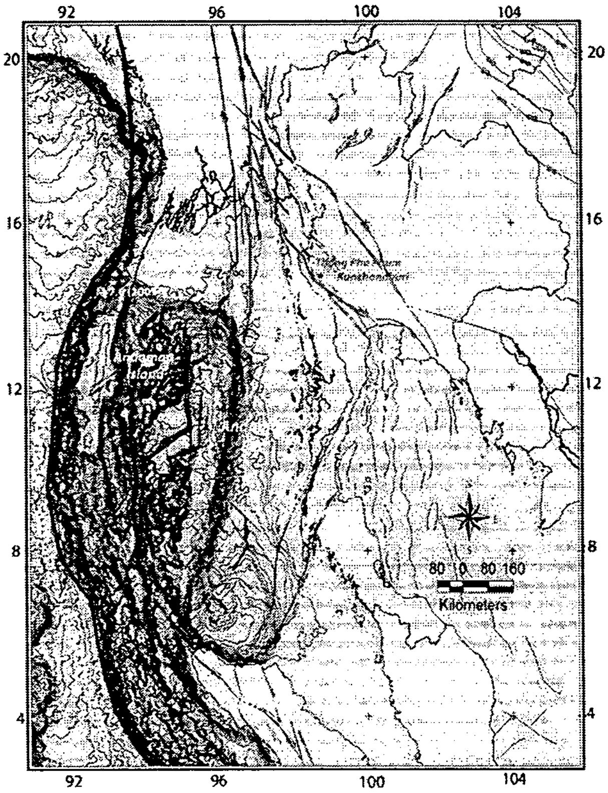

Figure 2. Major active faults (red) with their networks: Sagaing Fault (SF) in Myanmar, Mae Ping Fault (MPF) and Three Pagoda Fault (TPF) in Thailand. Red star represents the recent event of M 7.6 with the epicentre at northern Andaman Islands. Red dot shows the location of Thong Pha Phum, Kanchanaburi where the quake was felt by the author. Bathymetric contours indicated in blue. Green shade represents extensional basin in Andaman Sea.

Andaman subduction zone. Within an hour of the occurrence of the quake, the Pacific Tsunami Warning Centre sent a message alerting all the countries around the Indian Ocean for a possible teletsunami. Fortunately, no teletsunami hit the coastal region and the warning message was withdrawn a couple of hours later. Most importantly, such a M 7.6 earthquake has the potential for local tsunami generation and what would happen if an earthquake of equal or greater magnitude occurred in the night when people living in Indian Ocean coastal zone are asleep. This event, certainly, cannot be ignored and could be counted as one of the significant signs of early forewarning for future earthquakes and tsunamis that may recur at countries around Indian Ocean. These countries need to plan for the mitigation of earthquakes and night-time tsunamis that might recur in the next hundred years.

1. Magnitude 7.6 – Andaman Islands, India: http://earthquake.usgs.gov/paper
2. Mishra, O. P. *et al.*, Technical Report of GSI, 2009, pp. 1–4.
3. Borok, V. D., *Annu. Rev. Earth Planet. Sci.*, 2002, **30**, 1–33.
4. Rajendran, C. P. *et al.*, *Curr. Sci.*, 2003, **84**, 919–924.
5. Ortiz, M. and Bilham, R., *J. Geophys. Res.*, 2003, **108**, 16.
6. Bilham, R. *et al.*, *Seismol. Res. Lett.*, 2005, **76**, 299–311.
7. Chlieh, M. *et al.*, *Bull. Seismol. Soc. Am.*, 2007, **97**, 152–173.
8. Jankaew, K. *et al.*, *Nature*, 2008, **455**, 1228–1231.
9. Monecke, K. *et al.*, *Nature*, 2008, **455**, 1232–1234.
10. Pailoplee, S. *et al.*, *EPS*, 2009, **61**, 1313–1325.
11. Bertrand, G. and Rangin, C., *J. Asian Earth Sci.*, 2003, **21**, 1139–1153.
12. Songmuang, R. *et al.*, *Science Asia*, 2007, **33**, 23–33.

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Tsunamis versus storm deposits from Thailand

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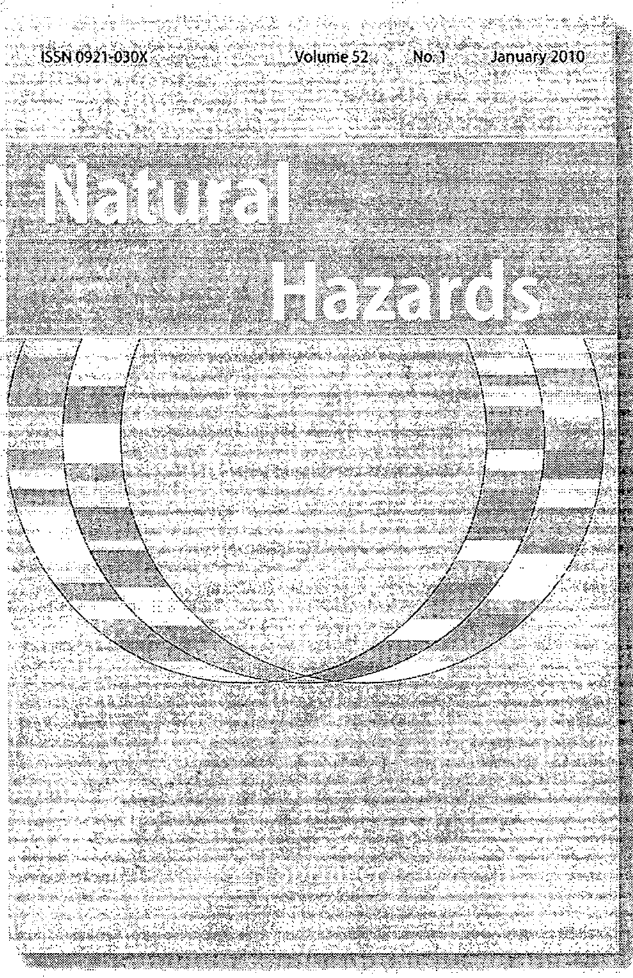

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ORIGINAL PAPER

Tsunamis versus storm deposits from Thailand

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Abstract Along the Andaman (west) coast of Thailand, the 2004 tsunami depositional features associated with the 2004 tsunami were used to describe the characteristics of tsunamis in a place far away from the effect of both recent and ancient storms. The current challenge is that a lack of precise sedimentological characteristics have been described that will differentiate tsunami deposits from storm deposits. Here, in sedimentological senses, we reviewed the imprints of the sedimentological characteristics of the 2004 tsunami and older deposits and then compared them with storm deposits, as analyzed from the deposits found along the eastern (Gulf of Thailand; GOT) coast of Thailand. We discuss the hydraulic conditions of the 2004 tsunami and its predecessors, on the Andaman coast, and compare them to storm flows found on the coast of the GOT. Similar to an extensive tsunami inflow deposit, a storm flow overwash has very similar sedimentary structures. Well-preserved sedimentary structures recognized in sand sheets from both tsunami and storms include single and multiple normal gradings, reverse grading, parallel, incline and foreset lamina, rip-up clasts, and mud drapes. All these sedimentary structures verify the similarity of tsunami and storm inflow behavior as both types of high-energy flow start to scour the beach zone. Antidunes are likely to be the only unique internal sedimentary structures observed in the 2004 tsunami deposit. Rip-up clasts are rare within storm deposits compared to tsunami deposits. We found that the deposition during the outflow from both tsunami and storms was rarely preserved, suggesting that it does not persist for very long in the geological record.

Keywords 2004 Indian Ocean tsunami · Storm surge · Washover deposits · Flow regime · Andaman coast

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1 Introduction

The 2004 Sumatra–Andaman tsunami event strengthened seismological and geological research worldwide. Among geological studies, the sedimentological works on tsunami sand sheets and ancient deposits onshore, derived from observations made on both sides of the Pacific after the 1960 Chilean tsunami, have expanded in the two past decades (Konno et al. 1961; Wright and Mella 1963; Atwater 1987; Dawson et al. 1988; Bourgeois et al. 1988; Long et al. 1989; Minoura and Nakaya 1991; Bryant et al. 1992; Hindson et al. 1996; Bondevik et al. 1997; Clague et al. 2000; Moore 2000; Goff et al. 2000, 2004; Fujiwara et al. 2003; Pinegina et al. 2003; Nanayama et al. 2003; Nelson et al. 2004; Cisternas et al. 2005; Williams et al. 2005; Nanayama and Shigeno 2006; Jaffe and Gelfenbaum 2007; Dawson and Stewart 2007). Most researchers have reported relatively in depth descriptive results on both the physical characteristics of modern and ancient tsunami deposits. However, only a few publications in the past decade have provided key analogs for the comparisons of the depositional characteristics of the modern and ancient tsunami deposits, and the same for the storm deposits from the Pacific side, in the past decade (Nanayama et al. 2000; Tuttle et al. 2004; Morton et al. 2007). This issue is limited to the deposits found only from those countries that are located close to the Pacific plate boundary. Because there are few written records of giant tsunamigenic earthquakes around the Indian Ocean before the 2004 event, less attention has been paid among the local geoscientists to make a concrete research on the comparison of characteristics between tsunamis and storm deposits. Therefore, the search for traces of ancient tsunamis and storms from the Indian Ocean side is still required.

The understanding of the physical and biological characteristics of the 2004 Indian Ocean tsunami deposits has improved following investigations focused on the effect of a tsunami at the regional scale, that included physical and biological descriptions of tsunami deposits from the coastal zone. Recently, this work has been extended to include areas, where the tsunami produced onshore sand sheets near the tsunami's source, such as in Indonesia (Moore et al. 2006), and along shores more than 500 km away from the source such as India (Chadha et al. 2005; Nagendra et al. 2005; Singarasubramanian et al. 2006; Bahlburg and Weiss 2007), Sri Lanka (Goff et al. 2006), Malaysia (Hawkes et al. 2007), Thailand (Szczucinski et al. 2005, 2006; Rhodes et al. 2007; Choowong et al. 2007, 2008a, b, 2009; Hawkes et al. 2007; Hori et al. 2007; Umitsu et al. 2007), Myanmar (Satake et al. 2006), and Kenya (Bahlburg and Weiss 2007). Most researchers have provided results on the detailed analysis of the facies, thickness, grain-size changes, and biological clues within tsunami deposits.

Along the Andaman coast of Thailand, several recent publications have revealed the local relationship among the 2004 tsunami deposits, coastal morphology, and run-up heights (Choowong et al. 2007; Umitsu et al. 2007; Hori et al. 2007). Other publications have analyzed the record of micro-fauna in the tsunami deposits in relation to the flow conditions (Hawkes et al. 2007; Sawai et al. 2009). A few publications have provided information on the nature of the hydraulic condition of tsunami flows, especially how large and how fast the tsunami was that created the different sequences of observed deposits (Higman et al. 2006; Choowong et al. 2008a). In addition, an offshore geological surveys along a part of the Andaman Coast was reported recently (Di Geronimo et al. 2009), and the deposits from tsunamis that predate the 2004 tsunami were discovered in Thailand and Indonesia (Jankaew et al. 2008; Monecke et al. 2008; Fujino et al. 2009), subsequently, leading to the prediction in a regional possibility of tsunamigenic earthquake along Sunda Trench (Choowong 2010).

After typhoon Nargis hit the west coast of Myanmar in 2008, the awareness of storms and tsunamis has spread to the Indian Ocean societies and is the focus of this paper. From written records of coastal disasters, Thailand has experienced at least three storm surge events in the coastal area along the GOT—two of these were induced by a typhoon and one was related to a tropical storm. In 1962, the "Harriet" tropical storm generated an unusual surge at the Laem Talum Puk sand spit in southern peninsular Thailand (Fig. 1a). It caused serious damage to infrastructures and more than 900 casualties were reported (Kanbua 2008). Two decades later, 1989 typhoon Gay hit with a maximum wind speed of 190 km/h and caused a storm surge flood over the northern part of the Chumphon coastal plain (Fig. 1b). In 1997, a storm surge from typhoon Linda hit the coastal area with its major track way crossing the Prachuap Khiri Khan area, along the western side of the Gulf (see

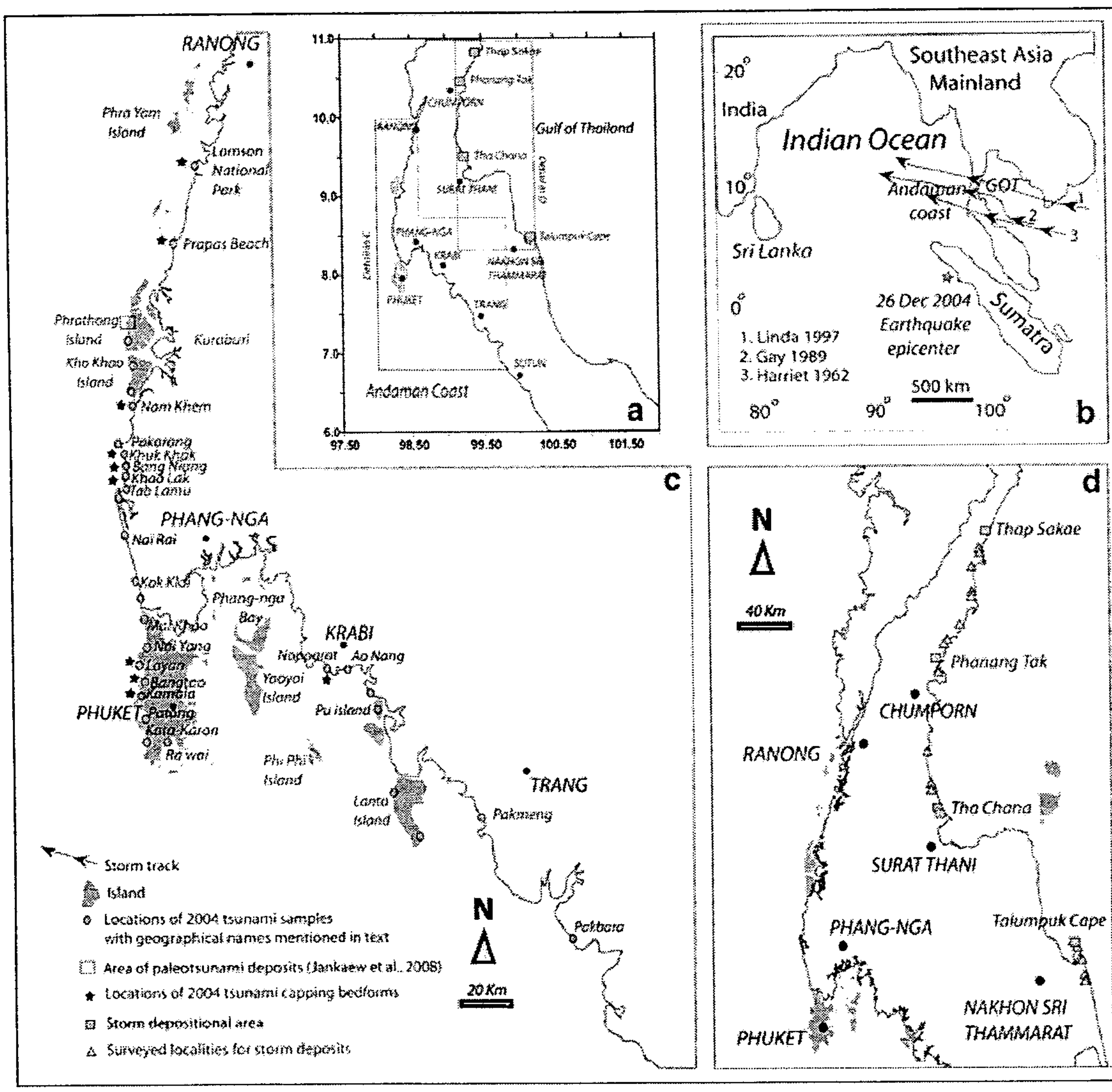


Fig. 1 Setting. **a** Location *map* of the main geographic provinces from the Andaman and Gulf of Thailand (GOT) coasts. **b** Physiographic *map* of the Indian Ocean region, the location of the 2004 earthquake epicenter, and records of the three severe storm track ways in the GOT. **c** Sample collection *map* with the local geographic names mentioned in the text; *dots* represent localities of the 2004 tsunami deposits; *square* is the location of the predecessor of the 2004 tsunamis found at Phrathong Island (Jankaew et al. 2008); *dark stars* represent locations where we found 2004 tsunami bedforms. **d** Localities where we surveyed storm deposits along the GOT

location in Fig. 1). All these decadal frequencies of typhoons and storms clarify the need for a detailed and definitive research.

Finding records of previous tsunamis and storms is geologically challenging. A few attempts have been made to describe storm deposits in Thailand, but no precise criteria were established for distinguishing them from other sources. Although the 1989 typhoon Gay ran across Thailand from the GOT to the Andaman coast, it did not register any sedimentological clues along the Andaman coastal plain. Only a few records of storm deposits onshore at locations along the GOT coastal area have been reported (Roy 1990; Phantuwongraj et al. 2008, 2010; Phantuwongraj and Choowong 2010).

In this paper, we summarize and review all the significant characteristics of the 2004 deposits from the Andaman coast (Fig. 1c) based solely on the descriptive sedimentology. We also discuss the stratigraphical records of the inflow and outflow from both the tsunami and storm deposits. The localities where we discover sand sheets, possibly deposited from ancient storms, as a candidate distinctive marker are registered (Fig. 1d).

The term "tsunami deposit" and "storm deposit" as used in this paper refer to the sediments formed from a wide range of tsunami and storm flow conditions, respectively. Both deposits can be generated by inflows (or overwash surges) and outflows (or return flow or backwash flows). In the case of the 2004 tsunami deposits found in Thailand, the bedform was produced in the depositional stage either during the tsunami inflow or outflow. In fact, bedforms are both a surficial and primary sedimentary structure; structures that form at the time of deposition of the sediment in which they occur and reflect some characteristics of the depositional environment. A unit of tsunami deposit means an accumulation consisting of a single or more layers, where a layer presents a single normal or reverse grading. Units are separated by an erosional surface with a sharp contact between layers (Choowong et al. 2008a).

During a coastal storm, both erosional and depositional features are usually formed by the overwash flow. Overwash is the flow of water and sediment over a beach crest that does not directly return to the water body where it originated (Donnelly and Woodruff 2007). It begins when the run-up level of waves, usually coinciding with a storm surge, exceeds the local beach or dune crest height. A decrease in overwash flow velocity on the landward side of the beach or barrier results in deposition bodies as sediment, the washover deposit, which is one of the most commonly observed depositional features related to extreme storm events (Morton and Sallenger 2003; Wang and Horwitz 2007). In this paper, washover deposit refers to the bodies of sediment that are the result of a storm-induced overwash flow. As storm deposits are the result of a high-energy process, they may have a similarity in sedimentary characteristics and may leave marine traces in coastal stratigraphic sequences like those of tsunami deposits. However, storm deposits have sedimentary characteristics that may be useful in distinguishing tsunami from storm deposits.

2 Setting and method

We analyzed the sedimentological characteristics of the 2004 tsunami and its precedents from the Andaman coast of Thailand (Fig. 1c, d), whereas, storm deposits were mostly investigated from the GOT coast (Fig. 1a, d). In the case of tsunamis, the characteristics of the 2004 tsunami deposits and its predecessor in Thailand were inferred mostly from Choowong et al. (2007, 2008a, b, 2009) and Jankaew et al. (2008). We, thus, focus in this paper the comparison of the 2004 tsunami and its precedent in one place, where both deposits were officially reported that is the Phrathong Island. In the case of storm deposits, we based this analysis solely in places where the work by Phantuwongraj et al. (2008, 2010), Phantuwongraj and Choowong (2010) was reported. The localities of the geological evidence for the tsunami deposits and the storm-induced washover deposits were recorded and analyzed from more than fifty sites both at the west (Andaman) and the east (GOT) coasts (Fig. 1b, d).

Previous tropical storms and typhoons in Thailand were generated in the South China Sea, Pacific Ocean, and the GOT. We traced the deposit from the storm surge of the last three catastrophic storm events along the GOT in the Southern peninsular, with these storm track ways shown in Fig. 1b. In this paper, we focus on the four areas within these storm tracts that have an appropriate environmental setting (Fig. 1d). The first is at the Thap Sakae area and is the northernmost of the four areas. Its topography exhibits a pocket beach plain with one swale between the beach ridge and the dune. The second site is at Panang Tak area, where the geomorphic condition shows as a paleo-lagoon about 1 km inland from the present shoreline. Its present topography becomes a large swale (approximately 300 m wide) between relict beach ridges. Multiple layers of sand sheets were found intervening between muddy layers in this swale. The third area is located south in the Tha Chana area, where storm deposits were found as a single sand sheet between muddy layers in a small swale behind the outer beach ridge that is overtopped by a series of washover fan lobes. Finally, the fourth area is located at the Talumpuk Cape sand spit, where the storm deposit was found as a washover fan behind the beach ridge at the middle and as a chenier at the distal part of the sand spit.

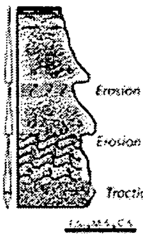
In the field, we firstly used a hand auger to recognize the general stratigraphy of ancient tsunamis and storm deposited material, mostly focusing on the swale. Pitting and trenching down to the original burial soil or beach sand were then carried out along each transect. Shore-normal transects perpendicular to the recent shoreline were carried out, and a detailed topographic survey was performed along all transects. Sand sheets from each pit and auger were collected from each layer of tsunamis and storm depositional sequences. Bulk samples were also collected from a unit. In the case of the 2004 tsunami deposited onshore, we made several transects and trenches. Lunch-box samples were also applied for soft X-ray radiography in place where the preservation of the deposits made it likely that we could detect internal sedimentary structures. Grain size analyses by sieving, settling tube, and laser granulometry were done.

3 Results

3.1 Characteristics of the 2004 tsunami and predecessor deposits

Close to the shore, the thickness and grain size of the 2004 tsunami deposits from the Andaman coast of Thailand showed landward thinning and fining, respectively (Szczucinski et al. 2005, 2006; Rhodes et al. 2007; Choowong et al. 2007, 2008a, b, 2009; Hawkes et al. 2007; Hori et al. 2007; Umitsu et al. 2007). The deposits, generally, consist of fine- to coarse-grained sands with one or more normally graded layers. Reverse grading of medium to coarse sands predominated at the base of a tsunami sequence and was mostly deposited during the inflow (Choowong et al. 2008b), and is superimposed by multiple normally graded layers of fine- to medium-grained sand (Higman et al. 2006). Particular internal structures of landward-inclined laminae were used to infer the first tsunami inflow sequence (Choowong et al. 2008b; Sawai et al. 2009) (Table 1). Interestingly, mud drapes within sand layers were rare and were inferred to have been deposited after the tsunami reached a

Table 1 Typical stratigraphy of the 2004 tsunami inflow and outflow from Thailand with recognizable internal sedimentary structures and inferred flow conditions

Typical 2004 tsunami stratigraphy	Observed sedimentary structures	Inferred flow conditions: *Condition*	*Flow regime*
Outflow Single normal grading is common  *Erosional occurred at the base* C.S, M.S, F.S	Mud cap Parallel laminae Foreset seaward inclined-laminae with mud drapes	1. Low density of sand in flow 2. High suspended mud content 3. Very low outflow velocity	Lower flow regime (Subcritical flow)
Inflow Multiple normal gradings are common  *Erosion occurred* *Erosion occurred* Normal grading Reverse grading *Traction carpet*	Mud cap, Mud drapes – Not common but possible in case of stagnant Ripples and dunes	1. Flow velocity, 2. Grain density – *Decrease* 3. Flow depth, 4. Time – *Increase*	Lower flow regime (Subcritical flow)
		Inferred transitional time	
	Antidune	1. High density turbulent 2. High flow velocity 3. Limit flow depth 4. Rapid deposition 5. Flat topography	Upper flow regime (Supercritical flow)

maximum height, and then, stabilized for a few minutes before multiple surges arrived (Choowong et al. 2008b).

However, the difficulty in distinguishing between the inflow and outflow layers of the 2004 tsunami deposits has arisen because there are very few sets of internal sedimentary structures that can positively identify the outflow. The occurrence of a thin layer of mud drape in between normal grading layers seemed to be the only possible indicator since it is deposited during the short stagnant period of tsunami after a continuous inflow wave stopped (Choowong et al. 2008b). However, a mud cap on top of the tsunami bedforms was rarely preserved (Choowong et al. 2007, 2008a). Rip-up clasts from buried soil are common within the 2004 inflow tsunami and ancient tsunami deposits (Fig. 2).

Two paleotsunami sand sheets (Fig. 3) resemble the characteristics found with the overlying 2004 deposit at Phrathong Island (Jankaew et al. 2008; Fujino et al. 2009). Both paleotsunami sand sheets are commonly 5–10 cm thick and contain coarse to very coarse sand and form a discontinuous basal layer that fills the pre-existing pockets in the underlying soil. The sand sheets show overall landward thinning and fining (Fujino et al. 2009) and contain horizontal laminae, rip-up mud clasts, and leaf fragments (Jankaew et al. 2008; Sawai et al. 2009). The lower sheet was formed sometime after 2,200–2,400 sidereal years ago, whereas the upper sheet was deposited about 550–700 sidereal years ago (Jankaew et al. 2008).

3.2 Storm deposits

Storm-induced washover deposits along the coastal area of the GOT are composed of medium- to very fine-grained sand and usually showed a normal grading and planar stratification. The grain size and thickness of the sand sheet are slightly decreased and thinned landward, respectively. Storm deposits are well-sorted and their major composition consists of quartz, bioclasts, and localized heavy minerals. The maximum thickness of storm deposits we found was 65 cm, which being at the Talumpuk Cape sand spit contained mostly fine sand to medium sand with a multiple lamina set of shell fragments (Phantuwongraj et al. 2008). The difference in the thickness of the sand sheet depended on

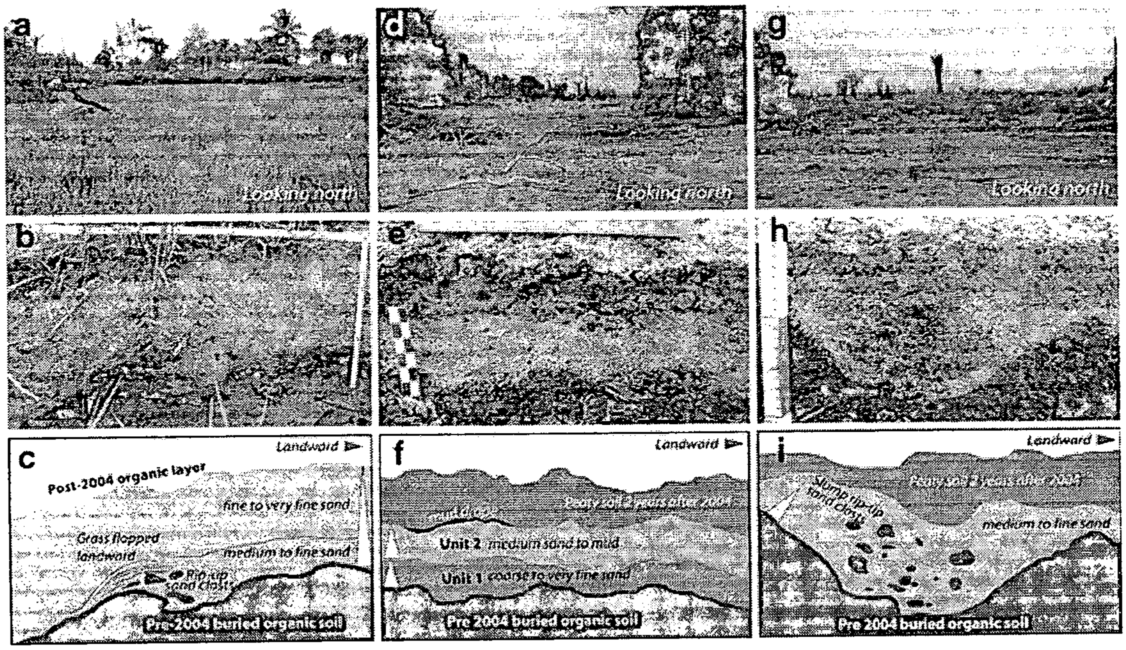


Fig. 2 Internal sedimentary structures of the 2004 tsunami deposited in wet- and dry-swales from Phrathong Island. **a** the nature of dry swale (*photo* taken in 2006). **b** and **c** the 2004 tsunami deposit with grasses flopped landward and rip-up sand clasts. **d** and **g** wet swale with no bioturbation. **e** and **f** post-2004 tsunami deposits reworked by surface runoff in wet swale and mud draped in 2004 tsunami deposits. **h** and **i** 2004 tsunami deposits within a micro-trough with slumped rip-up sand clasts along slope

the intensity of storm, type of washover deposits, source of sediment, and local micro-topography, very much like that for tsunami deposits. Foreset bedding is also found at the distal end of the washover fans with a landward dip angle of 22 and 9 degrees at the Tha Chana area (Fig. 4a, b) and Talumpuk Cape (Fig. 5a, b) area, respectively. At the Tha Chana area, two sets of foreset bedding were clearly observed with a thickness of 40 and 20 cm for each set. Additionally, the postdepositional deformed features are recognized on the topset of the washover deposit (Fig. 4c). Normally, foreset bedding structures are only found in storm deposits with a thickness of more than 20 cm, while the thinner sand sheets show only planar bedding. Debris such as rocks, rope, net, plastic bags, asphalt, and part of a tree were also found in the storm sand sheet at Talumpuk Cape and Thap Sakae (Fig. 4d–f), suggesting the high intensity of the storm surge event. Rare rip-up clasts from buried soil were also found.

At the Panang Tak area, at least nine sand sheets of possible paleo-storm origin from 18 cores were found with a sharp contact the intervening muddy layers in the wet swale (Fig. 5c, d). Most of the sand layers are 2–5 cm thick, containing fine- to very fine-grained sand. The thickest layer was found at a depth of about 110–140 cm and consisted of medium- to very fine-grained sand. Normal gradings with well-sorted particles in each sand sheet were obviously cleared. Shell fragments were found in the sand layer, while the articulated shells were found only in the mud layer. Disarticulated shells in the sand sheet indicated transportation process, while articulated infers in situ deposit in its living position.

The composition of the washover deposits varied as a result of the difference in local source materials (Nanayama et al. 2000; Sedgwick and Davis 2003; Morton et al. 2007). General washover sedimentary structures are normal grading, reverse grading, laminae of shell and heavy minerals, planar laminae and no textural trend, which is similar to those

Fig. 3 Sedimentological characteristics of the pre-2004 tsunami deposits from Phrathong Island. **a** three tsunami sand sheets including 2004 on top and ancient deposits at 550–700 years, 2,200–2,400 years (Jankaew et al. 2008). **b** parallel stratifications in the 2004 tsunami, and rip-up clasts in the pre-2004, deposits. **c** close-up of rip-up clasts in **b**

reported by Andrews (1970), Kortekaas and Dawson (2007), Morton et al. (2007), Phantuwongraj et al. (2008), Leatherman and Williams (1983), Davis et al. (1989), Sedgwick and Davis (2003).

4 Tsunami versus storm

4.1 Depositional styles and characteristics

The tsunami and storm flows mostly limit their depositional characteristics from place to place. We recognized that both high-energy flows revealed a variation in the style of deposition that generally depended on (1) the frequency of inflow waves, (2) the difference in the source of the deposit that is reflected in the difference in grain size and grain concentration in the flows, and (3) the local change in micro-topography. We found that, in the case of tsunami, the multiple normal gradings are likely formed by the multiple and continue surges in one wave train. For example, at Bangtao area, Phuket Island,

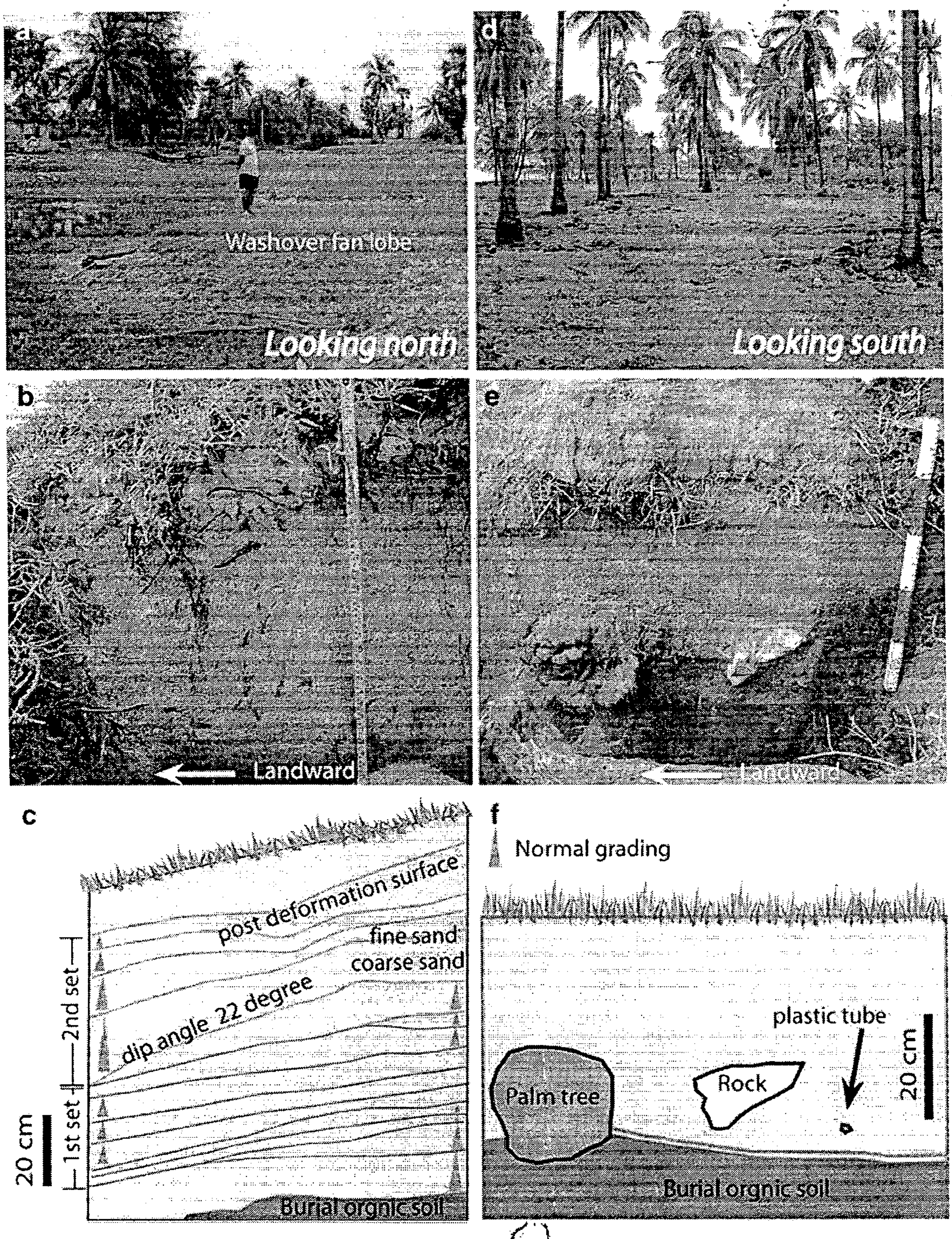


Fig. 4 Storm depositional characteristics from the GOT. **a** morphology of the washover fan lobes from Tha Chana. **b** internal stratigraphy at a distal part of the washover deposits from Tha Chana. **c** sketch of two foreset lamina from **b**. **d** and **e** setting of the area flooded by a storm at Thap Sakae. **f** debris in storm sand sheet

eyewitnesses confirmed that the area was hit by five inflows. The first inflow did not cross the beach ridge, only the second and the third inflows flooded over land and left behind the multiple normal gradings of tsunami deposits with a limit of landward extent of about 400 m. The fourth and fifth inflows came a few minutes after the seawater revision back to the normal shoreline level and, importantly, they did not flood over the beach ridge zone.

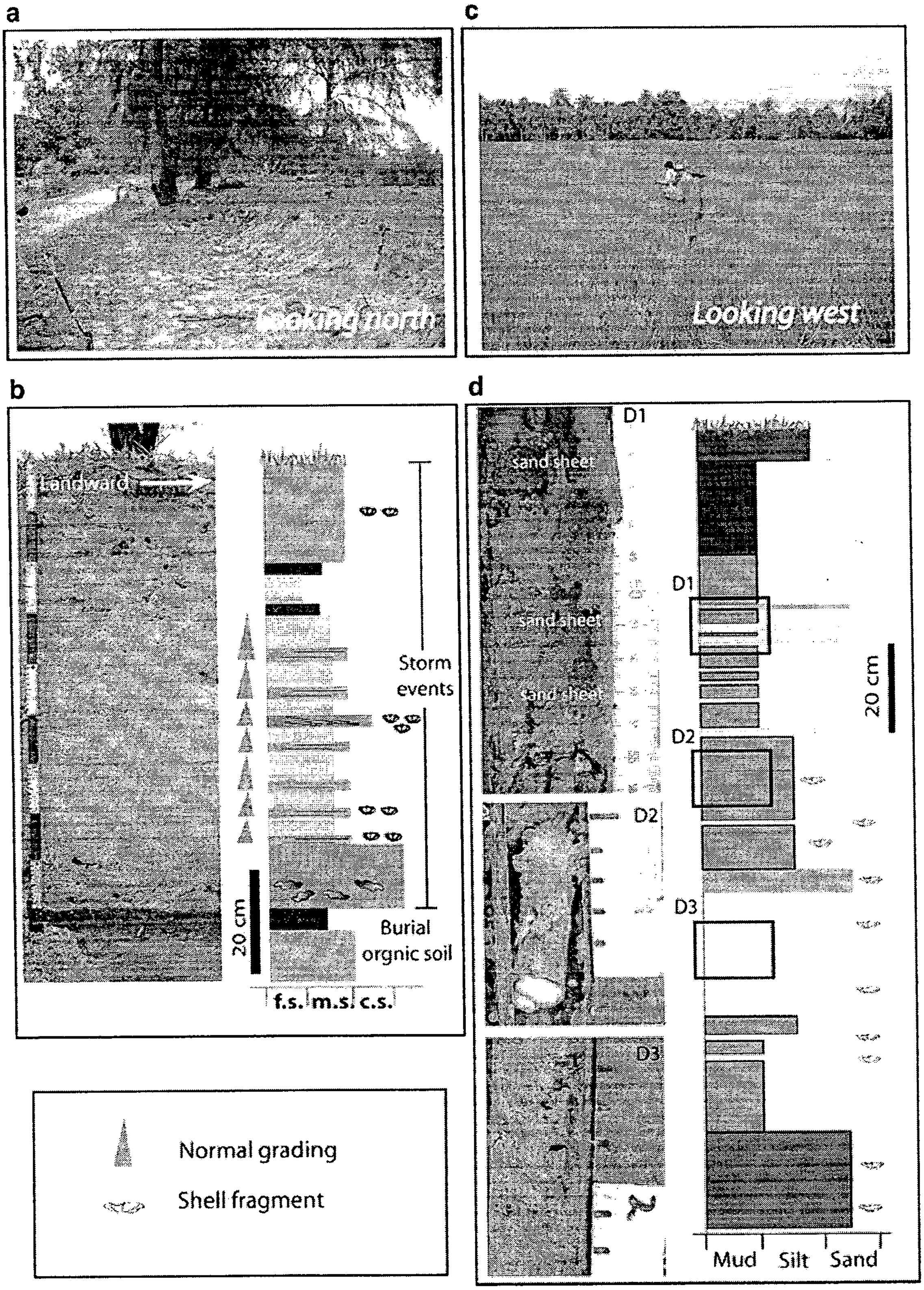


Fig. 5 Modern and ancient storm deposits from the GOT. **a** modern washover features at Talumpuk Cape sand spit. **b** multiple normal gradings in a modern storm-induced washover deposits from **a**. **c** large wet swale at Panang Tak bay. **d** nine sand sheets of candidate ancient storm deposits in swale with their sedimentological characteristics

The deposit also reflected two distinguishable units separated from each other by the intervening erosional surface between units (Choowong et al. 2008a). This is important to note here that a number of multiple grading structures in the 2004 and paleo-tsunami sand sheets may not necessary represents a number of inflows.

The difference in offshore configurations reflected the variety of grain size and grain concentration within the 2004 tsunami inflow. In places where the shoreface slope is gentle, much of the shoreface sediments were entrained onshore, like at the Khao Lak area (Choowong et al. 2009; Di Geronimo et al. 2009) and Lamson National Park (Choowong et al. 2008b). Much of shoreface sediments and eroded beach sand seemed to have been transported and deposited continuously, as confirmed by the presence of multiple normal gradings without any sharp contact between sand units.

One of the similar and common depositional features from both types of high-energy flow is a normal grading. In fact, normal grading is common in numerous kinds of sedimentary deposits, including beach foreshore and berm overwash laminations (Clifton 1969; Fisher 1971; Schwartz 1975; Leatherman et al. 1977), foresets of eolian and subaqueous dunes (Bagnold 1941; Inman et al. 1966; Hunter 1976), and the basal parts of some coarse-grained turbidites (Sanders 1965; Walker 1975) in both modern and paleo-tsunami deposits (Higman et al. 2006; Morton et al. 2007; Jankaew et al. 2008). Like the normal grading that is common in the 2004 tsunami deposits, reverse grading has been reported from Thailand at the north of Pakarang Cape, Phang-nga (Higman et al. 2006), and Lamson National Park, Ranong (Choowong et al. 2008b). A thin layer of reverse grading was also recognized in a storm deposit 65 m away from the present shoreline at Tha Chana, Surat Thani (Phantuwongraj et al. 2008). These then support that reverse grading can be formed by both tsunami and storm-derived high-energy flows due to the high grain concentration and mutual collisions among grains within a traction carpet or grain flow and were possibly formed at the initial stage of inundation with a low water depth (Choowong et al. 2008b; Phantuwongraj et al. 2008).

4.2 Flow conditions

Normally, tsunami-related deposition involves four progressive steps: (1) triggering stage (offshore), (2) tsunami stage (incoming waves), (3) transformation stage (near the coast), and (4) depositional stage (outgoing sediment flows) (Shanmugam 2006). Judging from the videos and photographic recordings, the 2004 Indian Ocean tsunami at the Andaman coast of Thailand generally started with a withdrawal of seawater at several places. After that, the first tsunami wave arrived with a large amount of shoreface sediments carried within the tsunami turbulent head (Ioualalen et al. 2007; Di Geronimo et al. 2009). In the case of a storm flow, it seems likely that the storm process contains only the transformation and deposition stages. Here, in this section, we focus on the discussion of the 2004 tsunami and general storm flow conditions during the transformation stage to the depositional stage as both stages are directly related to the deposition found extensively on land. In the case of the tsunami depositional stage, the processes start suddenly and span from just minutes to a few hours in duration, while storm flooding is commonly of a longer time course ranging from hours to days (Morton et al. 2007).

During the transformation stage, we hypothesize that tsunamis likely entrained much deeper offshore and shoreface sediments than storms did. Benthic fauna found within tsunami and storm deposits may be used to confirm this hypothesis. During the depositional stage, tsunami and storm deposits are generally formed under similar flow patterns. The sedimentary features of the 2004 tsunami and those of storms mostly have similar internal structures. Within the literature, tsunami deposits contain an enormous variability of features (e.g., planar stratification, inclined lamination, cross-laminations, imbrication of gravels, normal-graded sand, dispersed mud and mudstone clasts, hummocky cross-stratification, etc.). Likewise, many of these features could be found in storms (tempestites) as well.

4.2.1 Transformation stage

During the transformation stage near the coast, the initial tsunami wave and storm surge was expected to be an erosional wave (turbulent head) (Fig. 6a), which moved shoreface sediments onto the beach zone as the wave moved along the shoreface and became turbid sediments. Subsequently erosion happened again and beach sediments were stirred up resulting in a mixture of mixed beach sediments with shoreface sediments within the turbulent tsunami and storm surge head as they ran onto the land (Fig. 6a). Notably, the tsunami brought sediments and benthic fauna (Hawkes et al. 2007; Sawai et al. 2009) possibly from much deeper depths from the offshore than those carried by storms.

4.2.2 Depositional stage

Tsunami and storm depositional stages occur after their turbulent head hits the beach zone, causing a decreased flow speed (Fig. 6b). Under the condition that the tsunami head may contain a higher percentage of grain concentration in the flow than that for a storm, then a tsunami likely contains a good deal of both bed load and suspended load deposited on the ground surface as bed sediments. The high grain concentration inflow and fast flow speed also favored the occurrence of reverse grading, as is commonly seen for tsunamis. Once the tsunami head arrived on land, bedforms, indicators of bed load transport, persisted as ripple cross-lamination, or other cross-bedding, as exemplified in the Bangtao area, Phuket Island (Choowong et al. 2008a).

The recognition of an antidune structure from the 2004 tsunami deposit at Lamson National Park, Ranong (Choowong et al. 2008b), constrained the upper flow regime of supercritical flow that happened just after the end of the transformation stage. This flow regime is characterized by high current velocities, low flow resistance, and high sediment transport rates. This may be one of the key sedimentary structures to differentiate tsunami from storm flows, though it is difficult to detect this structure left behind by both events.

The deposition of a storm flow may occur under a lower flow regime from which it is characterized by the relatively slow flow velocities and low rates of sediment transport. Such a planar stratification of fine sand, which was the dominant appearance in the storm sand sheets from the GOT, also infers that it was deposited during a lower flow regime of storm surge. Like in the case of the tsunami bedform features at Bangtao area, Phuket, the transition from antidune to ripple at Lamson, Ranong, occurred during the decreasing flow velocity and increasing flow depth (Choowong et al. 2008a).

Due to the landward distribution of the storm and tsunami deposits, the zone of tsunami deposition usually has a much more inundated distance than that of a storm deposit, especially where the area is comparatively flat topography (Fig. 6c). The short wave period of a storm flow limits washover deposits to a hundred meters from the shoreline. In contrast, a tsunami results in a much further transport and entrained distances with one wave train, which reflects the longer wave period.

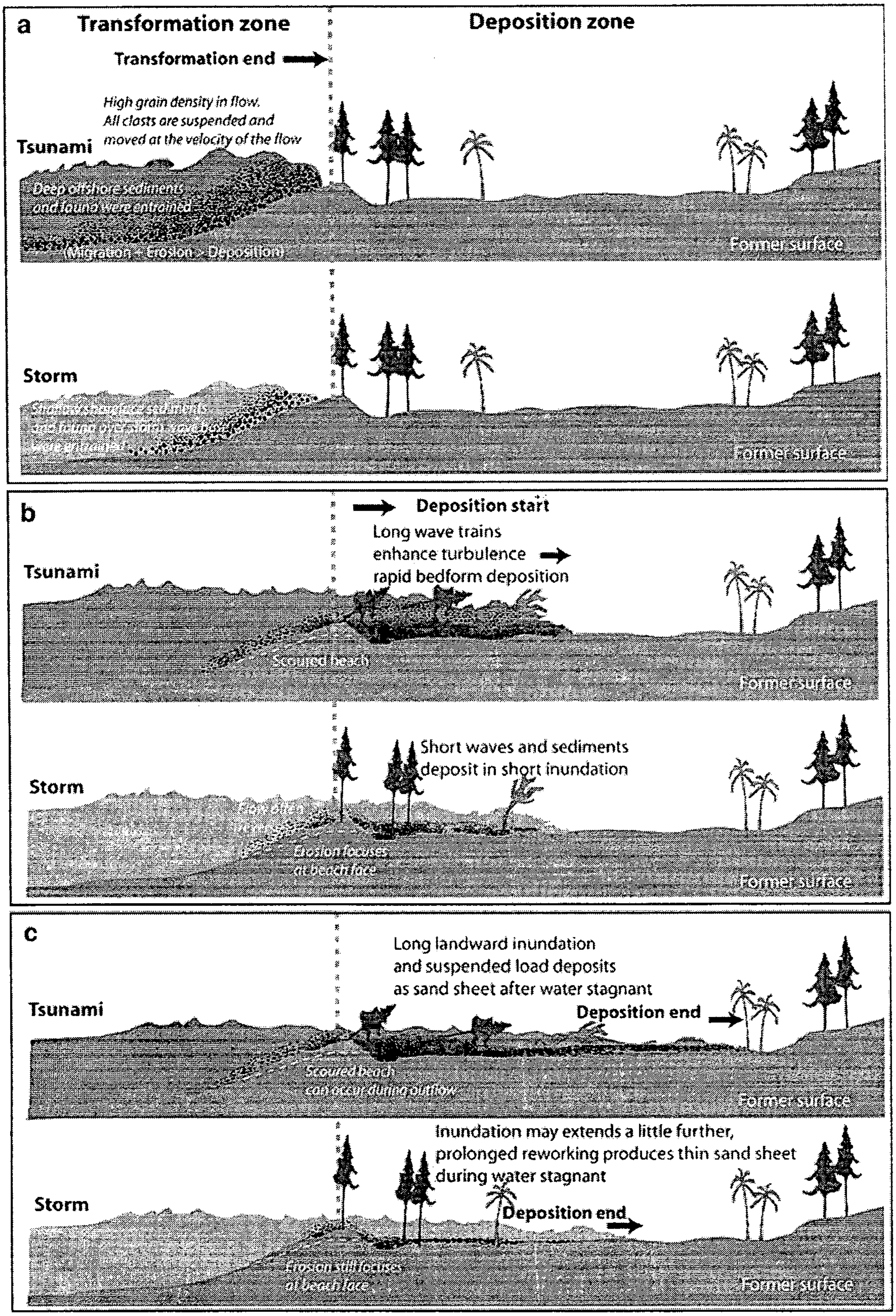


Fig. 6 Schematic model of the flow conditions for a tsunami versus that for a storm. **a** transformation stage. **b** early depositional stage. **c** the end of depositional stage (detail in *text*)

4.3 Depositional and preservation potentials

One of the limitations to find the predecessors of tsunami and storm deposits is due to the stochastic or chance nature of the preservation potential in different geological settings. Certainly and naturally, the preservation potential of the tsunami and storm sand sheets was controlled by the configurations of large-scale irregular topography and micro-scale topographical relief of the tsunami and storm flood-prone areas. The thickest deposit of the 2004 tsunami, at a maximum depth of 25 cm within a low topographical swale, was clearly observed and found to continuously extend landward (Hori et al. 2007; Umitsu et al. 2007; Choowong et al. 2007). Although storm washover deposits reached a maximum thickness of 65 cm superimposed on the Chenier ridge of Talumpuk Cape, southern peninsular Thailand (see locations in Fig. 1), its landward extension was limited to being at the end of the washover fan lobes. However, in terms of succession, the thickest deposits from both tsunamis and storms may contain one to several layers of normal grading. Once again, the multiple layers, however, may or may not correspond to the number of tsunami or storm inflow surges.

In fact, the 2004 tsunami and storm outflows at most places we recognized had played little role in producing its deposition, except at Phrathong Island where the 2004 tsunami outflow deposit was found at the rim of swale (Choowong et al. 2008b; Sawai et al. 2009). In general, the style of deposition during the 2004 tsunami outflow was limited to a thin layer of mud of a few millimeters thick coating the top surface of the entire depositional sequence. The occurrence of mud draped with a thickness up to 1 cm occurred during the inflow deposition was localized (Matsumoto et al. 2008).

In this paper, the depositional features and preservation potential of the 2004 tsunami and storm deposits were identified into four types with respect to the different topographical configurations.

4.3.1 Type A: Gentle and flat topography

Tsunami and storm flows can produce the deposit as continuous sand sheets, as in the case of the deposition found at Bangtao area, Phuket Island, and at Lamson National Park, Ranong, as well as at the storm deposit at Talumpuk Cape and Thap Sakae areas. Interestingly, in the case of the tsunami deposits in Type A, antidune and dune structures were preserved and recognized (Choowong et al. 2008a). Such structures have rarely been reported from storm deposits, possibly because storm flows have less flow velocity to do so.

4.3.2 Type B: Tidal channel embayment

The 2004 tsunami deposits were widely recognized in the channel embayment, as in the case of tsunami deposits found at the southern part of Pakarang Cape (Blue Village Resort), Phang-nga. To date, we have not found any storm deposition in channel embayment from the GOT. Only storm-induced washover fan lobes filling in incised tidal inlets/outlets have been recognized.

4.3.3 Type C: Swale and beach ridge

Type C has the highest preservation potential for both storms and tsunamis and is deposited on the beach ridge plain and in the swales. This is likely the best environment to trap both types of high-energy sediments. At Phrathong Island, we found sand sheets of both the 2004 tsunami and older deposits. Likewise, this environment favored the preservation of storm sand sheets in the muddy swale of Panang Tak bay, Chumphon, and also the recent storm deposit at Tha Chana which is characterized as multiple washover fan lobes behind the modern beach ridge. We conclude that the preservation potential of Type C is excellent to trap sediments from both high-energy flows and will mostly persist for a long time in the geological record due to it not being subject to much postdeposition surface disturbance.

4.3.4 Type D: Large-scale irregular topography

This type D environment induces variability in thickness of both high-energy deposits due to the irregularity of the land surface and is typically a narrow beach ridge plain with a high surface slope. As in the case of the 2004 tsunami deposits at Bang Niang transect, Khao Lak, Phang-nga area (Choowong et al. 2008b), we found that tsunami waves were limited in a short distance of inundation and its depositions can be mixed and reworked during the inflow and outflow.

5 Conclusions

1. Tsunami deposits mostly resemble storm depositional characteristics. Both high-energy flows produced a vast area of erosion in the shoreface and the beach ridge zone during the transformation stage. In the depositional stage, a large amount of entrained materials can be deposited onto the former land surface and can extend inland to where the inundation ends. Inundation of the tsunami and its deposit is likely to extend much farther inland than that for storms.
2. Internal sedimentary structures of the tsunamis and storm deposits in Thailand are mostly similar and are likely formed during the inflow. Both kinds of deposits showed overall landward thinning and fining. The most common internal sedimentary structures are parallel lamination, landward-inclined laminations with normal-graded sand grains, and local reverse grading. Rip-up mud clasts are common within the tsunami layer of inflows, but rare in storm deposits. Outflow deposition from both events was rarely preserved. However, the dominate structures of the tsunami outflow include seaward-inclined foreset laminae with mud drapes. To date, a set of antidune structures recognized in tsunami deposits may be one key to distinguish them from storms.
3. The nearshore and onshore flow behaviors of tsunami and storm are somewhat different. Both events generally start their erosion from the transformation stage. Definitely, tsunami has a longer transformation period and greater distance offshore than storms, so that benthic fauna and offshore bottom sediments can be extensively brought onshore. The tsunami flow depth is, generally, deeper than that for storm flows. However, a larger number of multiple gradings within storm deposits may be used to infer a longer period of flooding on the land than that for tsunamis.
4. Both the tsunami and storm preservation potentials were largely dependent on the large- and micro-scale topographic configurations on the land. The preservation of tsunami and storm inflows is more than outflows and mostly persisted longer in the geological record in swale environments. Large swales behind the beach ridges are likely to act as a good accommodation space to trap the tsunami and storm sediments.

The comparison of physical and sedimentological characteristics between tsunami and storm flows outlined in this paper (Table 2) increases our understanding of the nature of tsunami and storm deposition. As such this may then provide some clues and, perhaps, will help sedimentologists to identify and distinguish both depositional features in the geological records.

Table 2 Summary of similarity and difference between tsunamis and storm deposits

	Tsunamis vs. storm deposits		
	2004 Tsunami	Paleo-tsunami	Storm
Deposit characteristics			
Trench scale			
Sedimentary features			
Sorting	Poorly to moderate sorted[a]	Not reported	Well sorted[f]
Grading	One to multiple normal grading, local reverse grading	One to two normal grading[c]	One to multiple normal grading[f], local reverse grading
Internal structures	Parallel lamination, landward and seaward-inclined laminae, one set of seaward-inclined foreset bedding (outflow), set of antidune structures[a]	Horizontal laminae[b]	Parallel lamination, multiple sets of landward-inclined foreset bedding (inflow)
Surface structures	Dune and ripples[a, d, h]	Not reported	Not reported
Mud content	Mud cap coating on a surface of tsunami sand sheet[d], mud draped (Fig. 2f) in sand sheet[a]	Rare[c]	Rare
Thickest event deposit	25–30 cm[a, d, h]	20 cm[b]	65 cm
Composition	Quartz, shell fragments, heavy minerals, rocks, coral, debris	Quartz dominated, leaf fragments[b]	Quartz, heavy minerals, shell fragments, rock, and debris
Number of layers	Single to multiple layers	Single to two layers	Single to multiple layers[f]
Rip-up	Abundant burial soil, mud, and sand clasts (Fig. 2i)	Abundant burial soil and sand clasts (Fig. 3c)	A few burial soil clasts
Basal contact	Sharp contact common, gradational contact with sandy soil	Sharp and tabular shape with peaty soil[b], gradational contact with slightly organic soil[b, c]	Sharp contact common, gradational contact with slightly organic and sandy soil
Benthic fauna	Abundant (foram[g] and diatom[c])	Lack (foram, diatom)[b, c]	Not reported
Transect scale			
Maximum inundation limit in flat topography	3.5 km[a] (measured)	1–2 km (estimated)	<1 km (estimated)
Flow conditions	Up to supercritical flow[h]	Not reported	Not reported
Depositional feature in stratigraphy	Sand over burial soil, sand over beach sand, sand over artificial[d]	Sand intervening soils[b], coral layer intervening mangrove soil[c]	Sand over burial soil, sand intervening soils

Table 2 continued

	Tsunamis vs. storm deposits		
	2004 Tsunami	Paleo-tsunami	Storm
Trend of landward grain size and deposit thickness	Thinning and fining	Thinning and fining	Thinning and fining
Rating preservation potential			
Gentle and flat topography	Good to excellent	Poor	Good
Tidal channel embayment	Moderate to good	Poor[e]	Poor[f]
Swale between beach ridge	Excellent	Excellent	Excellent
Large-scale irregular topography	Moderate	Poor	Poor

[a] Choowong et al. (2008b), [b] Jankaew et al. (2008), [c] Sawai et al. (2009), [d] Choowong et al. (2007), [e] Rhodes et al. (2007), [f] Phantuwongraj et al. (2008), [g] Hawkes et al. (2007), [h] Choowong et al. (2008a)

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References

Andrews PB (1970) Facies and genesis of a hurricane washover fan, St. Joseph Island, central Texas coast. Report of Investigations No. 67. Bureau of Economic Geology, University of Texas at Austin

Atwater BF (1987) Evidence for great Holocene earthquakes along the outer coast of Washington state. Science 236:942–944

Bagnold RA (1941) The physics of blown sand and desert dunes. Methuen, London

Bahlburg H, Weiss R (2007) Sedimentology of the December 26, 2004, Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya. Inter J Earth Sci 96:1195–1209

Bondevik S, Svenden JI, Mangerud J (1997) Tsunami sedimentary facies deposited by the Storegga tsunami in shallow marine basins and coastal lakes, western Norway. Sedimentology 44:1115–1131

Bourgeois J, Hansen TA, Wiberg PL, Kauffman EJ (1988) A tsunami deposit at the Cretaceous-Tertiary boundary in Texas. Science 241(4865):567–570

Bryant EA, Young RW, Price DM (1992) Evidence of tsunami sedimentation on the southeastern coast of Australia. Geology 100(6):753–765

Chadha RK, Latha G, Yeh H, Peterson C, Katada T (2005) The tsunami of the great Sumatra earthquake of M 9.0 on 26 December 2004—impact on the east coast of India. Cur Sci 88(8):1297–1301

Choowong M (2010) Forewarning of M 7.6 earthquake at Andaman Islands: where next? Cur Sci 98(8): 1013–1014

Choowong M, Murakoshi N, Hisada K et al (2007) Erosion and deposition by the 2004 Indian Ocean tsunami in Phuket and Phang-nga Provinces, Thailand. J Coastal Res 23(5):1270–1276

Choowong M, Murakoshi N, Hisada K et al (2008a) 2004 Indian Ocean tsunami inflow and outflow at Phuket, Thailand. Mar Geol 248(3–4):179–192

Choowong M, Murakoshi N, Hisada K et al (2008b) Flow conditions of the 2004 Indian Ocean tsunami in Thailand inferred from capping bedforms and sedimentary structures. Terra Nova 20:141–149

Choowong M, Phantuwongraj S, Charoentitirat T et al (2009) Beach recovery after 2004 Indian Ocean tsunami from Phang-nga, Thailand. Geomorphology 104:134–142

Cisternas M, Atwater BF, Torrejon F et al (2005) Predecessors of the giant 1960 Chile earthquake. Nature 437(7057):404–407

Clague JJ, Bobrowsky TP, Hutchinson I (2000) A review of geological records of large tsunamis at Vancouver Island, British Columbia, and implications for hazard. Quater Sci Rev 19:849–863

Clifton HE (1969) Beach lamination: nature and origin. Mar Geol 7:553–559

Davis RA, Andronaco M, Gibeaut JC (1989) Formation and development of a tidal inlet from a washover fan, west-central Florida coast, USA. Sed Geol 65:87–94

Dawson AG, Stewart I (2007) Tsunami deposits in the geological record. Sed Geol 200(3–4):166–183

Dawson AG, Long D, Smith DE (1988) The Storegga slides: evidence from eastern Scotland for a possible tsunami. Mar Geol 82:271–276

Di Geronimo I, Choowong M, Phantuwongraj S (2009) Geomorphology and superficial bottom sediments of Khao Lak coastal area (SW Thailand). Polish J Envi Stud 18(1):111–121

Donnelly JP, Woodruff JD (2007) Intense hurricane activity over the past 5, 000 years controlled by El Niño and the West African monsoon. Nature 447:465–468

Fisher RV (1971) Features of coarse-grained, high concentration fluids and their deposits. J Sed Petrol 41:916–927

Fujino F, Naruse H, Matsumoto D et al (2009) Stratigraphic evidence for pre-2004 tsunamis in southwestern Thailand. Mar Geol 262(1–4):25–28

Fujiwara O, Kamataki T, Tamura T (2003) Grain-size distribution of tsunami deposits reflecting the tsunami waveform; an example from a Holocene drowned valley on the southern Boso Peninsula, East Japan. Quater Res 42(2):68–81

Goff JR, Rouse HL, Jones LL et al (2000) Evidence for an earthquake and tsunami about 3100–3400 yr ago, and other catastrophic saltwater inundations recorded in a coastal lagoon, New Zealand. Mar Geol 170:231–249

Goff JR, McFadgen BG, Chague-Goff C (2004) Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. Mar Geol 204(1–2): 235–250

Goff JR, Liu P, Higman B et al (2006) Sri Lanka Field Survey after the December 2004 Indian Ocean Tsunami. Earthquake Spectra 22:155–172

Hawkes A, Bird M, Cowie S et al (2007) Sediments deposited by the 2004 Indian Ocean tsunami along the Malaysia-Thailand Peninsula. Mar Geol 242(1–3):169–190

Higman B, Maxcia C, Lynett P, Alam S (2006) Horizontal and vertical grading in a tsunami deposit. Eos Trans AGU 87:52

Hindson RA, Andrade C, Dawson AG (1996) Sedimentary processes associated with the tsunami generated by the 1755 Lisbon earthquake on the Algarve coast, Portugal. Phy Chem Earth 21(1–2):57–63

Hori K, Kuzumoto R, Hirouchi D et al (2007) Horizontal and vertical variation of 2004 Indian tsunami deposits: an example of two transects along the western coast of Thailand. Mar Geol 239(3–4): 163–172

Hunter RE (1976) Comparisons of eolian and subaqueous sand-flow cross-strata. Amer Asso Petrol Geol Bull 60:683–684

Inman DL, Ewing GC, Corliss JB (1966) Coastal sand dunes of Guerrero Negro, Baja, California, Mexico. Geol Soc Amer Bull 77:787–802

Ioualalen M, Asavanant J, Kaewbanjak N et al (2007) Modeling the 26 December 2004 Indian Ocean tsunami: Case study of impact in Thailand. J Geophy Res 112:C07024. doi:10.1029/2006JC003850

Jaffe EB, Gelfenbaum G (2007) A simple model for calculating tsunami flow speed from tsunami deposits. Sed Geol 200(3–4):347–361

Jankaew K, Atwater BF, Sawai Y et al (2008) Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand. Nature 455:1228–1231

Kanbua W (2008) A recent storm surge event in Thailand. Thai Marine Meteorology Center. http://www.marine.tmd.go.th/paper/surge.html. Accessed 26 January 2010

Konno E, Iwai J, Kitamura N et al (1961) Geological observations of the Sanriku coastal region damaged by the tsunami due to the Chile earthquake in 1960. Tohoku University 961, vol 52, p 40

Kortekaas S, Dawson AG (2007) Distinguishing tsunami and storm deposits: An example from Martinhal, SW Portugal. Sed Geol 200:208–221

Leatherman SP, Williams AT (1983) Vertical sedimentation units in a barrier island washover fan. Earth Surf Proc Land Forms 8:141–150
Leatherman SP, Williams AT, Fisher JS (1977) Overwash sedimentation associated with a large-scale northeaster. Mar Geol 24:107–121
Long D, Smith DE, Dawson AG (1989) A Holocene tsunami deposit in eastern Scotland; Late Quaternary sea-level changes and crustal movements in the British Isles. J Quater Sci 4(1):61–66
Matsumoto D, Naruse H, Fujino S et al (2008) Truncated flame structures within a deposit of the Indian Ocean tsunami: evidence of syn-sedimentary deformation. Sedimentology 55(6):1559–1570
Minoura K, Nakaya S (1991) Traces of tsunami preserved in inter-tidal lacustrine and marsh deposits: some examples from Northeast Japan. J Geol 99:265–287
Monecke K, Finger W, Klarer D et al (2008) A 1,000-year sediment record of tsunami recurrence in northern Sumatra. Nature 455:1232–1234
Moore AL (2000) Landward fining in onshore gravel as evidence for a late Pleistocene tsunami on Molokai, Hawaii. Geology 28(3):247–250
Moore A, Nishimura Y, Gelfenbaum G et al (2006) Sedimentary deposits of the 26 December 2004 tsunami on the northwest coast of Aceh, Indonesia; The 2004 Great Sumatra earthquake and tsunami. EPS 58(2):253–258
Morton AR, Sallenger AH (2003) Morphological Impacts of Extreme Storms on Sandy Beaches and Barriers. J Coastal Res 19:560–573
Morton AR, Gelfenbaum G, Jaffe EB (2007) Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. Sed Geol 200(3–4):184–207
Nagendra R, Kamalak Kamman BV, Sajith C et al (2005) A record of foraminiferal assemblage in tsunami sediments along Nagappattinam coast, Tamil Nadu. Cur Sci 89(11):1947–1952
Nanayama F, Shigeno K (2006) Inflow and outflow facies from the 1993 tsunami in southwest Hokkaido. Sed Geol 187:139–158
Nanayama F, Shigeno K, Satake K et al (2000) Sedimentary differences between the 1993 Hokkaido-nansei-oki tsunami and the 1959 Miyakojima typhoon at Taisei, southwestern Hokkaido, northern Japan. Sed Geol 135:255–264
Nanayama F, Satake K, Furukawa R et al (2003) Unusually large earthquakes inferred from tsunami deposits along the Kuril trench. Nature 424:660–663
Nelson AR, Asquith AC, Grant WC (2004) Great earthquakes and tsunamis of the past 2000 years at the Salmon River estuary, central Oregon coast, USA. Bull Seismo Soc Amer 94(4):1276–1292
Phantuwongraj S, Choowong M (2010) Physical characteristics of washover sediments as trace of storm events along the coastal zone from the Gulf of Thailand side. RGJ Semin Ser LXVII, Geohazards: Incoming Disasters for Thailand. Bangkok, Thailand, p 17
Phantuwongraj S, Choowong M, Chutakositkanon V (2008) Possible Storm Deposits from Surat Thani and Nakhon Si Thammarat Provinces, the Southern Peninsular Thailand. In: Choowong M, Thitimakorn T (eds) Proc Inter Sym on Geo Res and Envi of Asian Terranes. Bangkok, Thailand, pp 395–399
Phantuwongraj S, Choowong M, Silapanth P (2010) Geological evidence of sea-level change: a preliminary investigation at Panang Tak area, Chumphon province, Thailand. The 117th Annu Meet of the Geol Soc of Jpn. Toyama, Japan, p 185
Pinegina TK, Bourgeois J, Bazanova IV, Braitseva OA (2003) A millennial scale record of Holocene tsunamis on the Kronotskiy Bay coast, Kamchatka, Russia. Quater Res 59:26–47
Rhodes B, Jankaew K, Kirby M (2007) Mangroves, coral, and the search for a paleotsunami deposit along the Andaman coast of Thailand. Eos Trans AGU 88:23
Roy PS (1990) Offshore minerals exploration in the Gulf of Thailand: Review of Quaternary geology of the coast and offshore seabed in exploration area 2. UNESCO Mission report: February 4–28, Thailand
Sanders JE (1965) Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms. In Middelton GV (ed), Primary Sedimentary Structures and their Hydrodynamic Interpretation. Soc Econ Paleont and Min Special Publication 12:192–219
Satake K, Than TA, Sawai Y et al (2006) Tsunami heights and damage along the Myanmar coast from the December 2004 Sumatra-Andaman earthquake. EPS 58(2):242–252
Sawai Y, Jankaew K, Prendergast A et al (2009) Diatom assemblages in tsunami deposits associated with the 2004 Indian Ocean tsunami at Phrathong Island, Thailand. Mar Micropaleon 73:70–79
Schwartz RK (1975) Nature and genesis of some washover deposits. U.S. Army Corps of Engineers, Coastal Eng. Research Center, Tech. Mem. no. 61
Sedgwick PE Jr, Davis RA (2003) Stratigraphy of washover deposits in Florida: implications for recognition in the stratigraphic record. Mar Geol 200:31–48
Shanmugam G (2006) The tsunamite problem. J Sed Res 76:718–730

Singarasubramanian SR, Mukesh MV, Manoharan K et al (2006) Sediment characteristics of the M 9 tsunami event between Rameswaram and Thoothukudi, Gulf of Mannar, southeast coast of India. Sci Tsu Hazards 25(3):160–172

Szczucinski W, Niedzielski P, Rachlewicz G et al (2005) Contamination of tsunami sediments in a coastal zone inundated by the 26 December 2004 tsunami in Thailand. Envi Geol 49:321–331

Szczucinski W, Chaimanee N, Niedzielski P et al (2006) Environmental and geological impacts of the 26 December 2004 Tsunami in coastal zone of Thailand—overview of short and long-term effects. Polish J Envi Stud 15(5):793–810

Tuttle MP, Ruffman A, Anderson T, Jeter H (2004) Distinguishing tsunami and storm deposits in eastern North America: The 1929 Grand Banks tsunami versus the 1991 Halloween storm. Seismo Res Lett 75(1):117–131

Umitsu M, Tanavud C, Patanakanog B (2007) Effects of landforms on tsunami flow in the plains of Banda Aceh, Indonesia, and Nam Khem, Thailand. Mar Geol 242(1–3):141–153

Walker R (1975) Generalized facies models for resedimented conglomerates of turbidite association. Geol Soc Amer Bull 86:737–748

Wang P, Horwitz MH (2007) Erosional and depositional characteristics of regional overwash deposits caused by multiple hurricanes. Sedimentology 54:545–564

Williams HF, Hutchinson I, Nelson AR (2005) Multiple sources for late-Holocene tsunamis at Discovery Bay, Washington State, USA. Holocene 15(1):60–73

Wright C, Mella C (1963) Modifications to the soil pattern of South-central Chile resulting from seismic and associated phenomena during the period May to August 1960. Bull Seismo Soc Amer 53(6):1367–1402

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Coastal geomorphic conditions and styles of storm surge washover deposits from Southern Thailand

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ABSTRACT

The characteristics of tropical storm washover deposits laid down during the years 2007 to 2011 along the southern peninsular coast of the Gulf of Thailand (GOT) were described in relation to their different geomorphic conditions, including perched fan, washover terrace and sheetwash lineations preserved behind the beach zone within 100 m of the shoreline. As a result, washover terrace and sheetwash lineations were found where the beach configuration was uniform and promoted an unconfined flow. Non-uniform beach configurations that promoted a confined flow resulted in a perched fan deposit. Washover sediments were differentiated into two types based on sedimentary characteristics, including (i) a thick-bedded sand of multiple reverse grading layers and (ii) a medium-bedded sand of multiple normal grading layers. In the case of thick-bedded washover deposits, the internal sedimentary structures were characterized by the presence of sub-horizontal bedding, reverse grading, lamination, foreset bedding and wavy bedding, whereas, horizontal bedding, normal grading, and dunes were the dominant structures in the medium-bedded washover sand. Rip-up clasts were rare and recognized only in the washover deposits in the bottom unit, which reflects the condition when a mud supply was available. All washover successions were found in the landward inclined-bedding with a basal sharp contact. A high elevated beach ridge associated with a large swale at the backshore proved suitable for a thick-bedded washover type, whereas a small beach ridge with uniformly flat backshore topography promoted a medium-bedded washover sediment.

1. Introduction

Washover deposits are one of the significant results of high energy seawater flooding across a beach or dune. They can be generated from such high intensity processes as tsunamis and storms. In the past decades, rapid flooding from tsunami and coastal storms have been among the main coastal hazards and have caused damage to coastal communities and infrastructure, e.g. 1960 Chilean tsunami, 1989 Typhoon Gay in Thailand, 2004 Sumatra tsunami, 2005 Hurricane Katrina in USA, 2008 Cyclone Nargis in Myanmar, 2009 Typhoon Morakot in China and Taiwan, 2011 Great East Japan tsunami, and 2011 Hurricane Irene in USA. These high energy flows usually bring the sediments from the seaward side, especially from nearshore to beach, to be deposited on the landward side beyond the beach zone.

In fact, the sedimentary characteristics and physical properties of storm-induced washover deposits have been published since the 1960s. The first observable features of storm incidence are changes in beach morphology, which has led to the subsequent study of the changes in the coastal morphology after storm events (Hayes, 1967; Wright et al., 1970; Schwartz, 1975; Morton, 1976; Kahn and Roberts, 1982; Morton and Paine, 1985; Thieler and Young, 1991; Wang et al., 2006; Claudino-Sales et al., 2008). Along these lines, Schwartz (1975) presented the common stratigraphy of storm washover deposits as a horizontal stratification of laminated sand which usually shows foreset laminae in its distal part if it penetrates into a pond or lagoon. Morton and Sallenger (2003) classified the changes in the coastal landform features after storm events into two types, (i) the erosional features (dune erosion, channel incision, and washout) and (ii) the depositional features (perched fan, washover terrace, and sheetwash lineations), based on their formation processes. Since then, these features are often applied as the key criteria to assist in the identification of the intensity and flow conditions of each storm event. Sedgwick and Davis (2003) also reported the five subfacies in storm deposits that represent the differences in flow conditions during overwash, the position relative to sea level, and

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variable degrees of reworking after deposition. Wang and Horwitz (2007) reported the different erosional and depositional characteristics of washover sediments induced by hurricanes from several barrier-island sub-environments, including dune field, interior wetland and back-barrier bay. They proposed that the different erosional and depositional characteristics are caused by the different overall barrier-island morphologies, vegetation types and densities, and sediment properties.

Within the literature, the sedimentary characteristics and bedform surfaces of storm deposits that have been characterized have included normal grading (Andrews, 1970; Sedgwick and Davis, 2003; Morton et al., 2007; Wang and Horwitz, 2007; Phantuwongraj et al., 2008; Spiske and Jaffe, 2009), reverse grading (Leatherman and Williams, 1983; Sedgwick and Davis, 2003; Morton et al., 2007; Wang and Horwitz, 2007; Phantuwongraj et al., 2008; Spiske and Jaffe, 2009), laminae/laminaset (Leatherman and Williams, 1977; Sedgwick and Davis, 2003; Morton et al., 2007; Wang and Horwitz, 2007), sub-horizontal bedding (Deery and Howard, 1977; Schwartz, 1982; Phantuwongraj et al., 2008), foreset bedding/laminae (Schwartz, 1975; Deery and Howard, 1977; Schwartz, 1982; Davis et al., 1989; Nanayama et al., 2000; Morton et al., 2007; Wang and Horwitz, 2007), antidune (Schwartz, 1982), rhomboid bedform (Morton, 1978 and Schwartz, 1982) and current ripples (Deery and Howard, 1977; Schwartz, 1982; Morton et al., 2007; Komatsubara et al., 2008). However, most of these sedimentary features are also found in tsunami deposits (e.g., Gelfenbaum and Jaffe, 2003; Choowong et al., 2007; Morton et al., 2007; Choowong et al., 2008a,b; Jankaew et al., 2008; Shanmugam, 2012). Thus, it is sometimes challenging to distinguish whether sand sheets in the geological records were originally formed as the result of a tsunami or a storm. This challenge has led many geologists and sedimentologists to develop the key criteria for distinguishing tsunami from storm deposits (Nanayama et al., 2000; Goff et al., 2004; Tuttle et al., 2004; Kortekaas and Dawson, 2007; Morton et al., 2007; Komatsubara et al., 2008; Switzer and Jones, 2008a; Phantuwongraj and Choowong, 2012). However, the identifiable features, such as the sedimentary characteristics, washover geometry and biological evidence, that are used in the differentiation of these two types of high energy flows are still equivocal because their deposition often depends on the topographical control, local source of sediments and the intensity of the event, and these factors usually differ from place-to-place.

The coast of Thailand has also been attacked by storm surges which cause damage to coastal communities. Although, Thailand has experienced storm surges at least three times recently from tropical storms ("Harriet" in 1962, typhoon "Gay" in 1989 and typhoon "Linda" in 1997), only a few reports on the storm deposits have been published (e.g. Roy, 1990). Phantuwongraj et al. (2008), subsequently, reported the possible storm deposits found along the coast at Surat Thani and Nakhon Si Thammarat on the Gulf of Thailand (GOT). The discovery in tracing the storm deposits was extended northwards along this coastline to Chumphon where Phantuwongraj et al. (2010) found multiple layers of paleo-storm sand sheets in a swale located 1 km inland and far away from the present shoreline. However, more detailed studies of the sedimentary characteristics, topographical and flow conditions of the washover deposits induced by storms are still required, particularly for Thailand where so little is known.

Here, in this paper, the sedimentary characteristics of storm washover deposits from different geomorphic conditions associated with the storm events during the period 2007–2011 in Thailand are described systematically. We start from the identification of the distinctive sedimentary features of washover deposits from the three different geomorphic settings preserved along the GOT coast. Comparison of the topographical and flow conditions from the individual and geological settings related to washover sediment features is also made. This study presents the first detail of recent storm deposits from the Southeast Asia region which also can be used as a modern analog for storm deposits from other areas. The similarity and differences in the sedimentary features found in storm deposits from different geological settings may help geoscientists to understand further what (and how) storms leave behind as their evidence in the geological record.

2. Setting and method

The climate of Thailand is under the influence of two main monsoon winds that are seasonal in character, being the southwest (SW) monsoon and NE monsoon. The SW monsoon in May–October brings a stream of warm moist air from the Indian Ocean towards the Thai Peninsula, resulting in an abundance of rain over the country. Subsequently, the NE monsoon in October–February, originally forming as cold and dry air, is driven from mainland China towards Thailand. This gradually causes the cold condition in the winter season, especially in the northern and NE highlands, whereas in the southern part of Thailand this NE monsoon normally causes a mild weather and heavy rain along the eastern (GOT) coast of the Thai Peninsula. During the NE monsoon season, sea level in the GOT is normally raised higher than mean sea level (MSL) (Fig. 1) due to seawater from South China Sea moving downward and then flowing into the GOT corresponding to the prevailing wind from the NE direction. In contrast, in SW monsoon season, the prevailing wind blows to the opposite side which leads to seawater moving out of the GOT, thus sea level in the GOT is lower than the average MSL. The average change of sea level in the GOT caused by the change in monsoonal wind is 0.4 m. Additionally, during November–December, the eastern side of southern Thai Peninsula is usually affected by depressions or tropical storms and sometimes typhoons from the eastern side of GOT, which can generate storm surges and cause overwash flow in the low-lying coastal area. However, Thailand has experienced storm surges induced by tropical storm or typhoon only three times since the 1960s. Apart from the storm events, the temporary increase in monsoonal wind velocity above its usual speed for a few successive days during NE monsoon season also causes a storm surge up to 1.25–2.5 m high in the low-lying coastal area along the Southern Thailand coast (Fig. 1). According to the frequency of their occurrence, at least once a year, washover deposits resulting from temporary strong NE winds are found to be more in number than the washover deposits induced by tropical storms or typhoons. This phenomenon of storm surge being induced by temporary strong NE winds usually occurs during November to January as it is the period of highest sea level during the year. A storm surge induced by strong winds during the NE monsoon season is also found in Singapore (Tkalich et al., 2012).

We focused on three sites (Fig. 2a), (1) Ban Takrop (BT) in Surat Thani (Fig. 2c), (2) Laem Talumphuk (LT) in Nakhon Si Thammarat (Fig. 2d), and (3) Khao Mai Ruak (MR) in Prachuap Khiri Khan (Fig. 2b), that were effected by storm surges during the period 2007–2011. Five storm surge events during this time were induced by (i) seasonal sea-level rise accompanied with temporary strong NE winds over 2007 to 2010 and (ii) a low-pressure system in 2011. The maximum wind speed measured from three weather stations closest to each study site was 20–22 knots. The potential heights of storm tide were at 2.30–2.96 m above MSL, as calculated from tide gauge data and significant wave height data at each study site (Fig. 3). Storm surges caused erosion to the beach and also expanded the inlet/outlet channels. The damage also extended to a road and house along the shoreline.

At the study sites, we investigated the damage and particularly aimed to record how the beach morphology had changed. The evidence of erosion and deposition features along the coastal area resulting from storm surges were measured and photographed. Trenching, coring, and pitting were made for examination of the washover sediment characteristics. The washover sediments were sampling systematically layer by layer from top to bottom. A detailed coastal topographical profile, using a digital survey camera, was performed. Grain size analysis was

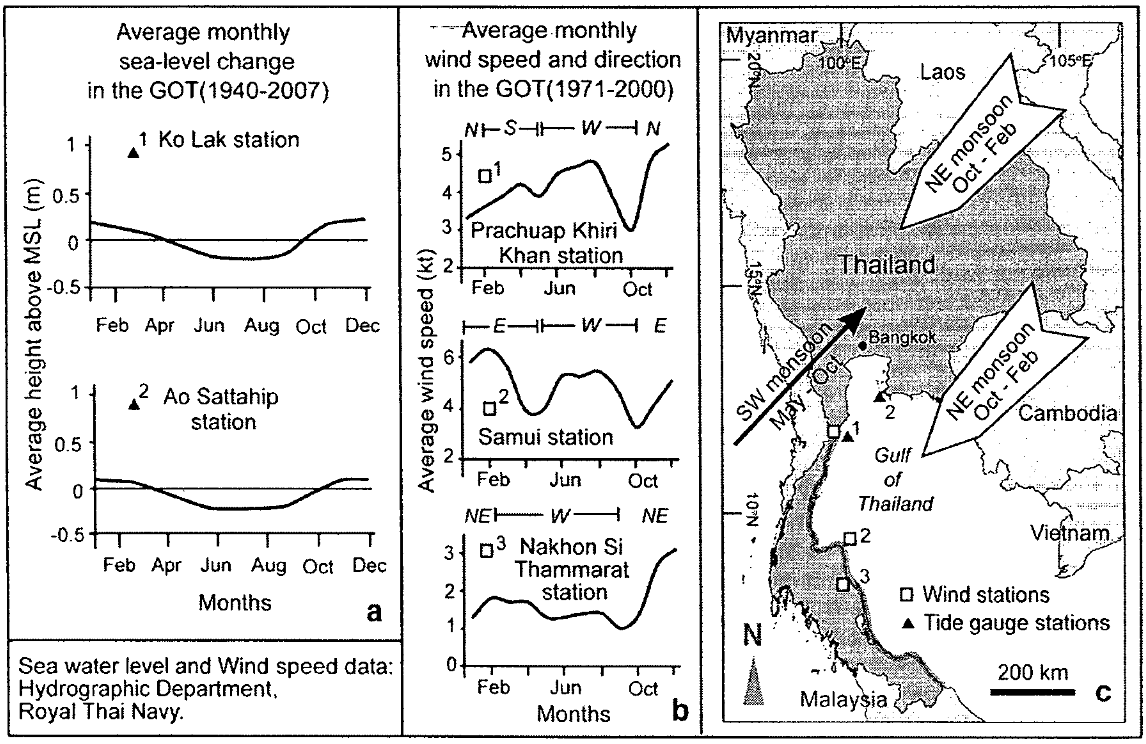

Fig. 1. (a) Average monthly sea-level change in the Gulf of Thailand (GOT) from 1940 to 2007. (b) Average monthly wind speed and direction from 1971 to 2000 from the nearest weather stations to the three study sites. (c) Map demonstrates usual NE and SW monsoon directions in Thailand and location of tide gauge stations and weather stations. Bold line bounds the areas commonly affected by overwash flow by storm surges.

carried out at the Geological Survey of Japan using a Camsizer. Sediment compositions were identified under a binocular microscope.

In this study, the classification of the type of washover deposits in terms of "perched fan", "washover terrace" and "sheetwash" was based on the work of Morton and Sallenger (2003) who described a perched fan as a small lobate to elongate washover feature that is oriented perpendicular to the shore. A washover terrace is then characterized as an elongate washover deposit that is oriented parallel to the shore. The washover terrace may form a uniformly wide band, or its landward margins may be highly irregular depending on the interactions between breaking waves and currents during washover deposition. Lastly, sheetwash usually shows narrow elongate zones of erosion and deposition that form lineations parallel to the direction of flow. The flood regime, including the overwash regime and inundation regime, followed the conceptual model of storm impact regime originally proposed by Sallenger (2000). Terminology used for differentiating the thickness of beds and laminae followed that of Campbell (1967).

3. Results

3.1. 2007–2008 storm deposits at Ban Takrop (BT), Surat Thani

At BT, the area displays as prograded shoreline which is composed of relict strand lines oriented in the northwest–southeast direction (Fig. 2c). Between the relict strand lines, the topography exhibits a swale which is about 10–15 m wide in the south and then narrows towards the north with an average width of 3–4 m. The outer beach ridge is 2 m high above mean sea level (MSL) and yields a slightly steep slope (8°) at the foreshore. The average tidal range here is 1.09 m while the maximum range during spring tide time can be up to 2.07 m. We visited BT in July 2008 after an overwash event on the 25th April 2008, to investigate the change in beach morphology. The storm tide high at least 2.96 m above MSL was calculated from Lang Suan tide gauge station and significant wave height data (Fig. 3). The maximum inundation distance of the 25th April 2008 storm surge was 100–300 m from the shoreline. The morphology of the wide swale between the relict strand lines also limited the flooding zone from overwash flow in this area.

The washover deposit found at BT exhibited as a narrow band of sand that was oriented parallel to the shore. Based on its morphology, washover deposition here was classified as washover terrace type following Morton and Sallenger (2003). The washover terrace is 30 m in width perpendicular to the shore and 600 m in length parallel to the shoreline (Fig. 4a). At the distal part in landward side, the washover deposit was spilt as a series of fan lobes into a swale behind the beach. More than ten lobes were observed and each of these was approximately 10 m in width orientating parallel to shoreline (Fig. 4b). The thickness of the washover sediment reaches a maximum of 80 cm in the proximal part and terminates with a steeply avalanche face into the swale (Fig. 5a). Some parts of washover sediment also penetrate into the Nipa palm habitat zone, as observed from the sand body the buried a palm tree (Fig. 5c). The bottom contact between washover sediment and mud in the swale shows as a sharp contact that indicates a sudden depositional process. Garbage possibly came along with the overwash flow also found within the washover sediment (Fig. 5d).

The washover deposit exhibited a bedding plane dipping in a landward direction, with eleven layers of coarse to very coarse-grained sand and multiple laminae of medium to coarse-grained sand were recognized (Fig. 5b). Each layer showed reverse grading (Fig. 5e) which consists of medium grained sand laminae 0.7–1 cm thick at the base and then changing to coarse to very coarse-grained sand upwards to the top, with a thickness varying from 2 to 7 cm (Fig. 5b, e). The washover deposit here can be divided into two units based on its difference in lithology, including the thickness and inclination of layers (Figs. 5b and 6c). The thickness of washover sand layers at the lower unit ranges from 2 to 6 cm and displays a low dip angle being almost horizontal to sub-horizontal bedding. In contrast, the thickness of

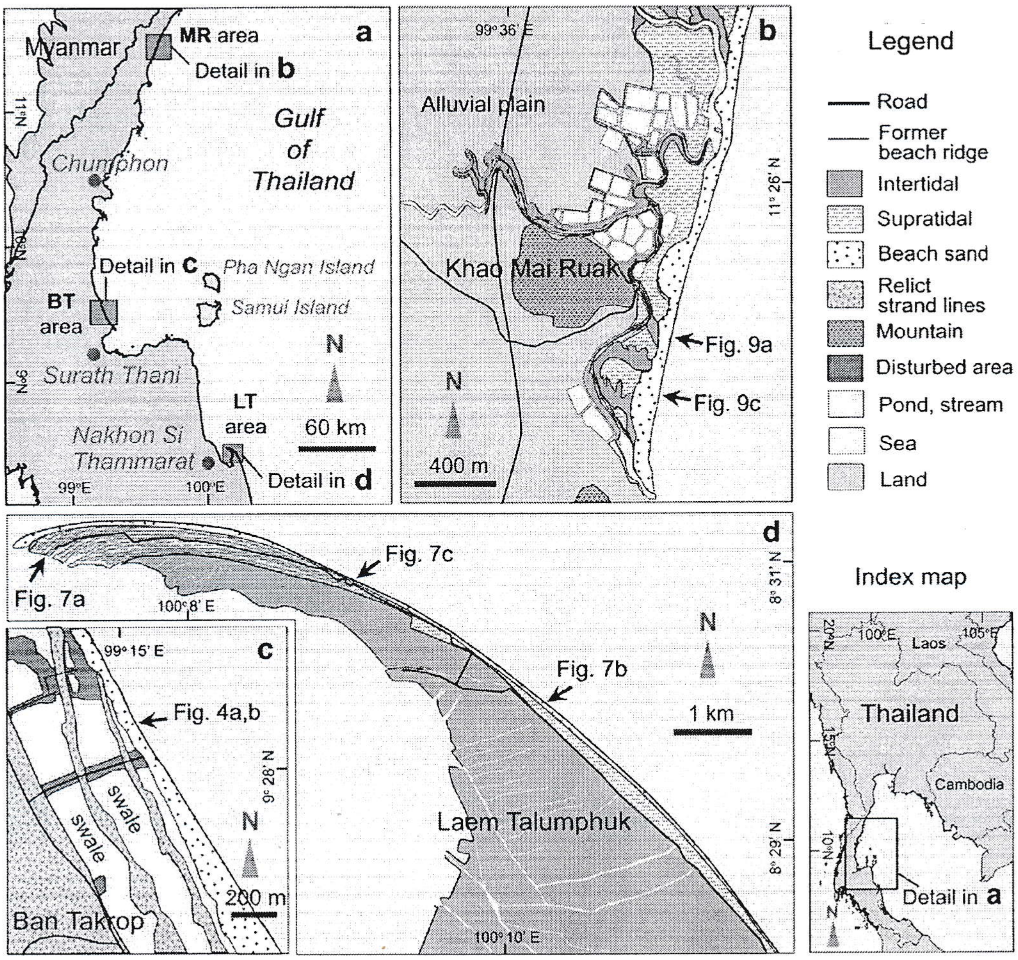

Fig. 2. Geomorphological map of the study sites. (a) The three sites along the GOT, with the geomorphic setting map at (b) Khao Mai Ruak (MR), Prachuap Khiri Khan, (c) Ban Takrop (BT), Surat Thani and (d) Laem Talumphuk (LT), Nakhon Si Thammarat. Also shown are the locations of subsequent figures.

washover layers in the upper unit was thicker, at about 4–7 cm, and the inclination of layers was also much steeper than the lower unit. The foreset bedding was inclined 22° and 35° in the upper unit, and was also observed at the washover margin (Figs. 5b and 6c).

Sediment samples were collected layer by layer from top to bottom. Nineteen samples were collected from washover sediment (layers 10 to 1) and sub-surface sediment (Fig. 6). According to the grain size analysis, the grain size distribution in the coarse to very coarse sand layer and the medium sand laminae shows unimodal and bimodal distribution whereas the sub-surface sediment shows only a unimodal distribution (Fig. 6a). In the medium sand laminae, there are three samples that show bimodal distribution (numbers 2, 5, and 12) which are clearly recognized as two peaks of medium sand and coarse sand. These two peaks of sediment size in the medium sand laminae may result from the contamination of the layer beneath during the sampling as coarse sand at the top of layer 9 is mixed during sampling of the base of layer 10. From the grain size distribution graph, the medium sand laminae shows an asymmetrical distribution with a negative skewness value, whereas the coarse to very coarse sand layer shows both symmetrical (1, 13, and 14) and asymmetrical distributions (3, 4, 6, 9, 11, 16, and 17) with positive skewness. However, sample 7 shows a negative skewness similar to sample 8 that is from a medium sand laminae. The average grain size of samples 7 and 8 are also close at 0.5 and 0.62 phi, respectively. Based on the lithology, the upper part of layer 6, indicated as a boundary layer between unit 1 and unit 2, as exhibited in the unusual grain size distribution and grain size value of sample 7, may have resulted from the aeolian process after the storm event. This reworked surface is similar to washover sediments found in Australia that are characterized by two storm layers separated by a thin veneer of sand that has been reworked by aeolian processes (Switzer and Jones, 2008b).

According to the poor compaction of washover sand, the fresh condition of garbage in the washover sediment, and a burial of a Nipa palm that is still alive, the lower unit of this washover deposit should be the result of a recent storm surge event that occurred within one year. From the tide gauge data from a station near the BT area, on the 29th November 2007, the potential storm tide with a height of 2.56 m generated overwash flow across beach and flooded into swale. Therefore, the 1st unit should be the result of the storm surge event on 29th November 2007 that is the only storm surge over the period October 2007 to April 2008. The reworked surface (i.e. sample 7) may then result from aeolian processes induced by high velocity NE winds during December to February.

The sedimentary structures in the washover deposits included lamination, foreset bedding, wavy bedding and reverse grading (Fig. 5b, d). At the proximal part, horizontal bedding is the dominant structure, whereas foreset bedding was principally found in the distal part of the washover deposits. The grain composition includes quartz, shell fragments, feldspar and rock fragments. Washover sand grains are moderately well to moderately sorted.

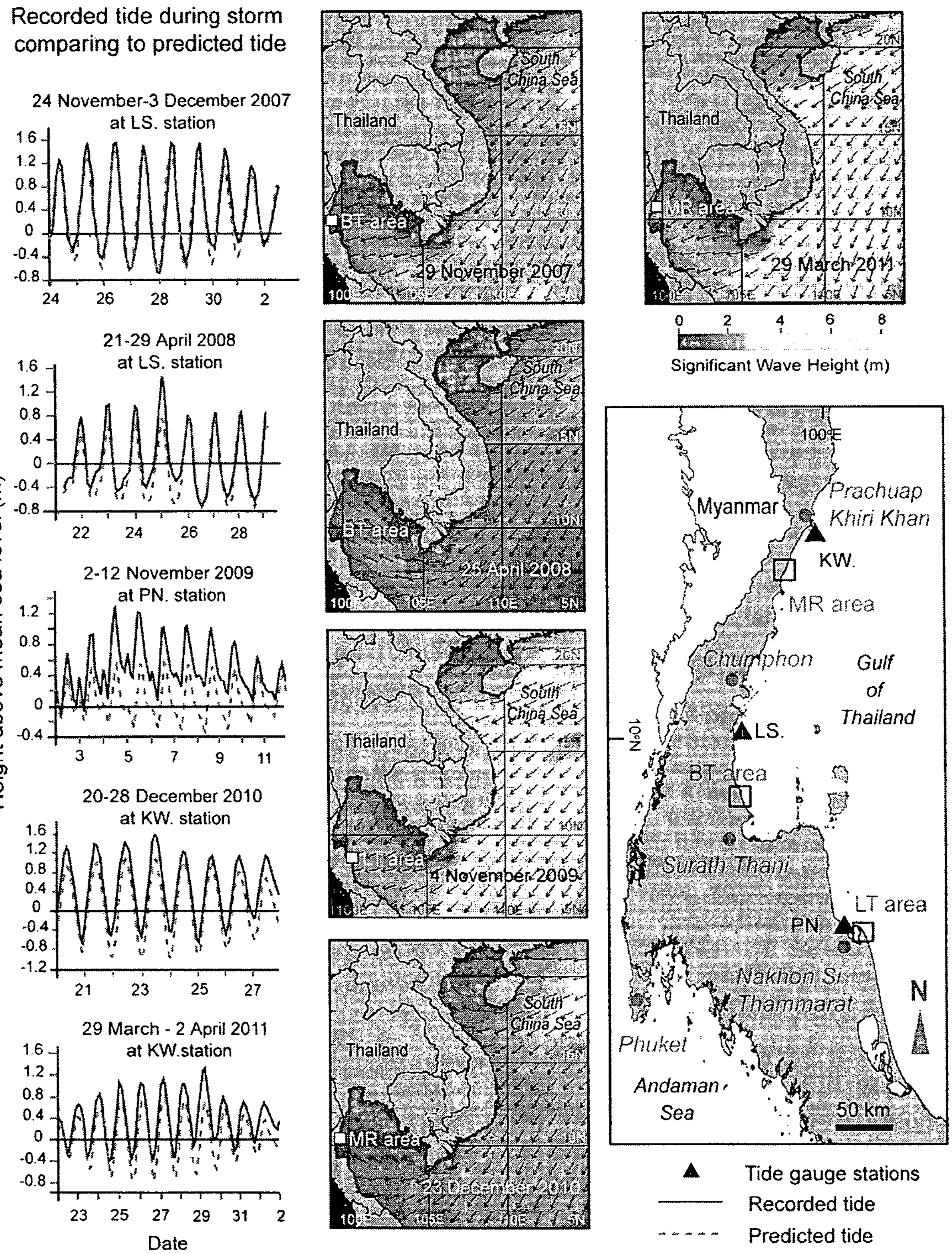

Fig. 3. Records of tide during storm surge from 2007 to 2011 in the study sites from the nearby tide gauge stations (left). Significant wave height and wave direction map in the South China Sea and the GOT during the 2008–2011 overwash events (middle). Location of tide gauge stations and the study sites (right). Recorded tide and predicted data; from Hydrographic Department, Royal Thai Navy. Significant wave height and wave direction data are from Oceanweather, Inc. and www.thaiwater.net.

3.2. 2009 storm deposits at Laem Talumphuk (LT), Nakhon Si Thammarat

LT is an active sand spit, 6 km long and 500–700 m wide with a south-north trending orientation that corresponds to the major present-day longshore current. The spit itself developed an east-west orientation of a series of former beach ridges. The distal part of the spit recurves to the west (Fig. 2d). The spit recently consists of a relatively small modern beach ridge of about 1–1.5 m above present MSL. Subaqueous sand bars can be seen during low tide while average tidal range here is 0.5 m. During the spring tide, the interval between high and low water level is 0.9 m. During the 4th–5th November 2009, a storm surge induced by temporary NE strong winds flooded over the LT sand spit. The potential storm tide with 2.3 m height was calculated from tide recorded and significant wave height data.

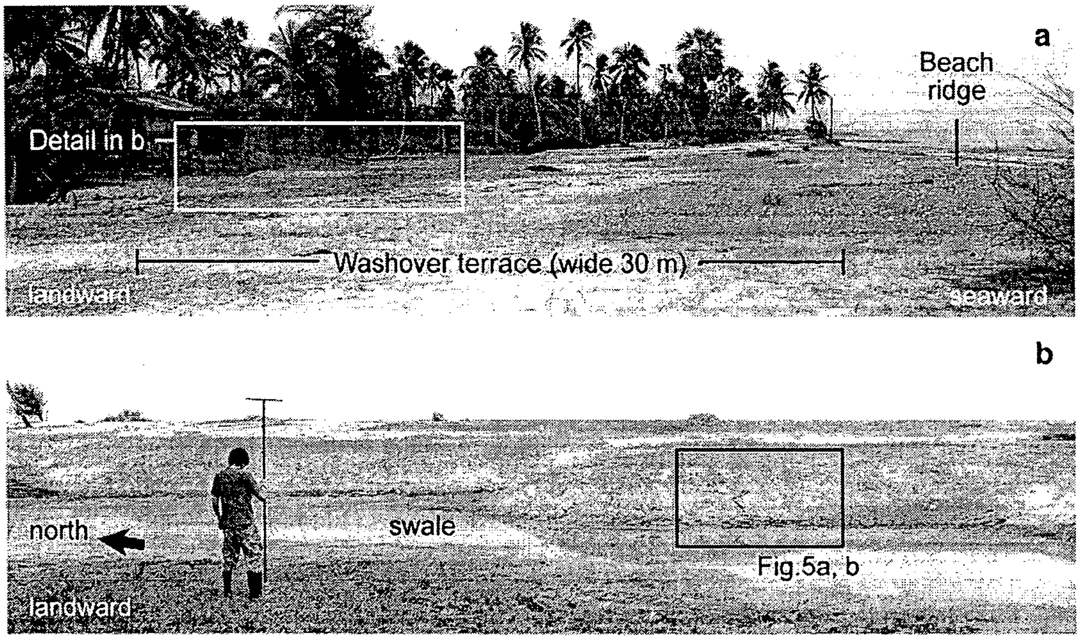

Fig. 4. (a) The washover terrace (wide 30 m cross-shore and long 600 m along-shore) at BT and (b) the washover lobes showing the avalanche face at the distal part of the terrace. Pictures were taken on 2 July 2008.

We visited the area on 9th November 2009 after the storm surge event. The erosional features that reflect strong wave attack were preserved along the beach as scoured and knocked down pine trees.

Washover sediments were deposited along the LT sand spit in several environments such as mangrove, shrimp pond, and on the road behind beach (Fig. 7). In mangrove area, the washover sediment

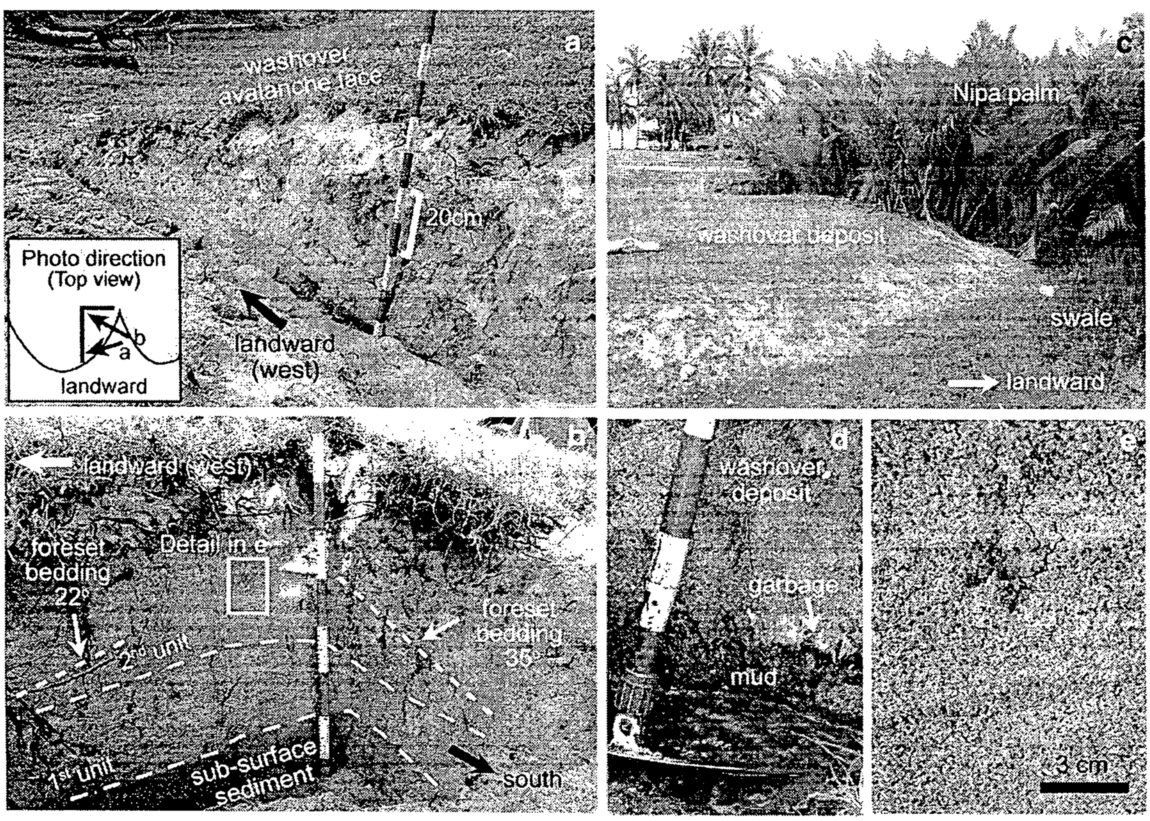

Fig. 5. (a) The washover successions and steeply avalanched face at the washover margin. (b) Two units within the washover deposit and foreset bedding at the distal end of the washover deposits. (c) Nipa palm in swale was partially buried by washover sediment. (d) Bottom sharp contact of washover sediment and mud in swale. (e) Reverse grading layer in the washover sediment.

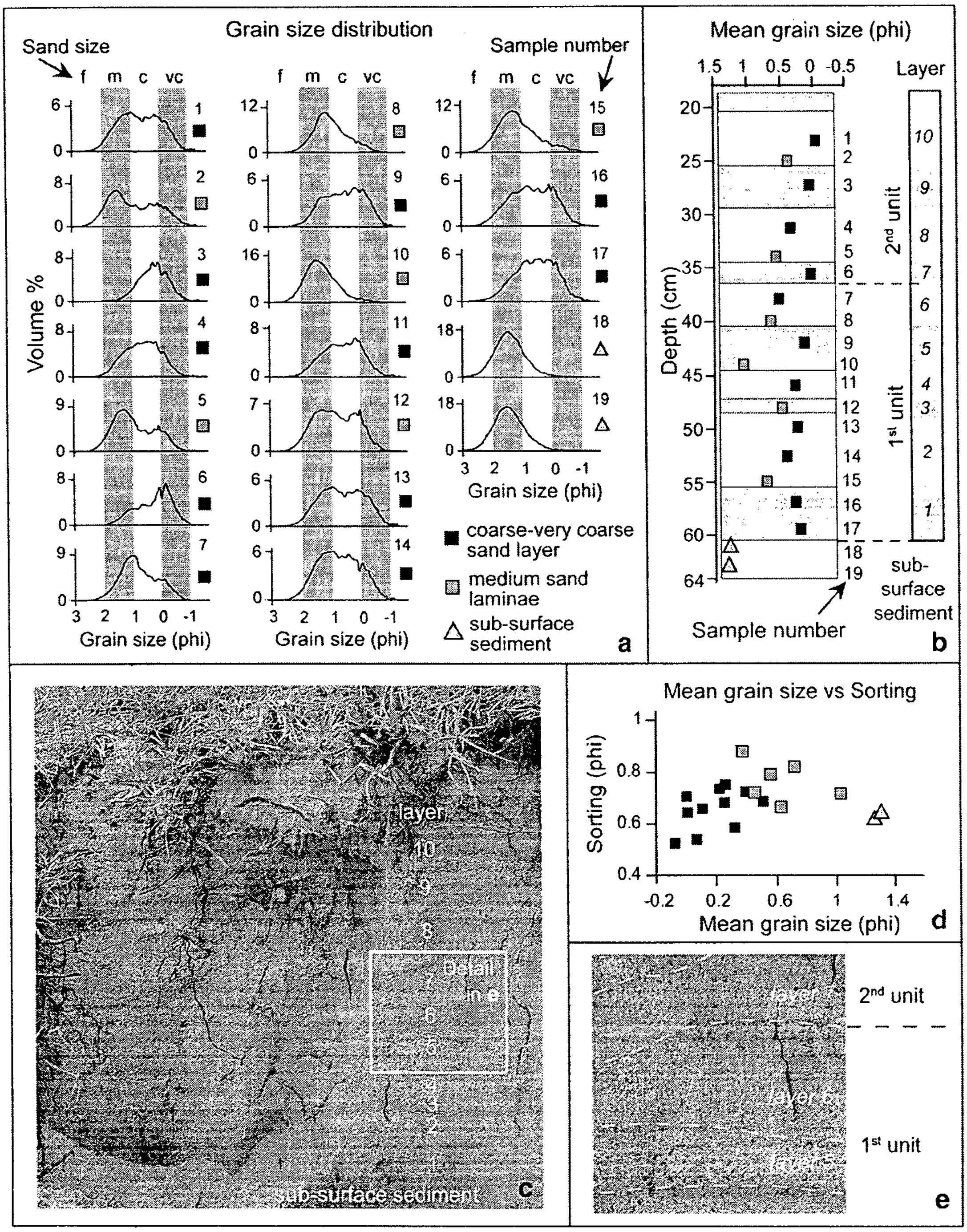

Fig. 6. (a) Grain size distribution graph of washover sediments and pre-storm surface sediments. (b) Average grain size change from top to bottom within the washover deposit and pre-storm surface sediment. (c) The sampling locations (at scour) in the washover deposit. (d) Mean grain size and sorting characteristics of three groups of sediments (coarse–very coarse layer, laminae layer and pre-storm surface layer). (e) Contact boundary between the 1st unit and 2nd unit.

was deposited as narrow band parallel to the shore similar to those recognized in the washover terrace type classified by Morton and Sallenger (2003). Whereas washover deposits found behind the beach in the shrimp pond and on the road were expressed as small lobate features and oriented perpendicular to the shore, and were thus classified as perched fan type following Morton and Sallenger (2003).

We made a small trench where the washover deposit was found on the road behind the beach in order to describe the physical characteristics and sedimentary structures (Fig. 7d, e). The topography behind the beach is exhibited as a slightly flat coastal plain without swale. Apart from the forested area behind the beach, a compacted surface road 4–5 m in width was constructed parallel to the shore. Washover sediments were found as a sand sheet with a basal sharp contact overlain on the pre-surface soil and the road. Grasses buried at the bottom part of washover sediment were still green, which indicated the recent timing of the washover deposit (Fig. 7e). The dimension of washover body was 25 m in length cross-shore and 8 m in width parallel to shore. The thickness of the washover sediment was relatively uniform at about 15–20 cm on the flat topography (Figs. 7d and 8a).

Two different sedimentary textures were recognized in the washover sand, being the fine sand grain unit at the bottom and the coarse sand grain unit from the middle to the top (Figs. 7e and 8a, b). The fine sand unit was dominated by fine to medium-grained sand containing rip-up clasts of the underlying soil that were then dispersed upwards into the lower zone near the base of the unit. The erosional contact at the bottom of the first unit was found only in the forested area behind the beach but not on the road. The spatial limit of the erosional contact at the base of washover deposit that was found only in the forested area may reflect the difference in overwash flow condition. The compacted surface of the road may act essentially as an armored bed with little to no erosion relative to areas away from the road. Additionally, drag on the flow would be significantly reduced as well when compared to the forested area. The vertical change in the grain size in the unit shows a normal grading from medium sand at the bottom to fine sand at the top. Additionally, in the distal part, a thin layer of dark organic material was found in the uppermost level of unit (Fig. 8c). The source of dark organic layer may come from the sub-surface soil in the forested area behind the beach. This organic layer may indicate a period of waning flow or possibly a falling flood level. The thickness of the 1st unit was confined by the antecedent topography to about 8 cm in the depression of buried soil and 2 cm on a flat road. Subsequently, the second unit, which is composed of coarse to very coarse-grained sand, was deposited on top of the fine to medium-grained sand unit (Fig. 8b). The coarser grain size in this unit may result from the removal of the fine grain sand from the beach surface by the initial stage of the storm surge, which was then transported to be deposited as the 1st unit and, thus, exposing the less eroded more coarse grain sand on the beach. Subsequently, these exposed coarser sediments were then eroded by the following surges to be deposited as the 2nd unit. The sedimentary characteristics of the 2nd unit was characterized as two multiple layers of coarse sand around 10 cm in thickness which were clearly separated by shell laminae at the base of each layer (Figs. 7e and 8d, e). Normal grading, from very coarse to coarse-grained sand at the bottom to medium grained sand at the top, was revealed in both layers (Figs. 7e and 8e). Dune bedforms (6 cm height and 50 cm in length), oriented perpendicular to shoreline, were recognized in the middle part of the washover deposit. Then, these dunes were gradually transformed into horizontal bedding as it extended further inland (Fig. 8b). The changing of sedimentary structure from dune bedform surface to structureless at the distal part of the washover deposit and the decrease in the overall grain size in the landward direction presumably reflects the decreased flow velocity.

The washover revealed a sequence of normal grading within the two units, where the average grain size of the first unit at the bottom was finer than the second unit on the top (Fig. 7e). Sorting of sediment in the first unit was also better than the second unit. The

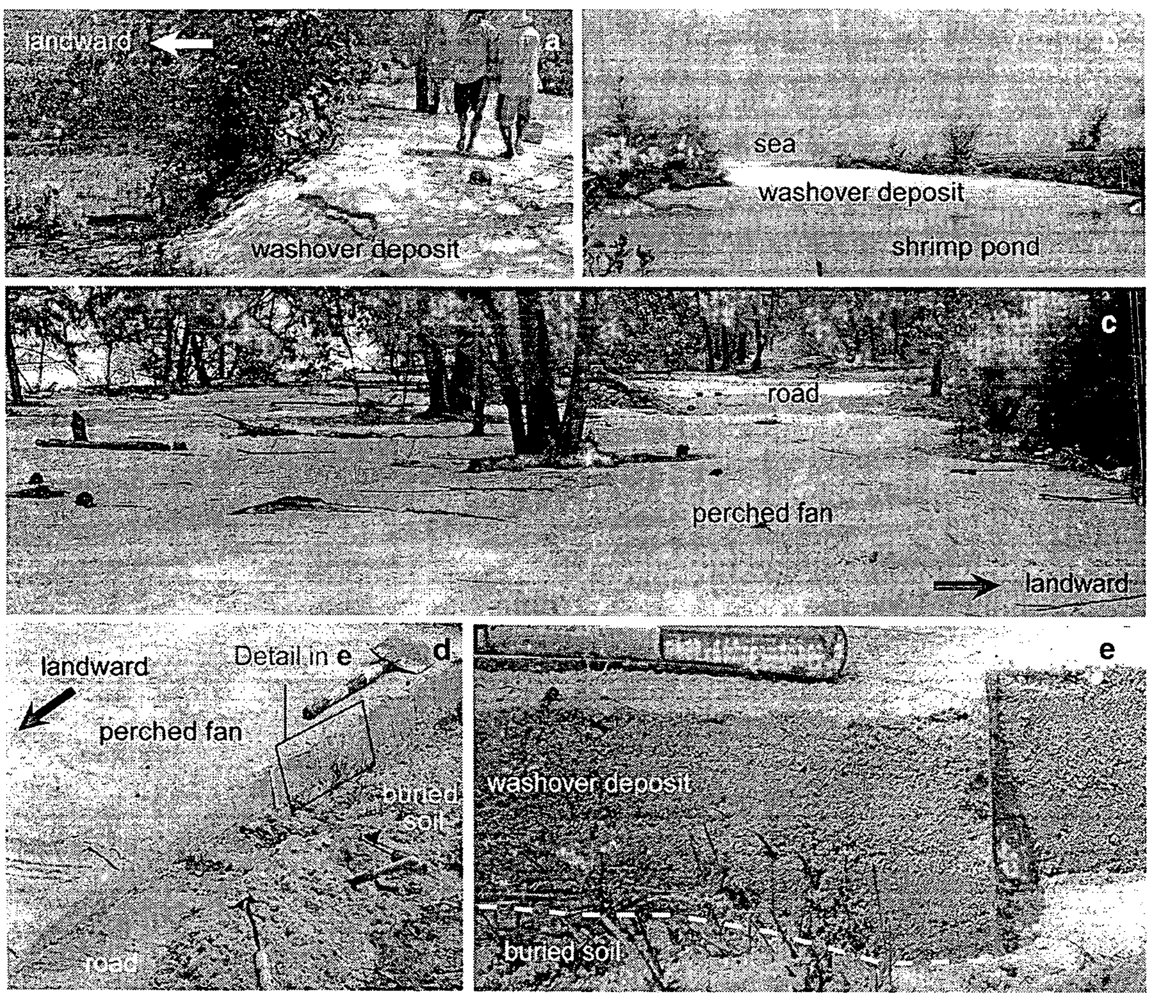

Fig. 7. (a) Washover sediment penetrated into the mangrove area at the head of LT sand spit (north of study site). (b) Washover sediment penetrated into the shrimp pond behind beach at the middle of LT sand spit (south of study site). (c) Washover deposit on the road as a perched fan shape. (d) Washover deposit showing landward thinning at the distal part (trenching perpendicular to the shoreline). (e) Three layers of washover deposit with a normal grading in the vertical direction.

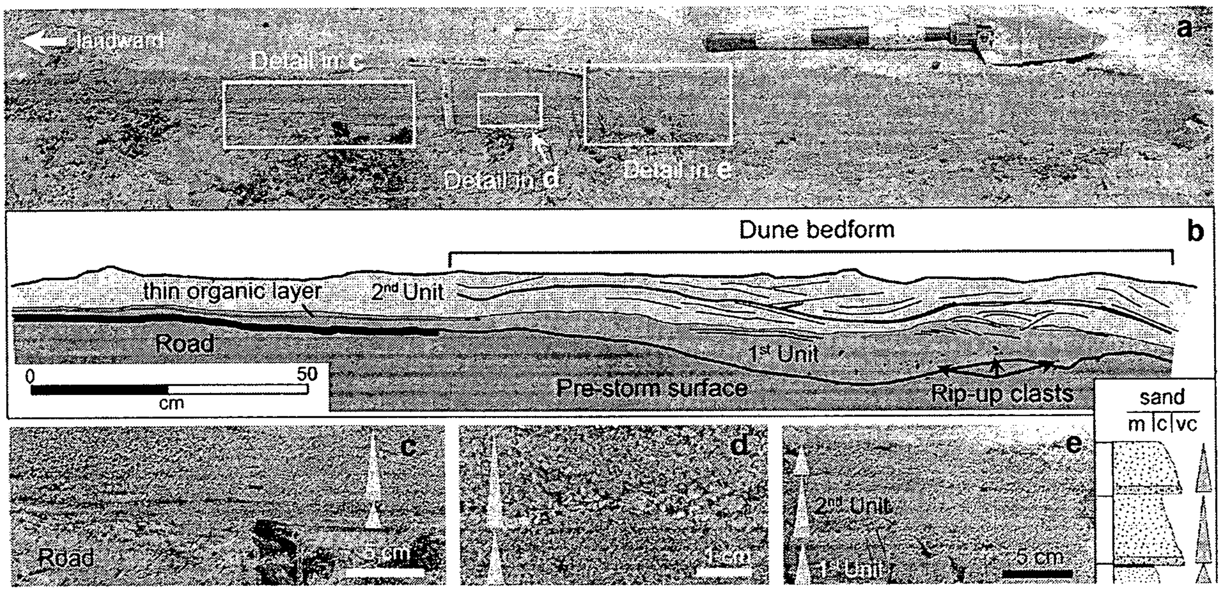

Fig. 8. (a) The internal structure of the washover deposits at LT. (b) A detail sedimentary structure in the washover deposits revealing two sediment units and a dune structure. (c) The thin organic layer found in the distal part of the washover sediment in the 1st unit and (d) shell lag laminae at the base of the 2nd unit and (e) normal grading in the washover sediments within the1st and 2nd units.

percentage of the mud content was high within the first unit due to the erosion of the underlying soil by the initial waves, whereas, the second unit was less so. Major sediment compositions included quartz, feldspar, shell fragments and rock fragments.

3.3. 2010 and 2011 storm deposits at Khao Mai Ruak (MR), Prachuap Khiri Khan

The topography of the MR area exhibits as sand barrier which was developed in front of the tidal channel (Fig. 2b). The barrier exposed a steeply slope of about 14° on the foreshore side. Behind the barrier, the tidal floodplain and marsh with an elevation of 2.5 m lower than barrier surface was observed (Fig. 9a). The tidal system here is a diurnal type with an average range of high and low levels of 1.12 m and 2.08 m during the maximum spring tide. On the 23rd December 2010, the MR area was flooded by a storm surge induced by temporary strong NE winds. According to the recorded tide data and significant wave height data, the potential storm set-up of 2.58 m was generated at MR. Subsequently, on the 29th March 2011, the storm surge generated by low pressure system in the GOT caused overwashing into the low-lying coastal area in the MR site. A storm tide high of 2.32 m was calculated based on recorded tide data and significant wave height data. We visited the MR area on 13th June 2011. Evidence of erosion by the 2010 and 2011 storm surges was found at the outer beach and behind the barrier along the shoreline. A beach scarp with 40–50 cm was exhibited along the shore over a distance of 500 m (Fig. 9b). Subsequently, behind the barrier, the coconut roots were exposed above ground surface about 50–60 cm as a result of sand eroded from pre-storm surface (Fig. 9a). We interpret that erosion of the pre-storm surface sand behind the barrier may have resulted from the storm surges during the initial stage that flowed across barrier and were of sufficient energy to erode the pre-storm surface sediment in the back-barrier zone. According to the storm tide height data, we believe that erosion of the pre-storm surface sand behind the barrier possibly resulted from the storm surge on 23rd December 2010 because its storm tide level was higher than the 29th March 2011 event. As the storm tide level was higher, the erosion was likely to be greater.

Apart from erosional features, depositional features were also recognized as washover sediment deposited behind the barrier. At the tidal floodplain behind the barrier, washover sediments were exhibited as multiple elongated narrow sand lines oriented perpendicular to the shore which were similar to the sheetwash lineations type as classified by Morton and Sallenger (2003). On the beach barrier where surface elevation was quite high, the small lobated shape of sand was found with the orientation perpendicular to the shore. We classified this feature as a perched fan type. Both of the sheetwash lineations and perched fan types are exhibited as being non-vegetated on their surface, thus indicating the recent timing of deposition.

At the southern part of where sheetwash lineations were preserved, there is no evidence of washover deposits from the 2010 and 2011 storm surge events due to the elevation of barrier at this part being too high (about 2.9–3 m). There is only a beach scarp feature resulting from strong wave attack found on the foreshore side. However, at the backshore side, the old washover deposits, indicated by dense grass on their surface, 50–83 m in length perpendicular to shoreline and 2 m in thickness, were deposited on the tidal marsh area (Fig. 9c). in the distal part, the lobes of old washover deposits were superimposed on the older lobe on the marsh surface (Fig. 9d) as a boundary between two washover deposits from at least two different events. From the historical record, the MR area had experienced storm surge at least three times from typhoon Gay in 1989, typhoon Linda in 1997 and a deep depression in 2002. Thus, these old washover deposits may be a product from these previous storm surge events. Additionally, Roy (1990) reported the washover sediment from typhoon Gay in 1989 deposited throughout the coastline of MR area. Consequently, the barrier became wider when comparing to the pre-storm surge event due to amount of washover sand adding to the back-barrier area. However, during the next rainy season after typhoon Gay, washover sediment that deposited in the middle of barrier may have been eroded away by flowing water in the channel during the heavy rainfall due to the deposited area being located at the erosional side of a tidal channel. Consequently, this part (middle part of barrier) became the narrowest when compared to the northern and southern sides. Since the barrier in the northern and southern areas was wider and higher than the middle part, when the next storm surge occurs, the overwash is effective only in the middle part, as seen from the 2010 and 2011 storm surge event. Additionally, the intensities of prior storm surge from typhoon Gay and typhoon Linda were also higher than 2010 and 2011 storm surge. Therefore, the overwash from 2010 and 2011 storm surge could not flood across the entire barrier.

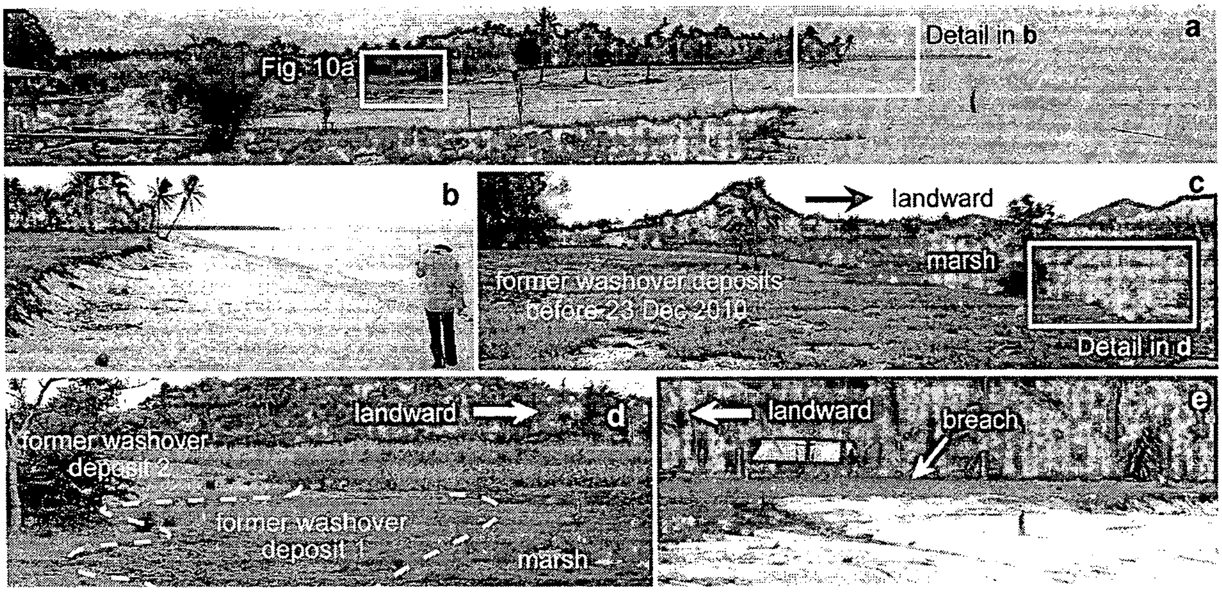

Fig. 9. (a) The cross-shore topography, breach point and washover deposits at MR, (b) the 40 cm high beach scarp along the beach, (c) the former washover deposits before 23 December 2010 that terminated in the marsh, (d) margin of the former washover deposits from two different events on the marsh surface and (e) the breach point at the beach resulting from strong wave attack during NE monsoon surge. Pictures were taken on 13 June 2011.

In contrast, in the sheetwash lineations area, the topography is expressed as a narrow barrier with surface elevation lower than the southern part. Consequently, this part of barrier is the most affected by storm surge attack, as can be seen from the breach of the barrier (Fig. 9e). A narrow and elongated zone of erosion and deposition as sand lineations was found behind the barrier on the tidal floodplain surface (Fig. 10a). These sheetwash lineations were straight and showed a flow direction from the NE to the SW (Fig. 10b). The crest of the sheetwash lineations was 20–30 cm in thickness and the gap between each lineation was 50–70 cm in width.

Behind the breached barrier, we found another washover sediment preserved as a perched fan shape overlain on the sheetwash lineations (Fig. 10c, d). Based on the storm impact scale for barrier islands proposed by Sallenger (2000), perched fan and sheetwash features result from different storm impacts as overwash regime and inundation regime, respectively. Sallenger (2000) also stated that the overwash regime occurs when wave run-up superimposed on the water level exceeds the beach or dune crest, which can transport sediment a distance of ten to hundreds meters inland. In contrast, the inundation regime occurs when the barrier or beach is completely flooded by a seaward-running water body which can transport sediment over a distance as far as 1 km inland. As stated before that the intensity of the 2010 storm surge was higher than the storm surge 2011, and according to the storm impact scale (Sallenger, 2000), the sheetwash lineations at this site should have resulted from the storm surges on the 23rd December 2010 and the perched fan deposit probably resulted from the 29th March 2011 storm surge.

The compaction of sediment in perched fan was very poor when compared to the sheetwash lineations. The new perched fan on the backshore showed a bottom sharp contact on the pre-storm surface brownish medium to coarse-grained sand (Fig. 10e). Floating materials, such as garbage and part of a dead tree, possibly mixed with the overwash flow, were found on the surface of the perched fan. The thickness conformed to the backshore topography with its stratification dipping landward.

In the distal part, the perched fan was spilt into 4–5 lobes at a distance of 70 m parallel to the shoreline (Fig. 10c, d). Trenching there revealed twelve sub-horizontal layers of very coarse grained sand with numerous laminae dipping landwards (Fig. 10e). Each layer showed a reverse grading of grain size from medium to coarse sand laminae at the bottom to very coarse sand at the top (Fig. 10f–h). A series of sub-horizontal layers and laminations were preserved in the middle part of the washover deposit. The thickest layer was found at the base and became thinner towards the top of unit, ranging from 12 to 0.8 cm thick (Fig. 10e–g). In the distal part, the thickness of washover sediment increased slightly by about 10 cm and revealed a foreset bedding projecting inland with a 9° dip angle (Fig. 10e). Mud content was rare due to the absence of any organic material from the sediment source zone. Quartz was the major composition found in the overall deposit, whereas shell fragments were concentrated only within the very coarse sand layer (Fig. 10g). Sorting was moderate to poor in the very coarse sand layer while the medium to coarse sand laminae yielded better sorting.

4. Discussion

In this study, three types of washover deposits (washover terrace, perched fan and sheetwash lineations) from three different geomorphic settings were deposited at a maximum distance of 100 m from the shoreline. A washover terrace with thick-bedded sand, thickness ranging from 60 to 80 cm, was found at BT, whereas perched fans with a thickness ranging over 15–50 cm were found at LT and MR. Lastly, elongate narrow sheetwash lineations running parallel to the flow direction were found at MR.

Sedimentary characteristics also showed the distinctive successions that corresponded to the topography and were classified into two types as (i) a thick-bedded sand, thickness ranging from 50 to 80 cm having multiple reverse grading layers which show laminae at the bottom of each layer, and (ii) a medium-bedded sand, thickness ranging from 15 to 20 cm which shows multiple normal grading layers. Here, in this part, we discuss the controlling factors of washover preservation type, flow condition and sedimentary characteristics from each location. The differences in the geomorphic settings, washover type, flow conditions and sedimentary characteristics are summarized in Table 1.

4.1. *Preservation type and flow condition of storm washover deposits*

We suggest that the different patterns of the washover deposits are related to a series of controlling factors, i.e. topography, bathymetry and flow depth, of which coastal topography is the major factor — a notion

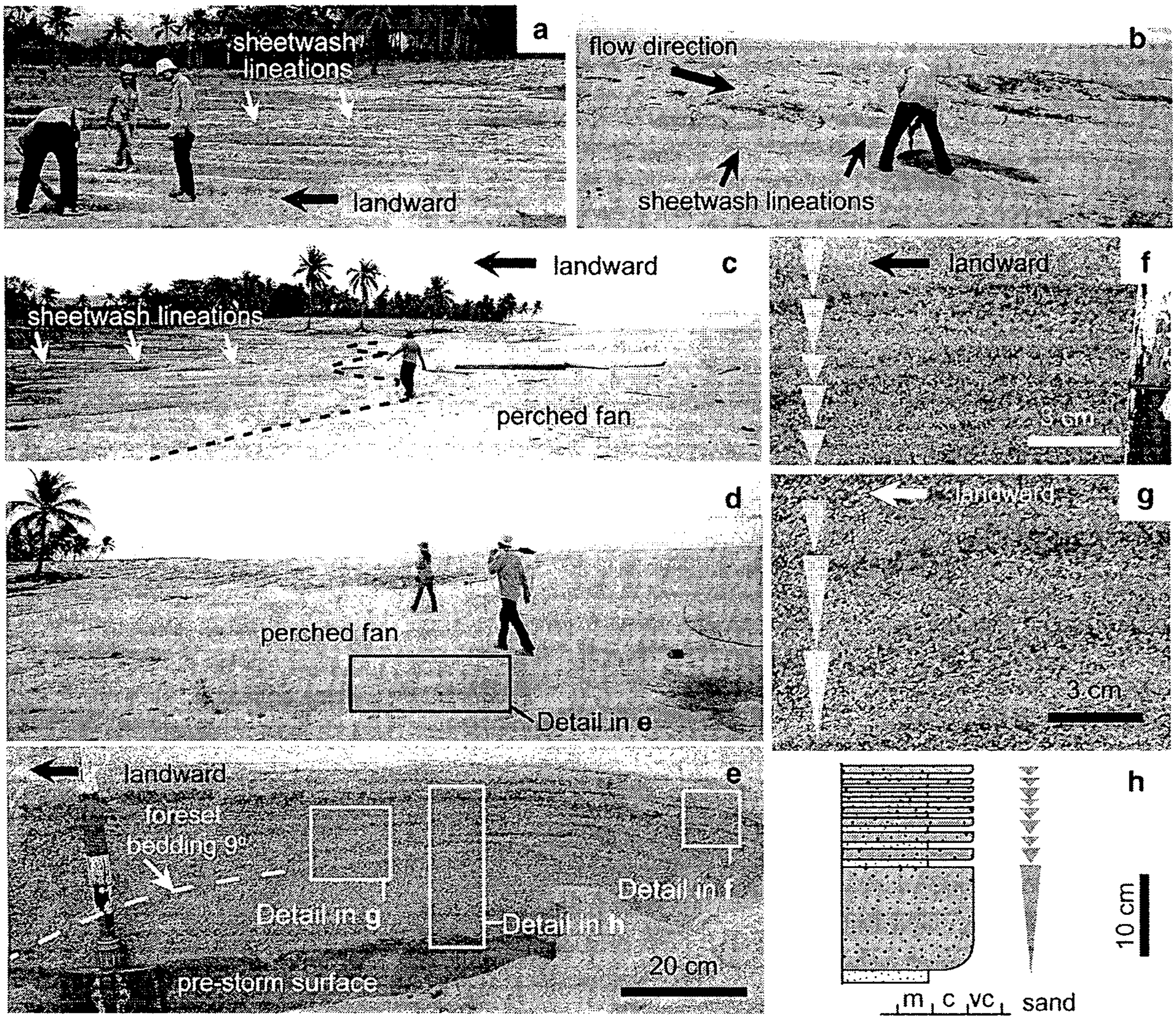

Fig. 10. (a) Elongated and narrow line of sheetwash lineations on the tidal floodplain at backshore. (b) Sheetwash lineations at backshore reflecting the flow direction from the NE to SW. (c) New perched fan deposited on top of the sheetwash lineations at the backshore that was spilt into 4–5 lobes at the distal part (d). (e) The multiple laminae and foreset bedding within the perched fan deposit showing the thin laminae layers at the upper part of perched fan deposit (f), the thick laminae layers at the middle part of the perched fan succession (g) and the sketch of washover stratigraphy, based on observation during field study, showing the reverse grading in each layer (h).

that is in agreement with Morton and Sallenger (2003). The topography also plays an important role in controlling the behavior of the flow condition when and where the overwash occurs. Morton (2002) and Morton and Sallenger (2003) reported that if the topography, in terms of the land elevation, is relatively uniform alongshore and lower than the maximum flooding level, it will be suitable for the unconfined flow condition. Consequently, a uniformly wide band as a terrace may be generated over a distance of hundreds of meters. In contrast, morphological criteria that favor the construction of perched fans include a narrow barrier island, low dunes, and gaps between dune crests. When overwash occurs, flow will concentrate in this low topography as a confined flow. Consequently, washover sediments are transported and deposited much farther inland, leading to the construction of a perched fan.

At BT, the beach configuration is gently uniform and the backshore topography displays a wide swale, thus promoting an unconfined flow (Fig. 11a). Therefore, when the overwash occurred during the storm event, the washover terrace was constructed at the backshore and continuously deposited into the swale as a wide band over a distance of 600 m parallel to the shoreline. In contrast, at LT and MR, the beach morphology and backshore topography are different. The beach configuration at LT is moderately uniform and the backshore topography is densely covered by pine trees (Figs. 11b and 7c). The non-uniform beach configuration and pine trees at the backshore are an obstruction to the overwash flow, resulting in a change of flow condition to be a confined flow, which resulted in the construction of a perched fan along the non-uniform beach zone at LT.

At MR, the beach configuration in the northern and southern parts is wider than elsewhere, whereas the middle part presents a narrow beach barrier. The surface elevation is slightly lower than the northern and southern parts (Figs. 11c and 9e). Consequently, when the storm surge hit the coast, most damage area occurred in the middle part where the narrow beach barrier was present. As the barrier was breached, the flow from the storm surge may have concentrated at this location and caused the back-barrier area to flood rapidly. Subsequently, sheetwash lineations were constructed behind the breach and prograded into the tidal floodplain as far as 100 m from shoreline. This is similar to the occurrence of sheetwash features resulting from storm surge flow during an inundation regime, as reported by Sallenger (2000). Three months later, a storm surge occurred at MR again but the intensity was lower than in December 2010, as confirmed by the lower storm tide level. Therefore, the March 2011

Table 1
Summary of geomorphic setting, washover type, flow condition, and sedimentary characteristic in washover deposits from each area.

Features	Ban Takrop	Laem Talumphuk	Khao Mai Ruak 1st event	Khao Mai Ruak 2nd event
Topographic setting	Prograded shoreline	Sand spit	Beach barrier	Beach barrier
Backshore topography	Swale lower from beach ridge 2 m	Flat coastal plain higher than beach ridge	Tidal flood plain lower from beach ridge 2.5 m	Tidal flood plain lower from beach ridge 2.5 m
Erosional features	Beach erosion	Beach erosion, scour	Beach scarp, Breached barrier	Beach scarp
Storm impact regime	Overwash regime*	Overwash regime*	Inundation regime**	Overwash regime*
Flow confinement	Unconfined flow	Confined flow	Unconfined flow	Confined flow
Washover type	Washover terrace	Perched fan	Sheetwash	Perched fan
Deposit thickness	60–80 cm	15–20 cm	30 cm at crest of sand lineations	50–30 cm
Number of layers	11	3	-	12
Vertical grading in layer	Reverse grading	Normal grading	-	Reverse grading
Sedimentary structure	Lamination, foreset bedding, sub-horizontal bedding, wavy bedding	Horizontal bedding, dune bedform	-	Lamination, foreset bedding, sub-horizontal bedding
Bedding Inclination	Landward	Landward	-	Landward
Rip-up clasts	None	Present at bottom unit	None	None
Basal contact	Sharp contact	Sharp contact, erosional contact	Sharp contact	Sharp contact
Shell laminae	None	Common	None	None
Geometry	Sand sheet, lobate sand, thickness increasing in the depression	Lobate sand, landward thinning	Elongate narrow parallel to flow direction	Lobate sand, thickness increasing in the depression
Lateral deposition	Extensive	Patchy	Discontinuous	Patchy

* Overwash regime occurring when wave run up superimposed on the water level exceeds the beach or dune crest.
** Inundation regime occurring when the barrier or beach is completely flooded by seaward running water body.

storm surge flowed as the overwash regime. As the barrier had still not recovered from the prior storm surge, the March 2011 storm surge focused at the same breached barrier zone. This breach promoted the confined flow, thus the washover sediment was deposited as a small lobe perpendicular to shoreline similar to those of the perched fan type described by Morton and Sallenger (2003).

To confirm our findings on the relationship between topographic factors and the pattern of washover deposits, we visited the BT and MR areas again in early January 2012 soon after the storm surge induced by temporary strong NE winds in December 2011. This storm surge generated overwash flow across beach in the low-lying coastal area from Prachuap Khiri Khan to Narathiwat provinces. At BT, the new washover deposits were found in the backshore as a terrace pattern similar to those previously described from storm surge events in 2007 and 2008. The new 2011 washover terrace at BT deposited on top of the 2008 washover deposits and extended further inland to the distal part as washover lobes (Fig. 12a, b). At MR, we also observed the new washover deposit, resulting from December 2011 storm, as a perched fan shape which was similar to the March 2011 washover deposit (Fig. 12c, d). Many marine shells transported by overwash flow were still preserved in the distal part of perched fan. Similar pattern of washover deposit from the two events in the same coastal topographic condition as found at BT and MR confirmed that the coastal topography has influenced the specific patterns of washover deposit. The repeat in the same pattern of washover deposit from different storms in the same affected area has also been reported from the US coasts (Hardin et al., 1976; Morton and Paine, 1985; Morton and Sallenger, 2003).

However, the topographic condition is not the only factor that influenced the washover depositional pattern since we had found locations with the same narrow beach topography where new sediment was deposited as a perched fan on top of the sheetwash lineations. This observation suggested that the magnitude of the storm surge is also important. The sheetwash lineations from the December 2010 storm surge indicated the high magnitude of the storm surge where it had more power in breaching the beach barrier to a distance as far as 100 m parallel to the shoreline. In contrast, the new perched fan deposits on March 2011 were indicative of a lower magnitude of storm surge that did not cause any new scour to the beach.

According to the preserved types of washover deposits, the perched fan and washover terrace yield a similar geometry of sand sheet that showed a continuity of lateral deposition. In contrast, the geometry of sheetwash lineations was narrowed and elongated parallel to the flow direction resulting either from deposition of sand eroded from the adjacent beach/dune system or from the redistribution of sand eroded locally (Morton and Sallenger, 2003). As a result of the discontinuity in the lateral deposition, sheetwash lineations are more difficult to preserve and identify in the geological record when compared to perched fans and washover terraces.

4.2. Sedimentary characteristics of storm washover deposits

We found that the lateral discontinuity in the deposition of sheetwash lineation is one significant characteristic making it difficult for these features to be preserved. In this section, we focus mainly on the description of sedimentary characteristics found extensively within the perched fans and washover terraces.

Two types of sedimentary characteristics were identified from the three areas, including (i) a thick-bedded sand, 50–80 cm in thickness, showing multiple reverse grading layers and (ii) a medium-bedded sand with thickness ranging from 15 to 20 cm and showing multiple normal grading layers. This characteristic of multiple grading (reverse or normal) layers is also similar to the storm washover deposit characteristics reported from previous study elsewhere, as stated by Schwartz (1982), Leatherman and Williams (1983), Sedgwick and Davis (2003), Morton et al. (2007) from the USA and Switzer and Jones (2008b) from Australia. The formation of the thick-bedded sand with several sand laminae at BT and MR (see locations in Figs. 4 and 9) is thought to have been influenced by the coastal topography and a high energy flow of storm surge. At both places, the backshore topography is exhibited as a swale (at BT) and a wide tidal floodplain (at MR) with surface elevation of 2–2.5 m lower than the maximum beach ridge. These topographic conditions, especially the lower backshore topography, played a suitable role for trapping the sediment and allowing it to be deposited as a thick-bedded washover terrace and perched fan, as found at BT and MR, respectively (Fig. 11a, c). Additionally, the existence of a large swale behind the beach is also a good preservation zone for sediment arising from high energy processes, such as a storm and tsunami, to be deposited and last longer in the geological record (Phantuwongraj and Choowong, 2012).

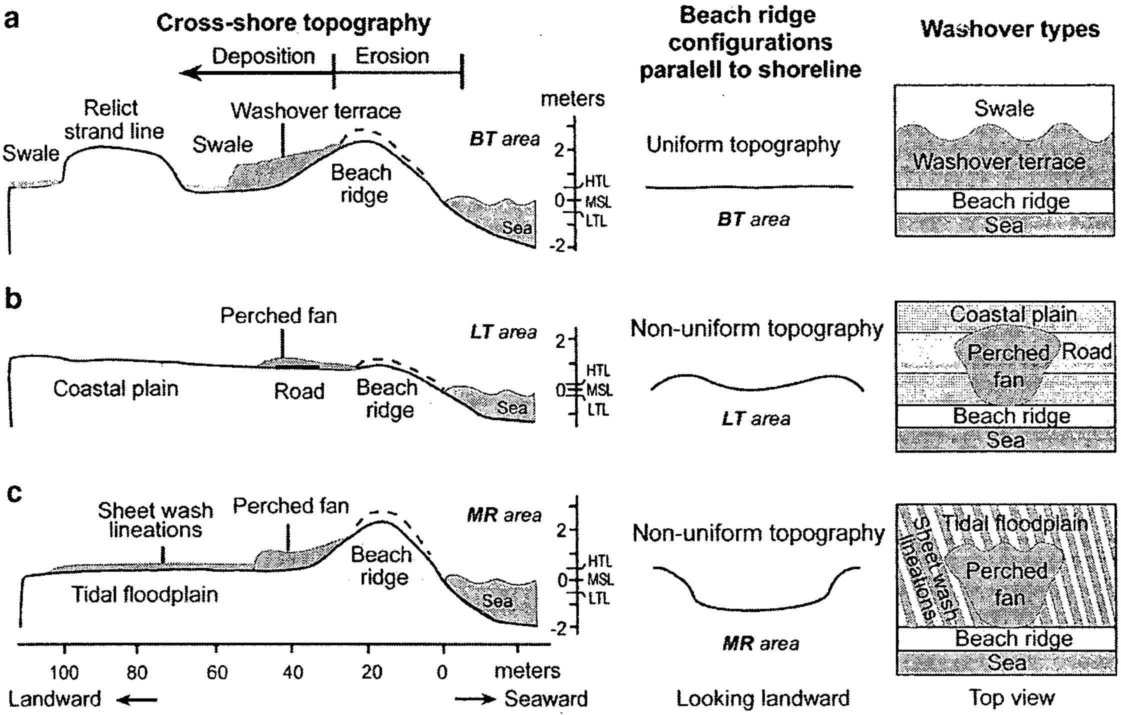

Fig. 11. Cross-shore topography and beach ridge configuration from three areas that control the preservation type and sedimentary characteristics of washover deposits. (a) A large swale behind the beach and uniform beach ridge configuration result in a washover terrace deposit at BT. (b) A flat and high coastal plain topography behind beach with a non-uniform beach ridge configuration results in perched fan deposits at LT. (c) The low-lying tidal floodplain behind the beach barrier associated with a non-uniform beach ridge configuration resulting in sheetwash lineations and perched fan deposition at MR. Beach ridge configurations (looking from seaward to landward) and washover preservation types (looking from top view). Cross-shore profile at BT is made from survey data, whereas BT and LT profiles are from qualitative sketch.

Reverse grading is one common feature observed in storm washover deposits, as previously reported by Schwartz (1975), Leatherman and Williams (1983), Sedgwick and Davis (2003), Morton et al. (2007), Phantuwongraj et al. (2008) and Spiske and Jaffe (2009). Leatherman and Williams (1983) proposed that reverse grading in washover sediments that show a heavy mineral layer at the base of units observed from the Atlantic coastline of USA resulted from an in situ sorting process which occurred when quartz and heavy minerals were initially deposited as a mixture, then post-depositional sorting allowed the heavy minerals to work their way through the matrix and become concentrated on the bottom of the unit. Sedgwick and Davis (2003) also found reverse grading in washover sediments from Florida, USA that show the concentrated heavy mineral in the unit which tended to be smaller in grain size than the overlying sediments. They described that this kind of reverse grading is a result of the basal concentrations of smaller heavy mineral particles that have settled out of flow before the quartz and carbonate fractions. At BT and MR, several sand laminae were found within the washover sediment, which are expressed as multiple reverse grading. These sand laminae, in which the grain size is smaller than the overlying sediments, were found at the base of each layer similar to the reverse grading in the washover sediment reported by Leatherman and Williams (1983) and Sedgwick and Davis (2003).

According to the sedimentary transport mechanism of storm deposition that is dominantly moved by traction processes (Morton et al., 2007), the sediments are thus concentrated at the base of flow. In this study, we suggest that the reverse grading in washover sediment may result from dynamic sorting during bedload transport under the condition of high grain concentration in the overwash flow. As the sediments are transported as traction load, the coarser grains preferentially roll over finer grains, thus resulting in reverse grading. Additionally, the sudden change of ground surface elevation about 2–2.5 m from the beach ridge to the behind low-lying swale during overwash may also induce the dynamic sorting of sediment as well. Each layer of sand with reverse grading at BT and MR reflects the pulsation of overwash flow in the overwash regime condition by the wave run-up superimposed on the water level exceeding the beach or dune crest.

In contrast, the beach ridge at LT is relatively small compared with BT and MR. The backshore topography also exhibited as flat coastal plain without swale (Fig. 11b). Small and narrow beach ridge implies that the volume of sediment supply to form the beach at LT was also relatively lower than that of BT and MR. Moreover, the flat and high topography behind beach is also not favorable for trapping the washover sediment. Therefore, when the overwash occurred, the washover sand was generated as medium-bedded sand with thickness ranging from 15 to 20 cm, which is thinner than BT and MR due to the limitation in sediment supply and the high and flat backshore topography (Fig. 11b). As suggested earlier, the high grain concentration and the backshore slope condition were thought to influence the occurrence of reverse grading at BT and MR, however at LT these two factors were totally ruled out. Due to the low grain concentration in the overwash flow and relatively uniform backshore topography, these conditions probably favored the formation of normal grading at LT area (Fig. 11b). The difference in washover preservation style and depositional characteristics are the result if the difference in coastal morphologies, vegetation types and densities and sediment properties, as stated by Wang and Horwitz (2007).

The sedimentary structures found in the thick-bedded washover deposits at BT and MR include sub-horizontal bedding, reverse grading, lamination, foreset bedding and wavy bedding. At LT, where washover deposition is exhibited as medium bedded, the sedimentary structures are composed of normal grading, horizontal bedding, rip-up clasts, and dune bedforms. These sedimentary structures are similar to the common sedimentary structures of storm washover deposits as stated earlier, except rip-up clasts that are not often reported for storm deposits. From our three study sites, washover successions were expressed in the inclined bedding in a landward

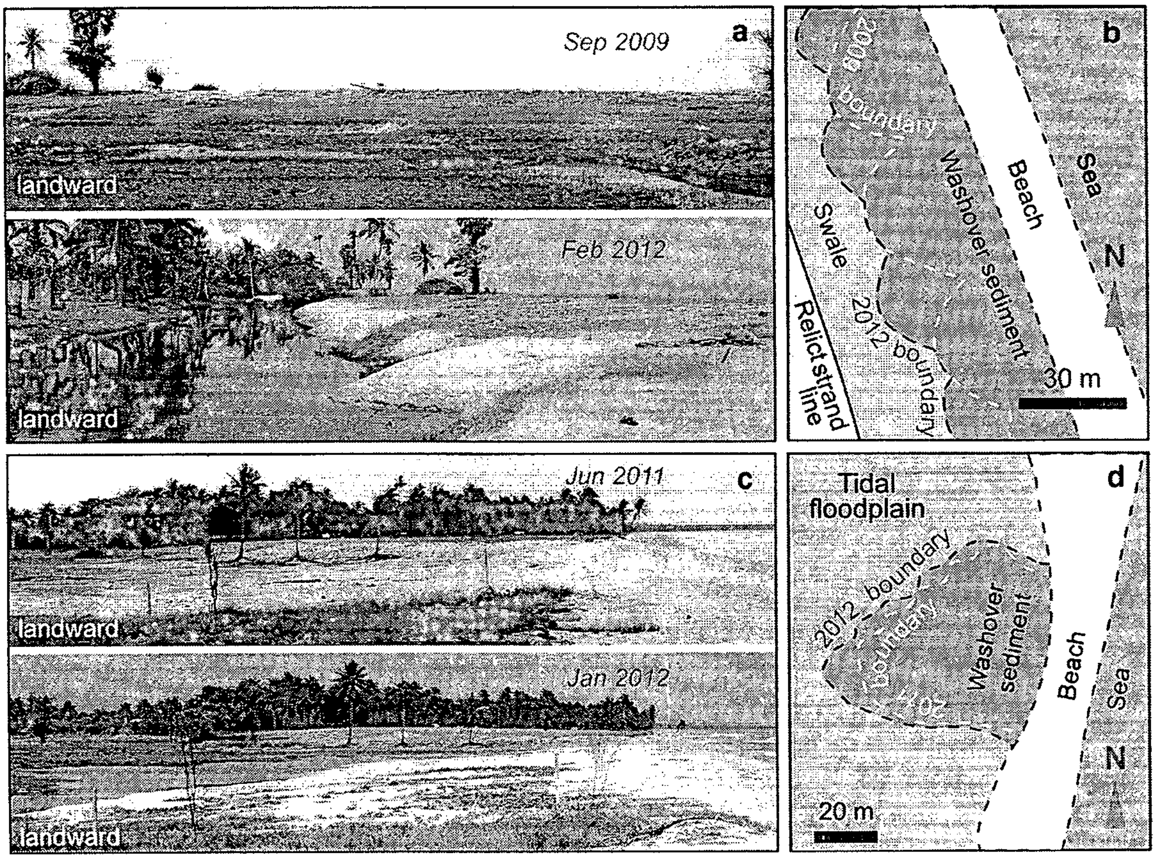

Fig. 12. Series of photographs taken from 2009 to 2012 and sketch maps showing similar pattern and shape of washover deposits in the same topographic area resulting from two different NE monsoon surge events. (a) Washover deposit as a terrace at BT resulting from the 2007, 2008 and 2011 NE monsoon surge. (b) Sketch map of BT area demonstrates the increase in landward penetration of washover sediment from 2009 to 2012. (c) Washover deposits as a perched fan shape behind beach at MR area which resulting from the 2010 and 2011 NE monsoon surge. (d) Sketch map of MR area demonstrates the increase in landward penetration of washover sediment from year 2011 to 2012.

direction with a basal sharp contacts that is commonly recognized as a typical feature of storm washover deposit elsewhere (e.g., Schwartz, 1975; Sedgwick and Davis, 2003; Wang and Horwitz, 2007).

The occurrence of similar sedimentary characteristics of storm washover deposits from Thailand and different places around the world confirms the same storm-induced processes that often result in the similar sedimentary characteristics. When comparing these typical storm depositional characteristics to the other high energy process, such as tsunami deposits, there are several features that also found in tsunami deposits, including normal grading, reverse grading, lamination, and landward inclination (e.g. Atwater and Moore, 1992; Hindson et al., 1996; Bondevik et al., 1997; Bourgeois et al., 1999; Clague et al., 2000; Nanayama et al., 2003; Nanayama and Shigeno, 2006; Higman and Bourgeois, 2008; Monecke et al., 2008; Sawai et al., 2009; Fujino et al., 2010; Naruse et al., 2010; Srisutam and Wagner, 2010). However, in this study we found some features that can be used to differentiate storm from tsunami deposits, including the number of layers, the multiple reverse grading layer, and foreset bedding structure. The number of layers in the storm deposits tended to be higher than in the tsunami deposits, which is confirmed by the eleven to twelve layers of storm deposits found in BT and MR, which is similar to the multiple layers of storm deposits found in USA and Australia (Morton et al., 2007; Switzer and Jones, 2008b). Furthermore, the multiple reverse grading layers and foreset bedding structure of storm washover deposits from BT and MR also suggested that these structures are more common in storm deposits than those we found in tsunami deposits, in agreement with those reported by Morton et al. (2007).

5. Conclusions

Small-scale washover sediments resulting from storm surges during 2007–2011 were observed from the southern part of Thailand at (1) BT, Surat Thani, (2) LT, Nakhon Si Thammarat, and (3) MR, Prachuap Khiri Khan on the eastern side of Thailand Peninsula. The geomorphic setting of these three areas included a prograded shoreline at BT, sand spit at LT and beach barrier at MR. Overwash flow induced by (i) temporary strong NE wind during the NE monsoon season in 2007–2010 and (ii) a low-pressure system in 2011 that occurred along the shoreline in the area where the coastal topography elevation is not higher than 2.5 m above the MSL. The maximum inundation distances from the storm surges are limited to 300 m from the shoreline. Three types of washover deposits, being perched fan at MR and LT, washover terrace at BT and sheetwash lineations at MR, were found behind the beach at a distance of 100 m from the shoreline.

The washover sediments displayed two types of sedimentary characteristics, (i) a thick-bedded sand, thickness ranging from 50 to 80 cm having multiple reverse grading layers and laminae at the bottom of each layer, as seen at BT and MR, and (ii) a medium-bedded sand, thickness ranging from 15 to 20 cm, which shows multiple normal grading layer, as seen at LT. The sedimentary structures found in the thick-bedded washover deposits at BT and MR included sub-horizontal bedding, reverse grading, lamination, foreset bedding and wavy bedding. Whereas, normal grading, horizontal bedding and dune bedform were common in the medium-bedded washover sand at LT. Rip-up clasts were also found in the washover deposit, particularly in the bottom unit where the mud supply was available. Washover successions were characterized by inclined bedding in a landward direction with a basal sharp contact.

Coastal topography, especially the beach configuration, which controls the flow condition during the overwash, was seemingly the major factor that influenced the preservation type of washover deposits behind the beach. A uniform beach configuration that promoted an unconfined flow was suitable for generating the washover terrace, as found at BT. In contrast, a non-uniform beach configuration that promoted a confined flow was appropriate for the formation of a perched fan deposit, as observed at LT and MR. However, the magnitude of storm surge can also influence the washover preservation type, as we observed perched fan deposits superimposed on sheetwash lineations in the same place at MR. The sedimentary characteristics of the washover successions were also influenced by the coastal topography, including the beach ridge elevation and backshore topography. A high beach ridge associated with a large swale at the backshore was suitable for trapping the sediment to form a thick-bedded sand of washover deposit, as recognized in 50–80 cm thick washover sediments at BT and MR. In contrast, a small beach ridge with a high and uniformly flat backshore topography promoted the deposition of a medium-bedded sand, as seen from the 15–20 cm-thick washover deposit at LT. Reverse grading at BT and MR was interpreted as a result of dynamic sorting during bed load transport influenced by a high grain concentration in the overwash flow and backshore slope condition. In contrast, at LT, low grain concentration and low backshore slope condition led to the formation of normal grading in the washover succession.

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References

Andrews, P.B., 1970. Facies and Genesis of a Hurricane Washover Fan, St. Joseph Island, Central Texas Coast. Report of Investigations, 67. Bureau of Economic Geology, University of Texas at Austin.

Atwater, B.F., Moore, A.L., 1992. A tsunami about 1000 years ago in Puget Sound, Washington. Science 258, 1614–1617.

Bondevik, S., Svendsen, J.I., Mangerud, J., 1997. Tsunami sedimentary facies deposited by the Storegga tsunami in shallow marine basins and coastal lakes, western Norway. Sedimentology 44, 1115–1131.

Bourgeois, J., Petroff, C., Yeh, H., Titov, V., Synolakis, C.E., Benson, B., Kuroiwa, J., Lander, J., Norabuena, E., 1999. Geologic setting, field survey and modeling of the Chimbote, Northern Peru, Tsunami of 21 February 1996. Pure and Applied Geophysics 154, 513–540.

Campbell, C.V., 1967. Lamina, laminaset, bed, and bedset. Sedimentology 8, 7–26.

Choowong, M., Murakoshi, N., Hisada, K., Charusiri, P., Daorerk, V., Charoentitirat, T., Chutakositkanon, V., Jankaew, K., Kanjanapayont, P., 2007. Erosion and deposition by the 2004 Indian Ocean tsunami in Phuket and Phang-nga provinces, Thailand. Journal of Coastal Research 23, 1270–1276.

Choowong, M., Murakoshi, N., Hisada, K., Charoentitirat, T., Charusiri, P., Phantuwongraj, S., Wongkok, P., Choowong, A., Subsayjun, R., Chutakositkanon, V., Jankaew, K., Kanjanapayont, P., 2008a. Flow conditions of the 2004 Indian Ocean tsunami in Thailand, inferred from capping bedforms and sedimentary structures. Terra Nova 20, 141–149.

Choowong, M., Murakoshi, N., Hisada, K.I., Charusiri, P., Charoentitirat, T., Chutakositkanon, V., JankaeW, K., Kanjanapayon, P., Phantuwongraj, S., 2008b. 2004 Indian Ocean tsunami inflow and outflow at Phuket, Thailand. Marine Geology 248, 179–192.

Clague, J.J., Bobrowsky, P.T., Hutchinson, I., 2000. A review of geological records of large tsunamis at Vancouver Island, British Columbia, and implications for hazard. Quaternary Science Reviews 19, 849–863.

Claudino-Sales, V., Wang, P., Horwitz, M.H., 2008. Factors controlling the survival of coastal dunes during multiple hurricane impacts in 2004 and 2005: Santa Rosa barrier island, Florida. Geomorphology 95, 295–315.

Davis Jr., R.A., Andronaco, M., Gibeaut, J.C., 1989. Formation and development of a tidal inlet from a washover fan, west-central Florida coast, USA. Sedimentary Geology 65, 87–94.

Deery, J.R., Howard, J.D., 1977. Origin and character of washover fans on the Georgia Coast, USA. Gulf Coast Association of Geological Societies Transactions 27, 259–271.

Fujino, S., Naruse, H., Matsumoto, D., Sakakura, N., Suphawajruksakul, A., Jarupongsakul, T., 2010. Detailed measurements of thickness and grain size of a widespread onshore tsunami deposit in Phang-nga Province, southwestern Thailand. Island Arc 19, 389–398.

Gelfenbaum, G., Jaffe, B., 2003. Erosion and sedimentation from the 17 July, 1998 Papua New Guinea tsunami. Pure and Applied Geophysics 160, 1969–1999.

Goff, J., McFadgen, B.G., Chague-Goff, C., 2004. Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. Marine Geology 204, 235–250.

Hardin, J.D., Sapp, C.D., Emplaincourt, J.L., Richter, K.E., 1976. Shoreline and Bathymetric Changes in the Coastal Area of Alabama. Information Series, 50. Geological Survey of Alabama.

Hayes, M.O., 1967. Hurricanes as geological agents: case studies of Hurricanes Carla, 1961, and Cindy, 1963. Report of Investigations, 61. Bureau of Economic Geology, University of Texas at Austin.

Higman, B., Bourgeois, J., 2008. Chapter 6 — Deposits of the 1992 Nicaragua Tsunami. In: Shiki, T., Tsuji, Y., Yamazaki, T., Minoura, K. (Eds.), Tsunamiites. Elsevier, Amsterdam, pp. 81–103.

Hindson, R.A., Andrade, C., Dawson, A.G., 1996. Sedimentary processes associated with the tsunami generated by the 1755 Lisbon earthquake on the Algarve coast, Portugal. Physics and Chemistry of the Earth 21, 57–63.

Jankaew, K., Atwater, B.F., Sawai, Y., Choowong, M., Charoentitirat, T., Martin, M.E., Prendergast, A., 2008. Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand. Nature 455, 1228–1231.

Kahn, J.H., Roberts, H.H., 1982. Variations in storm response along a microtidal transgressive barrier-island arc. Sedimentary Geology 33, 129–146.

Komatsubara, J., Fujiwara, O., Takada, K., Sawai, Y., Aung, T.T., Kamataki, T., 2008. Historical tsunamis and storms recorded in a coastal lowland, Shizuoka Prefecture, along the Pacific Coast of Japan. Sedimentology 55, 1703–1716.

Kortekaas, S., Dawson, A.G., 2007. Distinguishing tsunami and storm deposits: an example from Martinhal, SW Portugal. Sedimentary Geology 200, 208–221.

Leatherman, S.P., Williams, A.T., 1977. Lateral textural grading in overwash sediments. Earth Surface Processes and Landforms 2, 333–341.

Leatherman, S.P., Williams, A.T., 1983. Vertical sedimentation units in a barrier island washover fan. Earth Surface Processes and Landforms 8, 141–150.

Monecke, K., Finger, W., Klarer, D., Kongko, W., McAdoo, B.G., Moore, A.L., Sudrajat, S.U., 2008. A 1,000-year sediment record of tsunami recurrence in northern Sumatra. Nature 455, 1232–1234.

Morton, R.A., 1976. Effects of Hurricane Eloise on beach and coastal structures, Florida Panhandle. Geology 4, 277–280.

Morton, R.A., 1978. Large-scale rhomboid bed forms and sedimentary structures associated with hurricane washover. Sedimentology 25, 183–204.

Morton, R.A., 2002. Factors controlling storm impacts on coastal barriers and beaches: a preliminary basis for near real-time forecasting. Journal of Coastal Research 18, 486–501.

Morton, R.A., Paine, J.G., 1985. Beach and vegetation-line changes at Galveston Island, Texas. Erosion, Deposition, and Recovery from Hurricane Alicia. : Geological Circular, 85. Bureau of Economic Geology, The University of Texas at Austin.

Morton, R.A., Sallenger Jr., A.H., 2003. Morphological impacts of extreme storms on sandy beaches and barriers. Journal of Coastal Research 19, 560–573.

Morton, R.A., Gelfenbaum, G., Jaffe, B.E., 2007. Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. Sedimentary Geology 200, 184–207.

Nanayama, F., Shigeno, K., 2006. Inflow and outflow facies from the 1993 tsunami in southwest Hokkaido. Sedimentary Geology 187, 139–158.

Nanayama, F., Shigeno, K., Satake, K., Shimokawa, K., Koitabashi, S., Miyasaka, S., Ishii, M., 2000. Sedimentary differences between the 1993 Hokkaido-nansei-oki tsunami and the 1959 Miyakojima typhoon at Taisei, southwestern Hokkaido, northern Japan. Sedimentary Geology 135, 255–264.

Nanayama, F., Satake, K., Furukawa, R., Shimokawa, K., Atwater, B.F., Shigeno, K., Yamaki, S., 2003. Unusually large earthquakes inferred from tsunami deposits along the Kuril trench. Nature 424, 660–663.

Naruse, H., Fujino, S., Suphawajruksakul, A., Jarupongsakul, T., 2010. Features and formation processes of multiple deposition layers from the 2004 Indian Ocean Tsunami at Ban Nam Kem, southern Thailand. Island Arc 19, 399–411.

Phantuwongraj, S., Choowong, M., 2012. Tsunamis versus storm deposits from Thailand. Natural Hazards 63, 31–50.

Phantuwongraj, S., Choowong, M., Chutakositkanon, V., 2008. Possible storm deposits from Surat Thani and Nakhon Si Thammarat provinces, the southern peninsular Thailand. In: Choowong, M., Thitimakorn, T. (Eds.), Proc Inter Sym on Geo Res and Envi of Asian Terranes, Bangkok, Thailand, pp. 395–399.

Phantuwongraj, S., Choowong, M., Silapanth, P., 2010. Geological evidence of sea-level change: a preliminary investigation at Panang Tak area, Chumphon province, Thailand. The 117th Annu Meet of the Geol Soc of Jpn, Toyama, Japan, p. 185.
Roy, P.S., 1990. Offshore minerals exploration in the Gulf of Thailand: review of Quaternary geology of the coast and offshore seabed in exploration area 2. Mission Report. UNESCO.
Sallenger Jr., A.H., 2000. Storm impact scale for barrier islands. Journal of Coastal Research 16, 890–895.
Sawai, Y., Jankaew, K., Martin, M.E., Prendergast, A., Choowong, M., Charoentitirat, T., 2009. Diatom assemblages in tsunami deposits associated with the 2004 Indian Ocean tsunami at Phra Thong Island, Thailand. Marine Micropaleontology 73, 70–79.
Schwartz, R.K., 1975. Nature and Genesis of Some Storm Washover Deposits. Technical Memo, 61. U.S. Army, Corps of Engineers, Coastal Engineering Research Center.
Schwartz, R.K., 1982. Bedform and stratification characteristics of some modern small-scale washover sand bodies. Sedimentology 29, 835–849.
Sedgwick, P.E., Davis, R.A., 2003. Stratigraphy of washover deposits in Florida: implications for recognition in the stratigraphic record. Marine Geology 200, 31–48.
Shanmugam, G., 2012. Process-sedimentological challenges in distinguishing paleo-tsunami deposits. Natural Hazards 63, 5–30.
Spiske, M., Jaffe, B.E., 2009. Sedimentology and hydrodynamic implications of a coarse-grained hurricane sequence in a carbonate reef setting. Geology 37, 839–842.
Srisutam, C., Wagner, J.-F., 2010. Tsunami sediment characteristics at the Thai Andaman Coast. Pure and Applied Geophysics 167, 215–232.
Switzer, A.D., Jones, B.G., 2008a. Large-scale washover sedimentation in a freshwater lagoon from the southeast Australian coast: sea-level change, tsunami or exceptionally large storm? The Holocene 18, 787–803.
Switzer, A.D., Jones, B.G., 2008b. Setup, deposition, and sedimentary characteristics of two storm overwash deposits, Abrahams Bosom Beach, Southeastern Australia. Journal of Coastal Research 24, 189–200.
Thieler, E.R., Young, R.S., 1991. Quantitative evaluation of geomorphological changes in South Carolina after Hurricane Hugo. Journal of Coastal Research 8, 187–200 (Special Issue).
Tkalich, P., Vethamony, P., Babu, M.T., Malanotte-Rizzoli, P., 2012. Storm surges in the Singapore Strait due to winds in the South China Sea. Natural Hazards. http://dx.doi.org/10.1007/s11069-012-0211-8.
Tuttle, M.P., Ruffman, A., Anderson, T., Jeter, H., 2004. Distinguishing tsunami from storm deposits in eastern North America: the 1929 Grand Banks tsunami versus the 1991 Halloween storm. Seismological Research Letters 75, 117–131.
Wang, P., Horwitz, M.H., 2007. Erosional and depositional characteristics of regional overwash deposits caused by multiple hurricanes. Sedimentology 54, 545–564.
Wang, P., Kirby, J.H., Haber, J.D., Horwitz, M.H., Knorr, P.O., Krock, J.R., 2006. Morphological and sedimentological impacts of Hurricane Ivan and immediate poststorm beach recovery along the northwestern Florida barrier-island coasts. Journal of Coastal Research 22, 1382–1402.
Wright, L.D., Swaye, F.J., Coleman, J.M., 1970. Effects of Hurricane Camille on the Landscape of the Brenton–Chandeleur Island Chain and the Eastern Portion of the Lower Mississippi Delta. Technical Report, 76. Coastal Studies Institute, Louisiana State University, Baton Rouge.

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Geomorphology and Ground Penetrating Radar Profiles of Holocene Coastal Dune, Western Coastal Plain of the Gulf of Thailand

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Abstract

At Bang Berd Bay, a remarkable wind blown sand dune lies almost parallel to the present coastline with its highest elevation about 20 m above the present mean sea level. The formation of sand dune here has not yet concluded. This paper shows a result of Ground Penetrating Radar (GPR) to visualize the invisible dune structures as well as applying a remote sensing data to map the distribution. As a result from aerial photograph interpretation, dune morphology shows a majority of parabolic and transverse patterns. GPR profiles revealed some obvious macro-scale sedimentary patterns, clear boundary of dune overlying on the prograded beach ridge plain. Based on macro-scale sedimentary patterns, lee and stoss angles of some burial dunes from GPR signals and dune morphology indicated the direction of wind blown mainly from the east to the west. Series of beach ridges underneath sand dune indicated seaward progradation. This seaward progradation of beach ridges inferred its formation possibly after the mid-Holocene highstand. Thus, the formation of dune may have occurred during a dry condition probably during and after the mid-Holocene regression. OSL datings also reveal that the upper part of dune profile depth at 1-3 m formed between 2,220 to 2,960 years ago.

Keywords: Coastal dune, dune formation, Holocene, GPR

1. Introduction

The distribution of wind blown sand dune in the western coastal plain of the Gulf of Thailand is very limited and left behind some significant geological challenges for the explanation of its formation in relation with the past climate condition. Thus, this study is aimed to characterize sand dune morphology and sedimentology as the basic geological clues for explaining its formation. The GPR is also applied to visualize internal dune structures.

At Bang Berd Bay, a remarkable wind blown sand dune lies almost parallel to the present coastline with its highest elevation about 20 m above the present mean sea level. The highest elevation of dune is generally located in the south of Bang Berd Bay and decreased both altitude and its extension to the north ending at the northern headland.

Bang Berd sand dune is located at Bang Berd Bay, Pathio district, Chumphon province, in the western coast of the Gulf of Thailand (figure 1).

2. Methods

Ground-penetrating radar (GPR) is a geophysical method that basically uses radar pulses to image the subsurface morphology. The GPR images are also available to document and enhance the macro-scale internal dune structures both within the dune itself and the beach deposition underneath. GPR was undertaken for the first time at Bang Berd sand dune during October 2008. In this study, Plus 200 MHz GPR was used. The radar frequency and the properties of sand dunes limited the penetration of the radar signal to the uppermost 5 m. The reflections are recorded in real time and displayed on a monitor in the field to provide real-time data quality. During the survey, traces were collected every 0.50 m. A survey shore-normal and shore-parallel transect were 12 lines, with a total length of 1,510 meters (figure 1) were also assigned to characterize the continuity of deposit, boundary between beach and dune and thickness of dune. Basically, GPR lines were conducted along – transects oriented parallel and perpendicular to the dune's downwind axis. Transects parallel to the prevailing wind are labeled as GPR 4, GPR 5, GPR 7, GPR 9, GPR 10, GPR 11, and GPR 12. Transects perpendicular to the prevailing wind are labeled GPR 3, GPR 6, GPR 8, GPR 13, and GPR 14. Consequently, the profiles were not extended onto the slip-face.

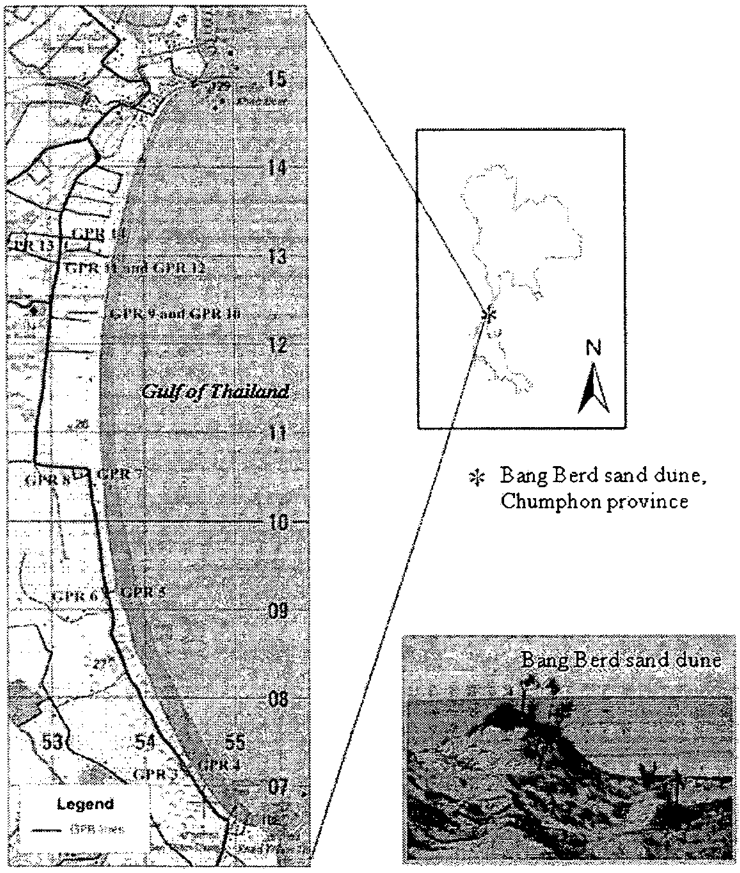

Figure 1. Bang Berd sand dune is located at Pathio district, Chumphon province, the western coast of the Gulf of Thailand. GPR lines survey was conducted along – transects oriented parallel and perpendicular to the dune's downwind axis, 12 lines (total length 1,510 m).

3. Results

3.1 Distribution of sand dune and dune morphology

As a result from aerial photograph interpretation, dune field distributes along the coastal plain mostly parallel to the present shoreline. In general, dune field can be subdivided into two zones; the coastal dune close to shore and the former dune close to swampy area in the west.

Coastal dune lies parallel to the shoreline in almost north-south trending with dimension of the dune body as wider as 500-600 m in the north and subsequently narrower to the south. Dune in the northern part of the area owns very low elevation with small irregular topography in comparison with the southern part. However, the widest dune field is recognized in the middle part of the area where the highest elevation reached about 20 m above the present mean sea level. Dune in the southern part becomes narrow but the elevation is somewhat equivalent to dune in the middle part. Old sand dune is interpreted to overly on top of the former beach deposits with its wider distribution than those younger dunes.

Dune morphology shows a majority of parabolic and transverse patterns. Star shapes were rarely and locally recognized (figure 2). Most of dune morphology indicated the direction of wind blown mainly from the east to the west.

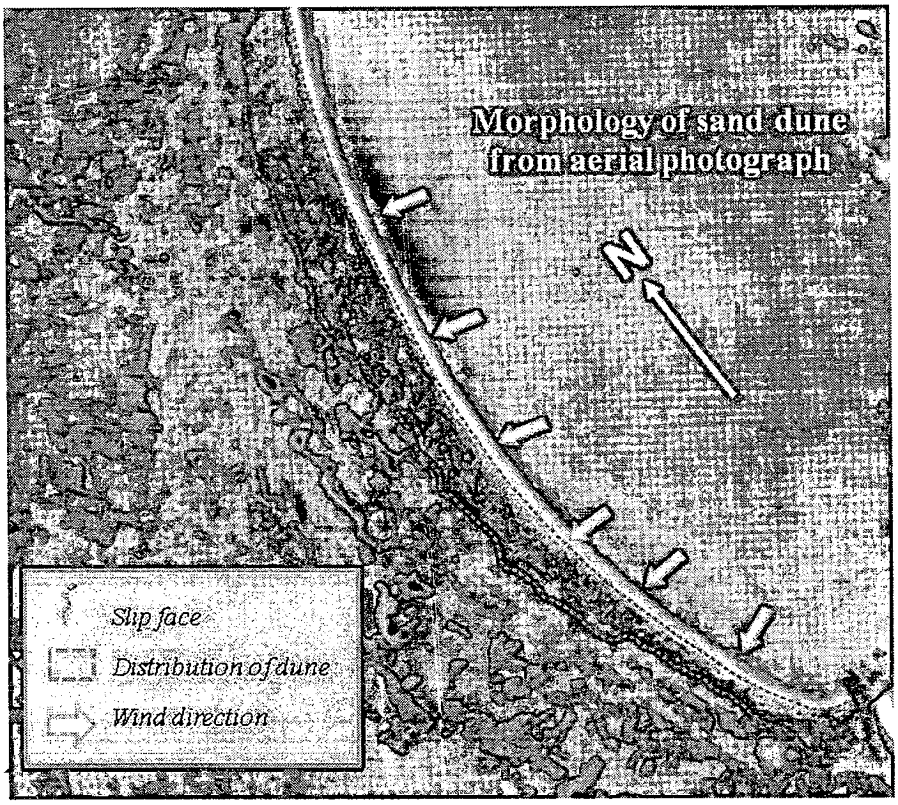

Figure 2. Patterns of sand dune with their distributions. Parabolic shape dominates in the outer part of dune field close to shore; transverse pattern is dominates in the western end of dune field and star pattern is locally recognized in the southern portion.

3.2 Ground Penetrating Radar

The characteristic reflection patterns of radar signal related to depositional environment from this dune field is mainly followed by Overmeeren (1998), Neal (2004), Hogenholz and Moorman (2007) and correlate with logging data from DMR (2006) and hand augers drilling.

3.2.1 GPR profiles oriented parallel to the prevailing wind

The resolution in the radargrams was sufficient enough to view in detail the internal sedimentary structures. Most of profile shows the clear contact between marine sediments on bottom and eolian sediment on top. The characteristics of marine sediment are classified into 2 types. The first is beach ridge (unit B1) generally dip seaward and littoral deposit (unit B2) (Figure 3). Within unit B1, radar profiles of GPR 9 and GPR 10 showed the sharp contact between three different dune generations (unit D1, D2 and D3) by third order bounding surface (Figure 4). All sub-units represents to coastal sand dune with cross-bedding in foresets and bounding planes. Sets of foreset dipping are rather steeply to the east. Major slip-faces are inclined to the western part of dune, representing the probable major direction of wind blown of its formation was from the east to the west. Although, radar signals at the top most of the dune in some places were chaotic, but they represented the winds have changed the direction seasonally. The water table was also detected and its depth was checked by measuring the depth from hand auger drilling and DMR logs (2006). The regional water table can be related with continuous high-amplitude reflection inside the beach ridge structure (Figure 4). Channel filled deposit (unit C) underneath beach ridges (Figure 5), is described as the trough-shaped reflections that possibly belong to braided small channels. Gravels are also found in this channel-filled deposit.

3.2.2 GPR profiles oriented perpendiculars to the prevailing wind.

GPR transects of the actively migrating on crest of dune showed the characteristic of coastal sand dune with cross-bedding in foresets and bounding planes. Sets of foreset dipping are rather steeply both to the north and the south. Profiles in GPR 13 and GPR 14 showed the contact between marine sediments on bottom and eolian sediment on top. Radar signals of beach ridges are sub-parallel and continuous.

3.2.3 Radar surfaces, Packages, and Facies

Radar lines along the windward slope and the crest of dune revealed a downwind dipping foreset bedding plane to which this structure is commonly recognized in the parabolic dunes, as well as other features visible within and below the dunes.

From the foregoing description of the radar profiles, those features of internal structures within the dune are possible to distinguish into GPR units using the principles of radar stratigraphy, which relies on the identification of systematic terminations or boundaries, to qualitatively classify different reflection patterns from the profiles. This classification is the first used of GPR facies in this area and can be served as a basis for the comparison with the other future dune studies. Parabolic dune description here may also serve as a reference for comparing with other dune morphology elsewhere along this coastal area.

The main feature from the radar profiles can be classified into 2 radar surfaces, 2 radar packages and 5 radar facies (figure 6). A qualitative scene was used to describe the relative dip of reflections because, however, it is not know whether or not the migration produced accurate dip angles (i.e., high-, moderate-, and low-angel). It is important to recognize that the discrimination of sedimentary surfaces, packages, and facies is highly subjective and dependent in the term of reference. The classification of radar surface in this paper is mainly followed the terminology proposed by Neal (2004) and Hogenholz et al. (2007) in order to identify and describe the main radar surfaces, packages, and facies.

Radar surfaces are termed as the bounding surfaces and represent depositional breaks or unconformities in the sedimentary sequence. Radar packages are depositional units consisting of genetically related strata that are bounded top and bottom by radar surfaces or bounding surfaces. Radar facies are comprised of sets or reflections with distinctive shapes, dip, and continuity that represent the bedding and internal structure of a sedimentary facies (Neal, 2004; Hogenholz et al. (2007).

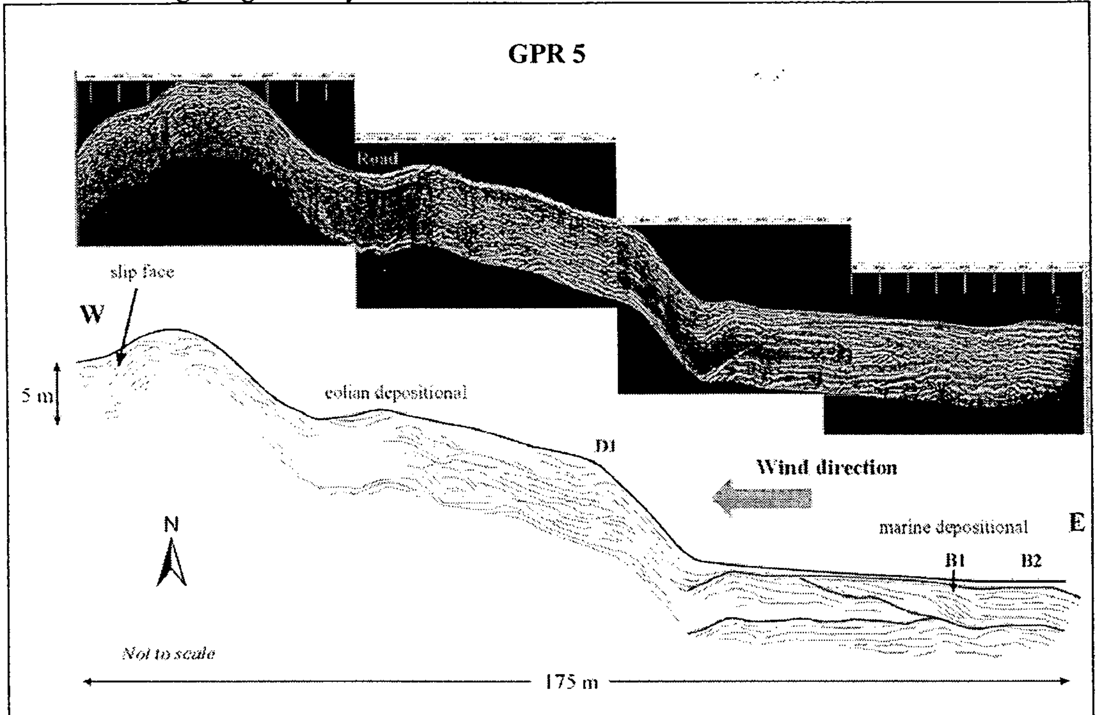

Figure 3. GPR 5 was conducted along – transects oriented parallel to the dune's downwind axis. The characteristics of marine sediment are beach ridge (unit B1) generally dip seaward and littoral deposit (unit B2) horizontal layer. Slip-faces of dune represent the probable direction of wind blown from the east to the west.

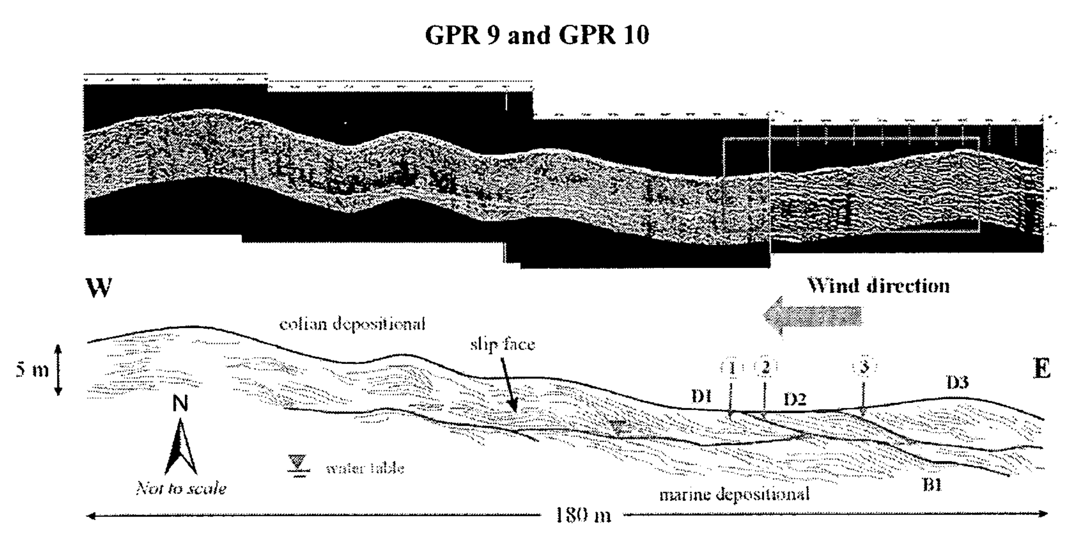

Figure 4. GPR 9 and GPR 10 were conducted along – transects oriented parallel to the dune's downwind axis, showing the contact between three different dune generations (unit D1, D2 and D3) by third order bounding surface (mark 1, 2 and 3 in picture). Direction of wind blown was expected from the east to the west.

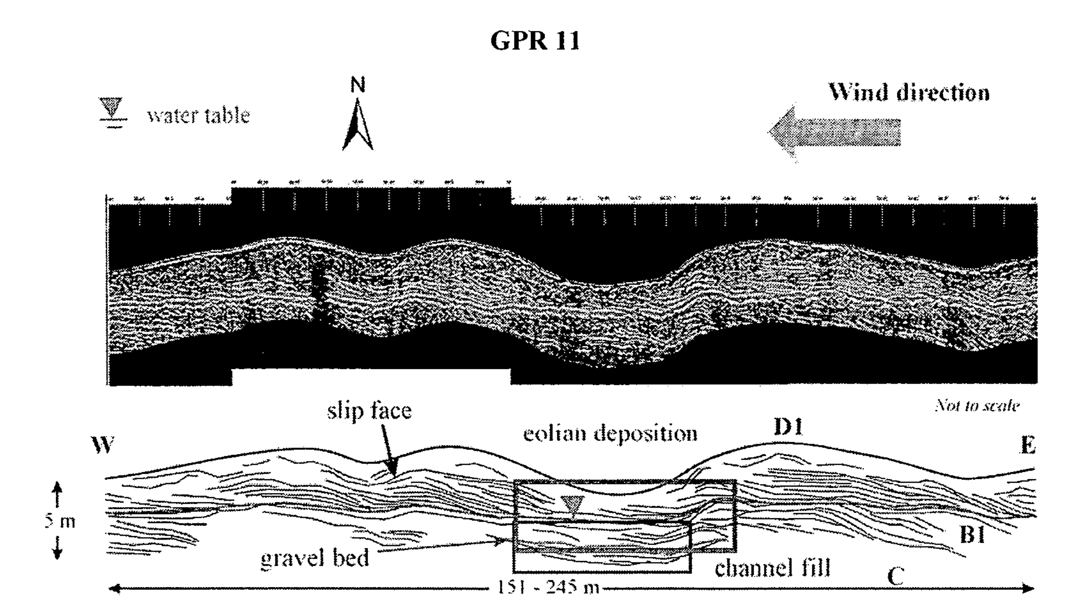

Figure 5. GPR 11 was conducted with orientation parallel to the dune's downwind axis, showing a trough shape underlie beach ridges represent to channel fill deposit (unit C). Direction of wind blown was expected from the east to the west.

In this survey, the two radar facies are classified as the concordant (Rs1) and the erosional truncation (Rs2). The two radar packages are spur (Rp1) and trough (Rp2) and the other 5 radar facies included a planar (Rf1a) and wavy (Rf1b) representing the reflection configuration of shape. High angel planar (Rf2b) and high-oblique angel tangential (Rf3b) represented the reflection configuration of dip.

Result from GPR showed some obvious macro-scale sedimentary patterns, especially the lateral and vertical extensions of the older dune superimposed by the younger one. Clear boundary of dune and the underlain prograded beach ridge plain is also detected from GPR. Based on macro-scale sedimentary patterns, lee and stoss angles of some burial dunes ascribed mainly two directions of wind. First was formed by wind blown from the north to the south and second was in almost northwest to southeast direction. This result in analyzing wind direction based on GPR signals is corresponded well with dune morphology interpreted from aerial photographs and the modern record of wind blown direction.

3.2.4 Radar facies from GPR

Stratigraphy units from the radargrams are shown as eolian deposit, marine deposit and channel fill deposit. Eolian deposits have signal represent to grain movement to form dune, comprised of sets of reflection with distinctive shape, dip and continuity that represent the bedding and internal structure of a sedimentary facies. Eolian unit can be identified by third order bounding surface (mark 1, 2 and 3 in figure 4.6), divided in to three sub-units are D1, D2, D3 represent to three phases of sedimentation. Eolian unit D1 is depositional history appears to be of more complex nature, judging by variation of the foresets dips inside D1. Units D2 and D3 shows dip angles about 30° in W-E direction. Therefore, judging by the similarities of the foresets dips inside D1, D2 and D3, the prevailing past wind was probably from the east to the west.

The horizontal layer of littoral deposit from GPR signal can correlate with the profile of sand sheet at the coastal, northern study area. The characteristic of seaward prograded can define to beach ridge. Sediments from dune and beach ridges are differentiable by characteristics of sand sediments, especially color. A trough-shaped reflection underlies beach ridges layer, correlated with the core logging of DMR (2006) can define to channel fill deposits. Radar surface is occurs between layer of dune deposit, marine deposit and channel fill deposit, represent depositional breaks or unconformities in the sedimentary sequence.

3.3 Optically Stimulated Luminescence (OSL) dating

Samples for OSL dating were taken from the topmost layer (depth at 1-3 m from surface) of dune profile. Result of OSL dating of sand grains indicates the age of dune deposited between 2,220 to 2,960 years ago.

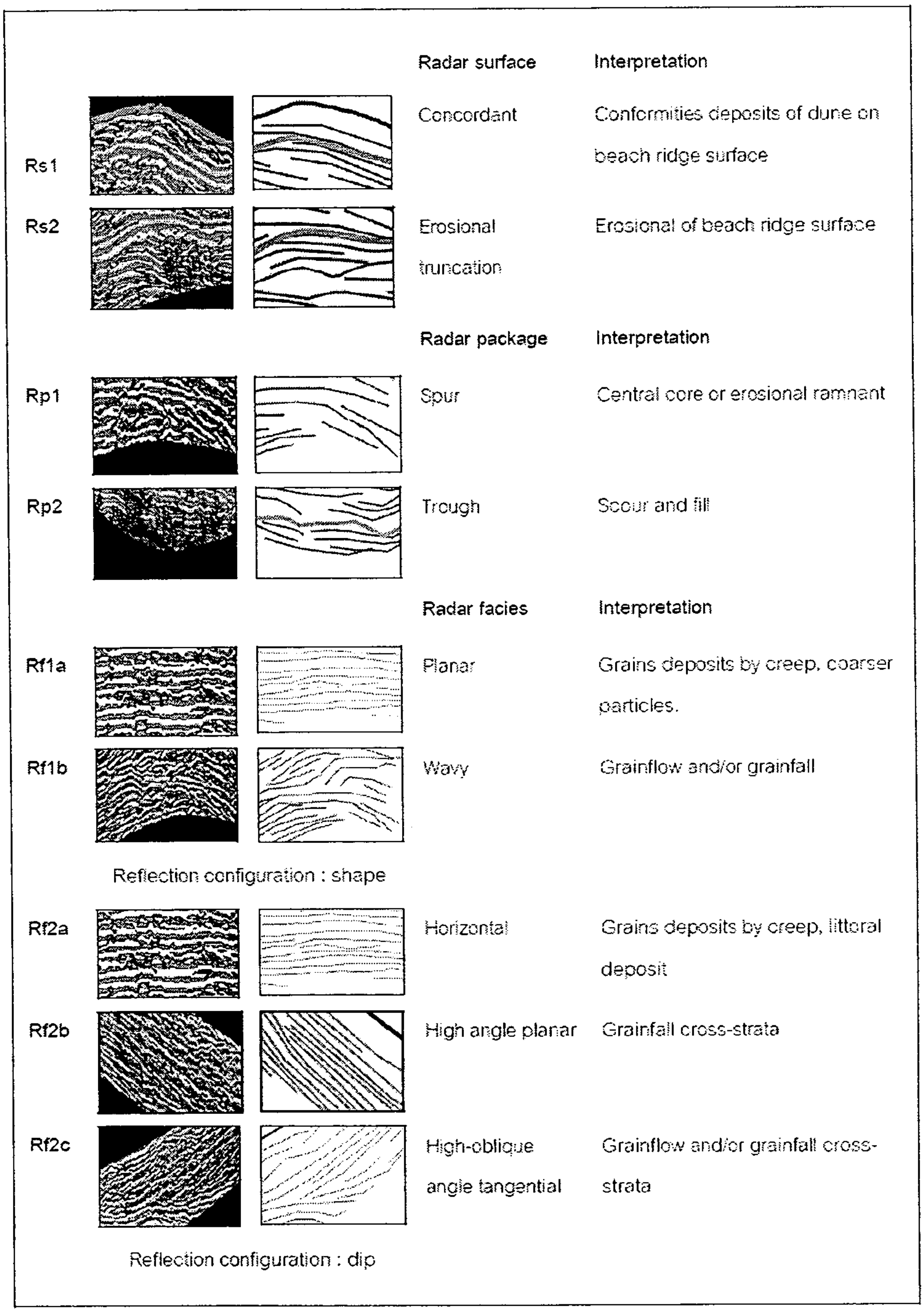

Figure 6. Main feature from the radar profiles can be classified into 2 radar surfaces. They are concordant (Rs1) and erosional truncation (Rs2). Two radar packages are spur (Rp1) and trough (Rp2) and five radar facies included a planar (Rf1a), wavy (Rf1b), horizontal (Rf2a), High angel planar (Rf2b) and high-oblique angel tangential (Rf3b).

4. Discussions

4.1 Wind-blown directions

Dune morphology and orientation detected from aerial photograph indicated a majority of parabolic and transverse patterns, whereas, star shapes were rarely and locally recognized. They formed under the condition that the wind energy was able to carry sediments from the beach in a landward direction and deposited them wherever an obstruction hinders further transportation. Source of sediment supply to form the dune was likely the key limiting factor in the explanation of dune development of this area. However, most of dune shapes indicated the major directions of wind blown from the east to the west.

It is interesting that dunes in this area formed where the constructive waves encouraged the accumulation of sand, and where prevailing onshore winds possibly blown this sand inland. There needed to be obstacles (e.g. vegetation, pebbles etc.) to trap the moving of sand grains. As the sand grains got trapped they started to accumulate, starting dune formation. The wind then started to affect the mound of sand by eroding sand particles from the windward side and depositing them on the leeward side. Gradually, this action caused the dune to migrate inland as it did so it accumulated more and more sand.

This work proofed that the GPR survey over the surface of an inactive parabolic sand dune in Bang Berd, Chumphon province provided excellent detail of the macro-scale internal structures within the dune itself and beach deposits. The radar was able to resolve a variety of high-angle, low angel, and curved reflections that are interpreted as the primary sedimentary structures. Radar profiles parallel to the direction of migration also revealed a complex arrangement of cross-strata that reflects different phases in the development of dune. Major slip-faces are found from the western part of dune, representing the possible major direction of wind blown of its formation from the east to the west.

4.2 Dune formation

The recent environmental history of coastal dune systems from Bang Berd, Chumphon province, has been examined using the combination of result from geomorphological, GPR, sedimentological and OSL dating techniques. Dune stratigraphies were determined mainly from 10 GPR survey lines. All dunes here are associated with the regressive shorelines consequently upon a fall in relative sea level (RSL) from its Holocene highstand peak, and indicated RSL functioned as a macro-scale control on dune development. Where dunes are anchored on terrestrial sediment, dune expansion may have been either transgressive or regressive in nature. Where near-shore marine sediments formed the dune substrate, a regressive (prograding) dune model seems most likely. Most dune building occurred probably in association with specific climatic and morpho-sedimentary conditions, principally periods of easterly circulation, a greater frequency of severe Gulf of Thailand storms, RSL fall, and sediment and accommodation space availability. The majority of dune formation here is, therefore, inferred to have formed in the early Holocene.

Stabilized parabolic sand dunes are extensive in the northern part of Chumphon province. Orientations of the parabolic dunes indicated a paleo-wind blown from the east to west. The age of dune formation (2,220-2,960 years ago) also confirmed its formation continued to the late Holocene to which an earlier dry phase is expected to cause the extensive eolian sands. The underlied parabolic dunes are likely formed during the early to middle Holocene; whereas some are currently exposed to the surface. Some of these older sands may represented the dry environment during the mid-Holocene where the river distributaries are rejuvenated leading to an increase in the supply of sand and silt. Meanwhile, beaches are widened and beach ridge dunes may possibly be able to form.

4.3 Possible sources of sand dune

Based on dune sedimentology, GPR and aerial photographs, the major sources of fine to very fine-grained sand to form a majority of parabolic dune here are possibly from the dry Quaternary sediments locating in the western and the northwestern parts of the bay. Series of prograded beach ridges underneath sand dune indicated seaward deposition. This seaward progradation of beach ridges are inferred its formation after the mid-Holocene highstand (Choowong et al., 2004). Thus, the formation of dune may have occurred during a dry condition probably during and after the mid-Holocene regression (Havholm et al., 2003; Orford et al, 2003; Pederson and Clemmensen, 2005; Tamura et al, 2008).

5. Conclusion

The goal of this paper is to characterize sedimentology and morphology of sand dune in the study area for evaluating the possible sources of dune and build up model dune formation of study area. Results of study are concluded as follows:

(a) Dune in this area showed a majority of parabolic pattern; whereas linear and star shapes are localized.

(b) Dune texture is characterized by very homogenous fine- to very fine grained sand mainly. Very rare micro-scale sedimentary structures were observed.

(c) Major direction of wind blown was expected from the east to the west direction.

(d) OSL datings in the top-half of sand dune profile revealed that the formation of this dune section was at around 2,220-2,960 years ago.

(e) Possible sources of Bang Berd sand dune are thought to come from the Quaternary sediments locating in the western and northwestern part of the bay, and transported to deposit by wind and the minor part on top of dune profile shows some clues of its formation during storms.

(f) Formation of dune may have occurred during a dry condition probably during and after the mid-Holocene regression.

6. Acknowledgements

The authors would like to thank the Department of Mineral Resources for the loan of GPR equipments, geological data, maps, aerial photographs. The faculty of science, Chulalongkorn University (A1B1) and the Thailand Research Fund (TRF) provided funds to M.C. Pailoplee. S is thanked for OSL dating and calculation. T. Charoentitirat, V. Chutakositkanon and A. Meesook are thanked for the discussions. Thanks are to S. Phantuwongraj for field assistance.

7. References

Choowong, M., Ugai, H., Charoentitirat, T., Charusiri, P., Daorerk, V., Songmuang, R. and Ladachart, R. 2004. Holocene Biostratigraphical Records in Coastal Deposits from Sam Roi Yod National Park, Prachuap Khiri Khan, Western Thailand. *The Natural History Journal of Chulalongkorn University* 4(2): 1-18.

Havholm, K. G., Bergstrom, N. D., Jol, H. M. and Running G. L. 2003. GPR survey of a Holocene aeolian/fluvial/lacustrine succession, Lauder Sandhaills, Manitoba, Canada. *The Geological Society of London:* 47-54.

Hugenholtz, C. H. and Moorman. 2007. Ground penetrating radar (GPR) imaging of the internal structure of an active parabolic sand dune. *The Geological Society of America:* Special paper 432: 35-45.

Neal, A. 2004. Ground-penetrating radar and its used in sedimentology: principles, problems and progress. *Earth-Science Review* 66: 261-330.

Orford, J. D., Murdy, J. M. and Wintle, A. G. 2003. Prograded Holocene beach ridges with superimposed dunes in north-east Ireland: mechanisms and timescales of fine and coarse beach sediment decoupling and deposition. *Marine Geology* 194: 47-64.

Overmeeren, R. A. 1998. Radar facies of unconsolidated sediments in The Netherlands: A radar stratigraphy interpretation method for hydrogeology. *Journal of applied geophysics* 40: 1-18.

Pederson, K. and Clemmensen, L. B. 2005. Unveiling past aeolian landscapes: A ground-penetrating radar survey of a Holocene coastal dune field system, Thy, Denmark. *Sedimentology Geology* 177: 57-86.

Tamura, T., Murakami, F., Nanayama, F., Watanabe, K. and Saito, Y. 2008. Ground-penetrating radar profiles of Holocene raised-beach deposits in the Kujukuri strand plain, Pacific coast of eastern Japan. *Marine Geology* 248: 11-27.

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Characteristic of Former Beach Ridge Plains from Remote Sensing Data at Chumphon Estuaries, Southern Thailand

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Abstract

Chumphon coastal zone in southern Thailand owns its very long coastline and the coastal area preserves spectacular geomorphological landforms especially beach ridge plains. The old set of beach ridge plain was recognized clearly from satellite images in which it is located almost 10 km far away inland from the present shoreline. This geographic setting of beach ridge plain can be inferred the rising and falling of sea-level in the past. Not only series of beach ridges we recognized, the old lagoon, old tidal flat, and old intertidal flat were also seen farther inland. They show the progradation seaward direction.

Keywords: Coastal geomorphology, Chumphon, Beach ridge plains

1. INTRODUCTION

The study in history of sea level change with close relation to the evolution of coastal landforms can be indicated from the progradation of beach ridge plains; the plains that were possibly deposited at the same time of the mid to late Holocene marine regression (Choowong et al., 2004). At Pak Nam, Chumphon there has been mentioned that the Holocene sea level transgression has reached about 10 km inland (Choowong, 2002b). Thus, the formation of coastal plain in this area may be related to the history of sea-level change and the evolution of the coastal landforms. Additionally, the western coastal area of the Gulf of Thailand, particularly at Chumphon exhibits various geomorphological differences which these geomorphological features may own its individual depositional style that reflected the difference in direction of longshore current.

2. OBJECTIVE AND METHODS

The interpretation of aerial photograph and satellite images is one practical way to recognize the orientation of beach ridge plain here at Pak Nam. Not only the recent geomorphology can be seen from the aerial photograph and satellite image, but the relict coastal landforms that are located far away inland can also be recognized clearly. The aerial photographs applied to this study are approximately 1:50,000 scales officially produced by the Royal Thai Survey Department, 1998 covering Amphoe Muang, Changwat Chumphon. The aerial photographs include the area number 0066, 0067 ,0068 ,0069, 0070, 0118, 0119, 0120, 0121 and 0122 (Figure 1). After aerial photograph interpretation, the coastal geomorphological mapping in the field was done with special attention to classify and describe each of interpreted landform. All maps were done by ArcMap program.

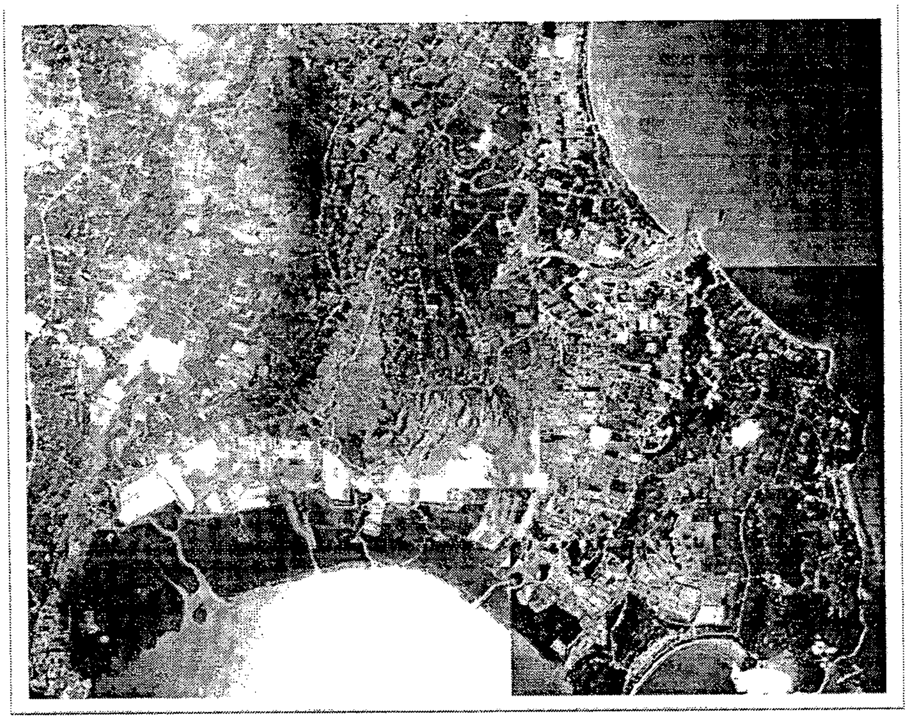

Figure 1. Mozaic of aerial photographs covering the study area (not to scale) (modified from Thai Survey Department, 1998).

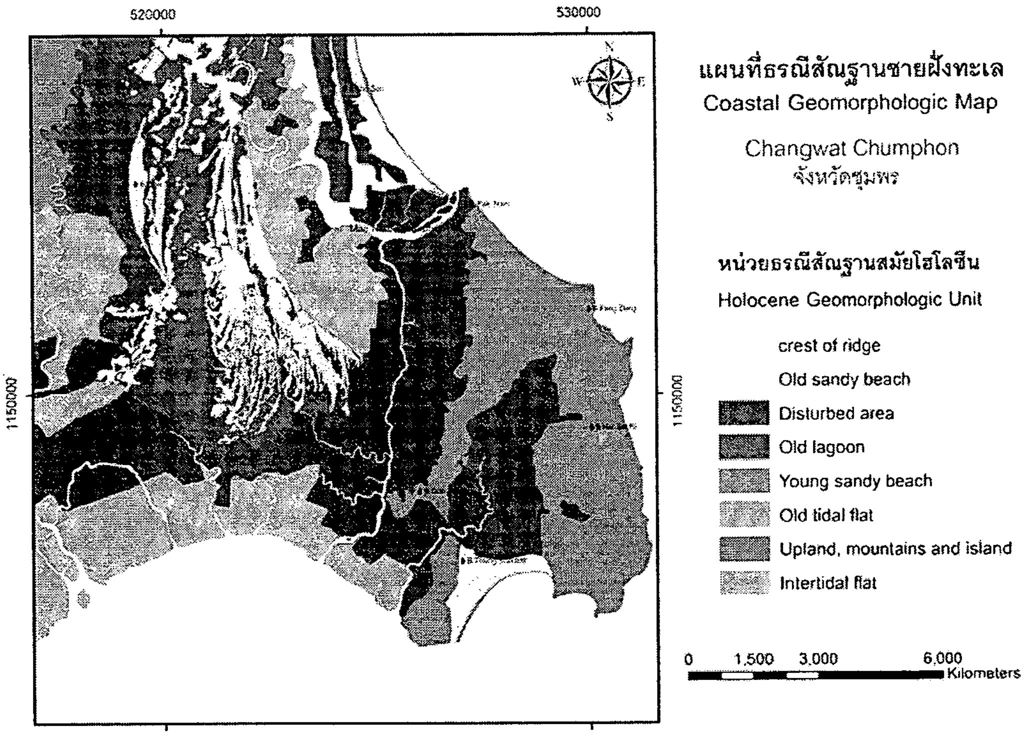

Figure 2. Interpreted coastal geomorphological map of Pak Nam Chumphon, Amphoe Muang, Chumphon.

3.1 Classification of landforms

The aerial photographs interpretation of geomorphological landform can be divided into 6 units as follows:

3.1.1 Old sandy beach

Three different beach ridges are re-defined as entirely wave formed deposits which are most commonly formed during high wave conditions and/or elevated water levels (Hesp et al., 2005). Old sandy beach ridge shows dark gray color curve line, and it branch out to many line in one series of beach ridge. It is irregular topography. We recognize at least 3 series of beach ridge plains here where they show different direction of longshore current. The direction of longshore current of the inner beach ridge series is oriented in northward direction and at the end it split into four small beach ridge lines. Longshore direction of the middle and outer beach ridge series changed to southward direction, and there is extensive of small beach ridges at the end of each series. The area in between beach ridges is commonly displayed as old lagoon. The elevation of former beach ridge is 4-5 m higher than the present beach at the shoreline.

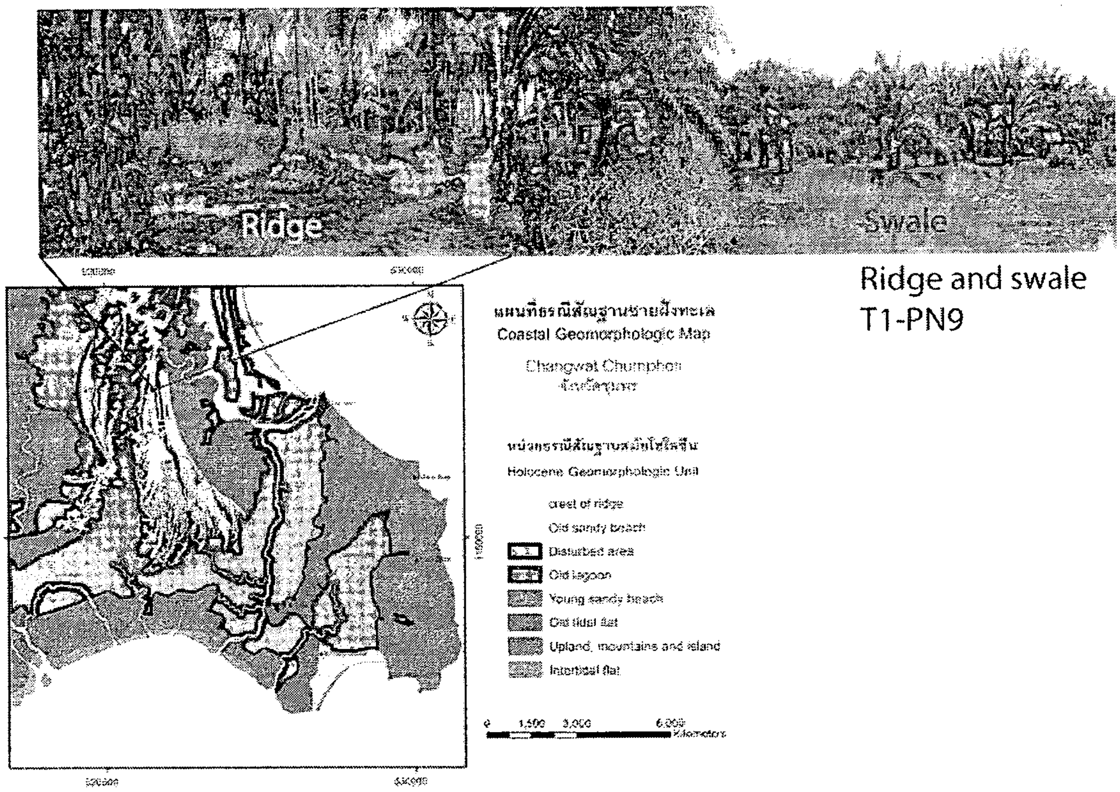

Figure 3. Old sandy beach (beach ridge) and old lagoon (disturbed swale) in inner ridge series.

3.1.2 Old lagoon

Old lagoon can be seen in light gray color and flat topography. The former lagoon in some regions is disturbed by aquaculture area (shrimp farm) and man-made canal. It is commonly located between old sandy beaches. This landform are composed of mud, sandy mud confound with shell, shell fragments and peat. Almost of old lagoon is being made as agriculture palm forest. Some areas we found oyster shell fossil and other shell fossil.

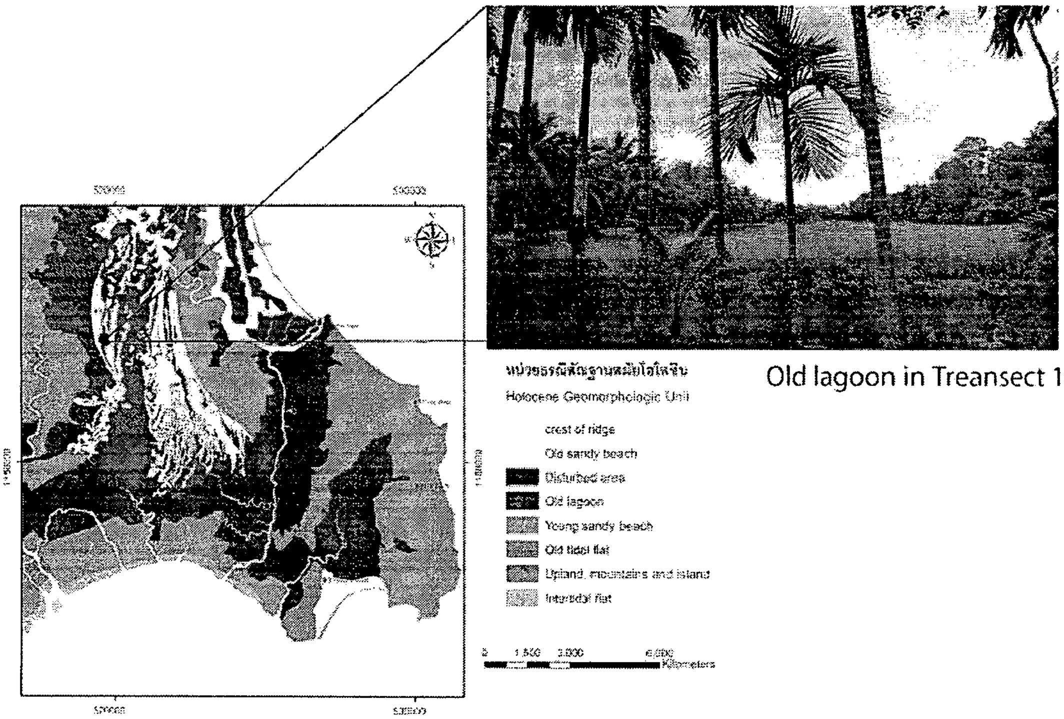

Figure 4. Old lagoon in between old sandy beaches is commonly composed of muddy sand and mud with some peat fragments.

3.1.3 Young sandy beach

Young sandy beach is white color, long and narrow line at the present shoreline. Its geomorphology is contributed by headland as Khao Matsi, and it is sandstone headland. Younger sandy beach is located at Ao Pak Hat, Hat Pharadon Phap, Had Sai Ree and Ao Thung Kham Yai. Young sandy beach is commonly gentle slope and is composed of laterite and lateritic granule. The younger beach ridges occur parallel with the shoreline.

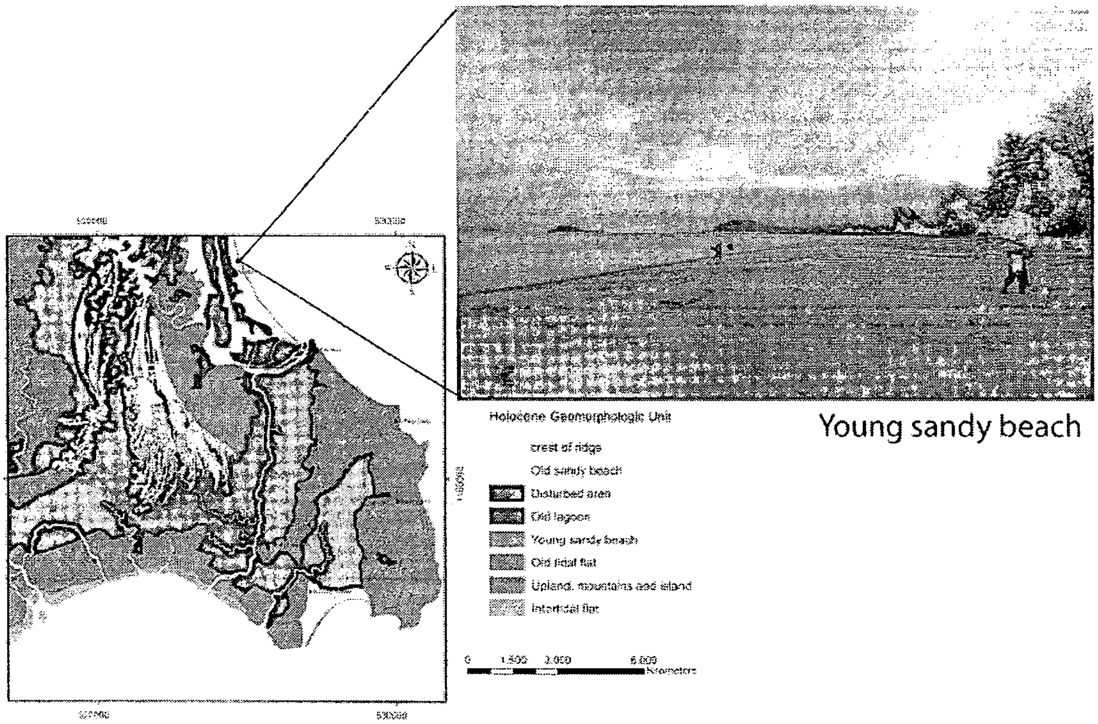

Figure 5. Young sandy beach in Ban Kho Son is gentle slope to seaward.

3.1.4 Old tidal flat

Old tidal flat can be seen in gray color and flat topography in aerial photo. This area has been affected by incursion of sea water via tidal inlet. Mud sediments with shell fragment are dominated. The evidence of shell fragments indicates former tidal flat environment (Sinsakul, 1988).

3.1.5 Mountains

Jurassic pebbly sand stone, sandstone, siltstone hill are exposed in the eastern part of the area. These mountains are in NE-SW area in Lam Thab Formation (Ridd, 2012).

3.1.6 Intertidal flat

Inter tidal flats can be seen in light gray color and are located in coastal wetlands. Inter tidal flat forms when mud is deposited by tides or rivers. Intertidal flat may be viewed geologically as exposed layers of bay mud, resulting from deposition of estuarine silts, clays and marine animal detritus. This geomorphological feature is composed of tidal channels.

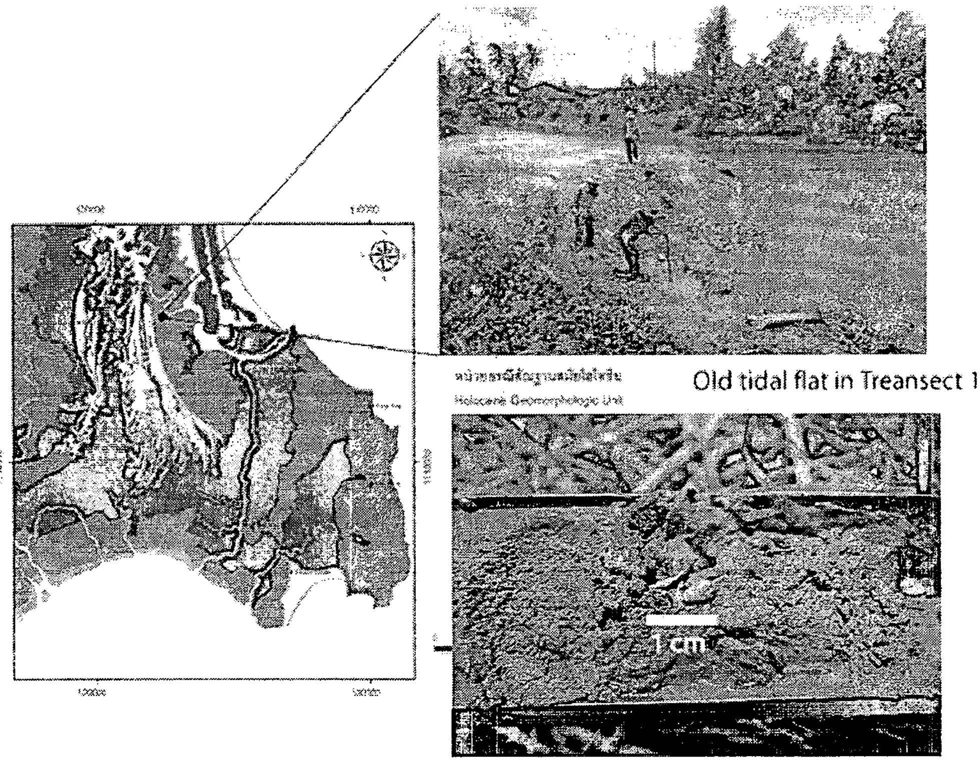

Figure 6. Old tidal flat compose mainly of gray-dark gray mud may be and found shell and shell fragment.

3.2 Sedimentology of beach ridge and swale

The sedimentological study in Pak Nam Chumphon area has been done by collecting sample in different landforms. Old sandy beach and old lagoon are interested in this study and hand augers were carried out. The average depth of the drilling is approximately 300 cm. The basic description of sediment samples was recorded during fieldwork based on lithologic description that is described from the oldest layer in bottom to the youngest layer at top soil. Inner most beach ridge (old sandy beach) are found at station T1-PN1.The location of beach ridge, UTM grid of 519617 E 1153469 N on map sheet number 4829 IV (Amphoe Maung Chumphon). The 400 cm is the total thick and depth of the core. It can be described into 8 layers as shown in figure 6.

Old lagoon location is located at UTM grid of 519649 E 1153504 N on map sheet number 4829 IV (Amphoe Maung Chumphon). The total depth of the core is the 190 cm. It can be described into 2 layers and some layers were disturbed from human and animal as shown in Figure 7.

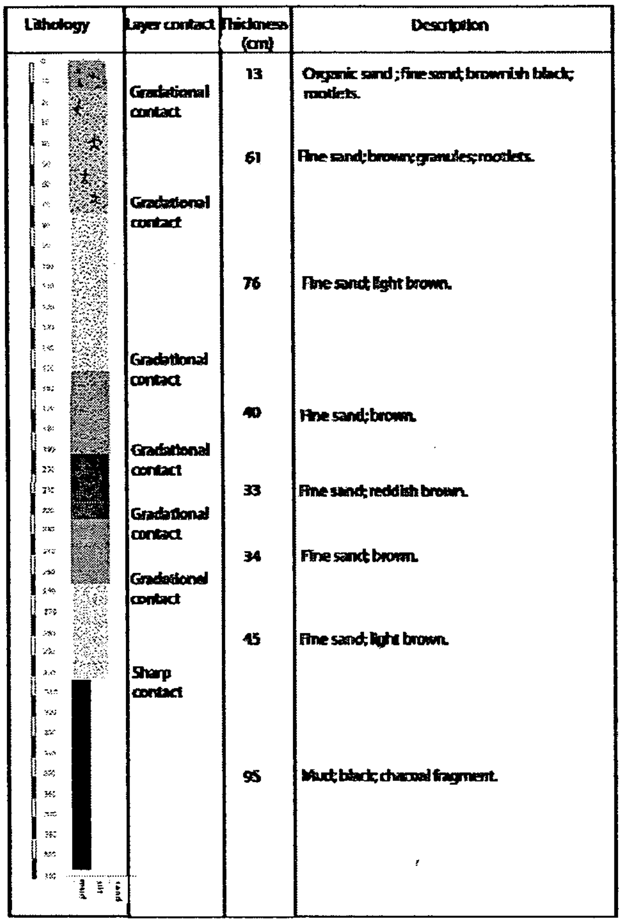

Figure 6. The lithologic log of inner most old beach sand at station T1-PN1.

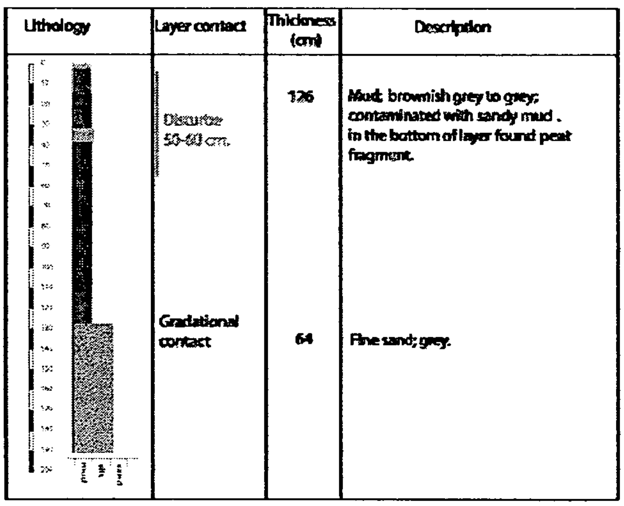

Figure 7. The lithologic log of old lagoon at station T1-PN2.

The cross section shows elevation of each landform relate to the present mean sea level in Pak Nam Chumphon area is shown in figure 8. It shows the progradation of beach ridge to seaward direction. Shell fossils were also recorded in some small swamps between ridges. These shell assemblages indicate shore or near shore environment.

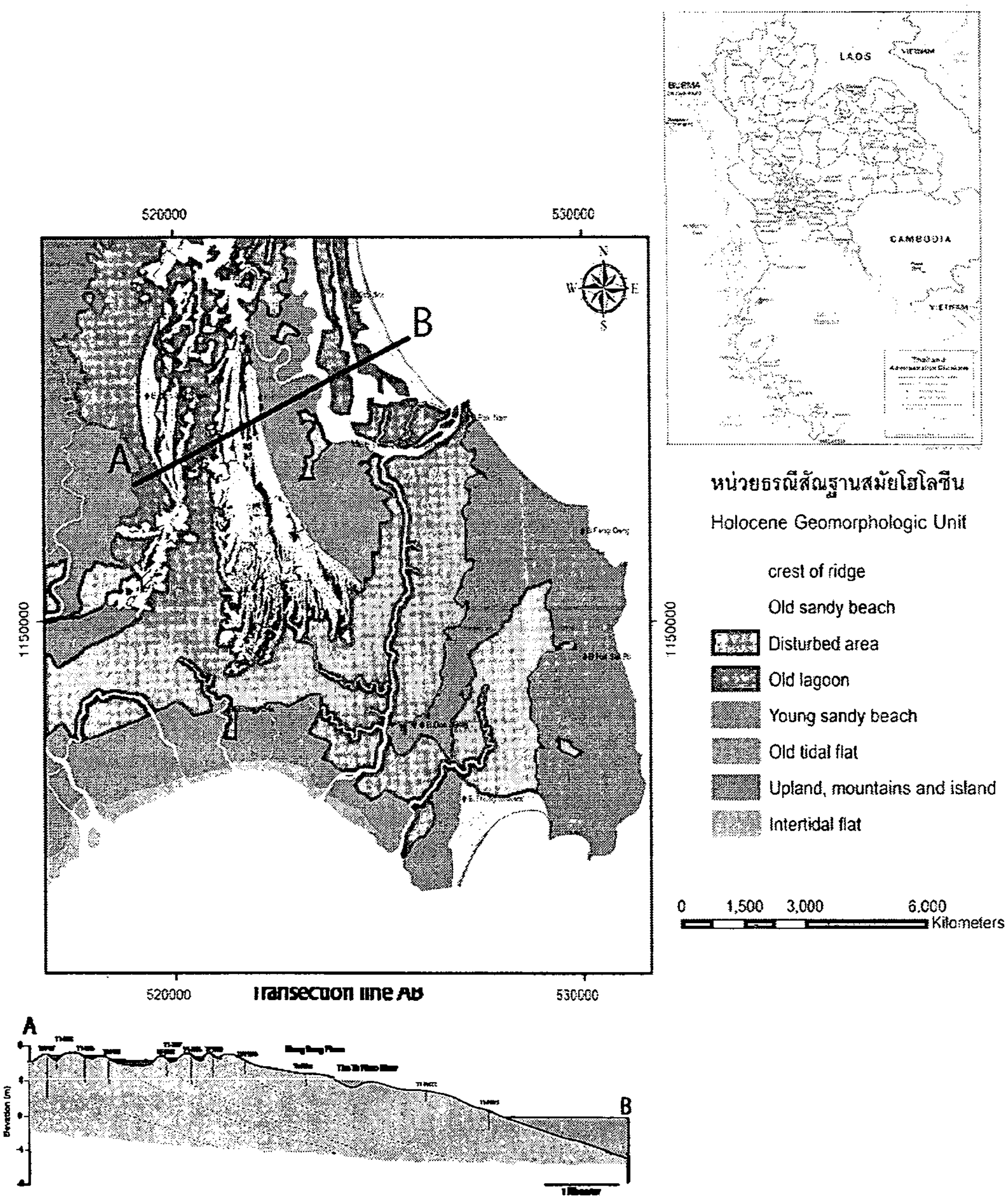

Figure 8. Geomophological map of Pak Nam Chumphon, Chumphon province western of Thailand (top) and cross section along transect line AB (bottom).

4. CONCLUSIONS

The geomorphological classification of coastal landform of the area, has led to following conclusions:

1. The coastal geomorphology can be divided into 6 units as old sandy beach, old lagoon, young sandy beach, old tidal flat, upland and mountain, intertidal flat and it can be related with sea level change.

2. The evident of shell and peat fragments indicates former tidal deposit (Sinsakul, 1988). Broken shell fragments in the marginal area indicate a relatively shallow, near shore environment.

3. Aerial photo interpretation is first key to reveal historical change and can be help to detect the longshore current direction using trend of former beach ridge that prograding to seaward.

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6. References

Choowong, M., Ugai, H., Charoentitirat, T., Charusiri, P., Daorerk, V., Songmuang, R. and Ladachart, R. 2004. Holocene Biostratigraphical Record in Coastal Deposit from Sam Roi Yod National Park, Prachuap Khiri Khan, Western Thailand. The Natural History Journal of Chulalongkorn University 4(2): 1-18.

Choowong, M. 2002b. The geomorphology and assessment of indicators of sea-level change to study coastal evolution from the gulf of Thailand. International Symposium on Geology of Thailand. pp. 208-220. Department of Mineral Resource, Bangkok, Thailand.

Hesp, P.A., Dillenburg, S.R., Barboza, E.G., Tomazelli, L.J., Ayup-zouain, R.N., Esteves, L.S., Grumer, N.S., Tolda, E.E., Tabajara, L.D. and Clerot L.C. 2005. Beach ridges, foredunes or transgressive dunfields? Definitions and an examination of the Torres to Tramandaí barrier system, Southern Brazil. Anais da Academia Brasileira de Ciências. 77(3): 493-508

Sinsakul, S. 1988. Geomorphic and stratigraphic analysis of the west coast, evidence from Ban Pak Bara-Pak Langu, southern Thailand. Proceeding of the workshop correlation of Quaternary successions in south, east and Southeast Asia, Bangkok Thailand on 21-24 November, 1998

Ridd, M.F., Barber A.J. and Crow, M.J. 2011, the Geology of Thailand. The Geological Society of London. 626p.

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The Geology of Thailand

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Contents

12 Quaternary

MONTRI CHOOWONG

Quaternary deposits in Thailand crop out widely in five physiographical regions: (1) the highlands of Northern Thailand; (2) NE Thailand; (3) the Central Plain; (4) the Upper and Lower Gulf of Thailand coast; and (5) the Andaman Sea coast (Fig. 12.1). Classification of the Quaternary depositional environments in Thailand has tended to be largely dependent on the relationship between landforms and the chronological evidence. The Pleistocene deposits are mainly found to be related to changing river courses, alluvial and braided systems and the degree of weathering of the rock basements. Instances where deposits are related to neotectonics are rare in the literature. Holocene deposits were much influenced by changes in climatic conditions and the sea level.

The distribution of Quaternary deposits (Fig. 12.2) reflects a variety of physiographic settings which in turn determine the stratigraphy from one region to another. In the highlands of the north of the country, the river systems are constrained by the complex basement geology and fluvial deposits reflect this. They are present along the four major river courses (the Ping, the Wang, the Yom and the Nan). They were laid down within restricted intermontane basins, generally as terraces within a limited avulsion plain. Some deposits derived from basaltic rocks are locally lithified. In NE Thailand where Mesozoic sandstones form the basement rocks of the Khorat Plateau, relict terrace gravel beds and aeolian sandy soil (possibly loess) are the dominant Quaternary deposits. Large areas of Quaternary deposits occupy the low-lying Central Plain and the coastal plain of the Gulf of Thailand. Along the Chao Phraya River of the Upper Central Plain the deposits are fluvial-dominated. Downstream from Nakhon Sawan to Ayutthaya the Chao Phraya is joined by tributaries including the Sakaekrung, the Lopburi and the Pasak Rivers. In that zone and in the Lower Central Plain there was interaction between Holocene fluvial and marine depositional environments which resulted in great thicknesses of brackish and marine sediments. Along the coastal plain of the Gulf of Thailand and the Andaman Sea coast, the deposits are considered to be the product of the Holocene marine transgression and regression, and to have formed in both tide- and wave-dominated environments. Wind-blown sand dunes of probable storm origin have been recognized locally.

History of Quaternary studies in Thailand

Pioneer geological mapping of Quaternary deposits on a regional scale was carried out by Brown *et al.* (1951). Extensive research began a decade later to relate Quaternary deposits to eustatic changes in sea level and episodes of coastal evolution during the late Pleistocene and Holocene (e.g. Alexseev & Takaya 1967; Takaya 1968, 1971, 1972; Hattori 1969, 1971, 1972; Supajanya 1981, 1983; Takaya & Thiramongkol 1982; Chonglakmani *et al.* 1983; Thiramongkol 1983*a–c*; Chaimanee *et al.* 1985; Sinsakul 1992; Somboon & Thiramongkol 1992; Robba *et al.* 1993) (Table 12.1). In the Lower Coastal Plain, where most of these studies were carried out, Pleistocene exposures are very rare and so interpretations are mostly based on subsurface unconsolidated sediments.

In the past decade a number of researchers have used geomorphological evidence to infer Holocene sea-level history. Geophysical surveys over onshore and offshore Quaternary deposits and the interpretation of possible physical evidence left behind by sea-level changes have revealed information about the detailed Quaternary environment (e.g. Intasen *et al.* 1999; Choowong 2002*a–d*). The first sea-level curve for Thailand was constructed by Sinsakul *et al.* (1985) and revisions have been constructed by, for example, Choowong *et al.* (2004) and Horton *et al.* (2005). Recently, the emphasis of research has changed from basic survey to the use of more advanced techniques to evaluate modern hazards, for example, landslides, flooding, subsidence, coastal erosion, earthquake activity on active faults and the 2004 tsunami.

Quaternary terrestrial deposits and landforms

Northern Thailand

Quaternary deposits in Northern Thailand are mainly confined to elongate fault-bounded intermontane basins. The structural axes of the basins are regionally parallel to the main direction of faults. The basins themselves vary in size and are controlled by the underlying geological structure. The Quaternary sediments deposited in them were transported by the four main rivers: the Ping, Wang, Yom and the Nan. Each river flows and meanders within a limited avulsion belt and, through time, avulsion and down-cutting of the river resulted in the extensive formation of terraces. Three terrace levels are common and there is local evidence of Quaternary neotectonics affecting the highest terrace, for example on the Ping River in Tak Province where local uplift is thought to account for a set of normal faults which cut the upper surface of the highest terrace (Bhongaraya 1998).

Site selection of one archaeological site within the avulsion plain of the Yom River in the northern Central Plain in Sukhothai Province, named Sisatchanalai, is related to a change of the avulsion course. Radiocarbon dating of sediments infilling palaeochannels shows that the site may have a close relationship with changes of a meandering channel which took place, probably in the late-Holocene. The composition of bed material of the palaeochannels and of the modern Yom River at Sisatchanalai also confirms that the palaeochannels represent earlier courses of the Yom (Bishop & Godley 1994). The most recent palaeochannel of the Yom was abandoned about 1800 years ago when the modern course was established, probably by avulsion during a period of increased runoff and flood activity. The very tight bend of the Yom River at Phra Prang temple, part of Sisatchanalai archaeological site, probably dates from the last 2000 years. The earliest signs of occupation at this very important site in Thai history are currently set at about 1250 years (Bishop 1988). This suggests that the change of the avulsion plain in northern Thailand may be a criterion for site selection and the re-location of some historic communities.

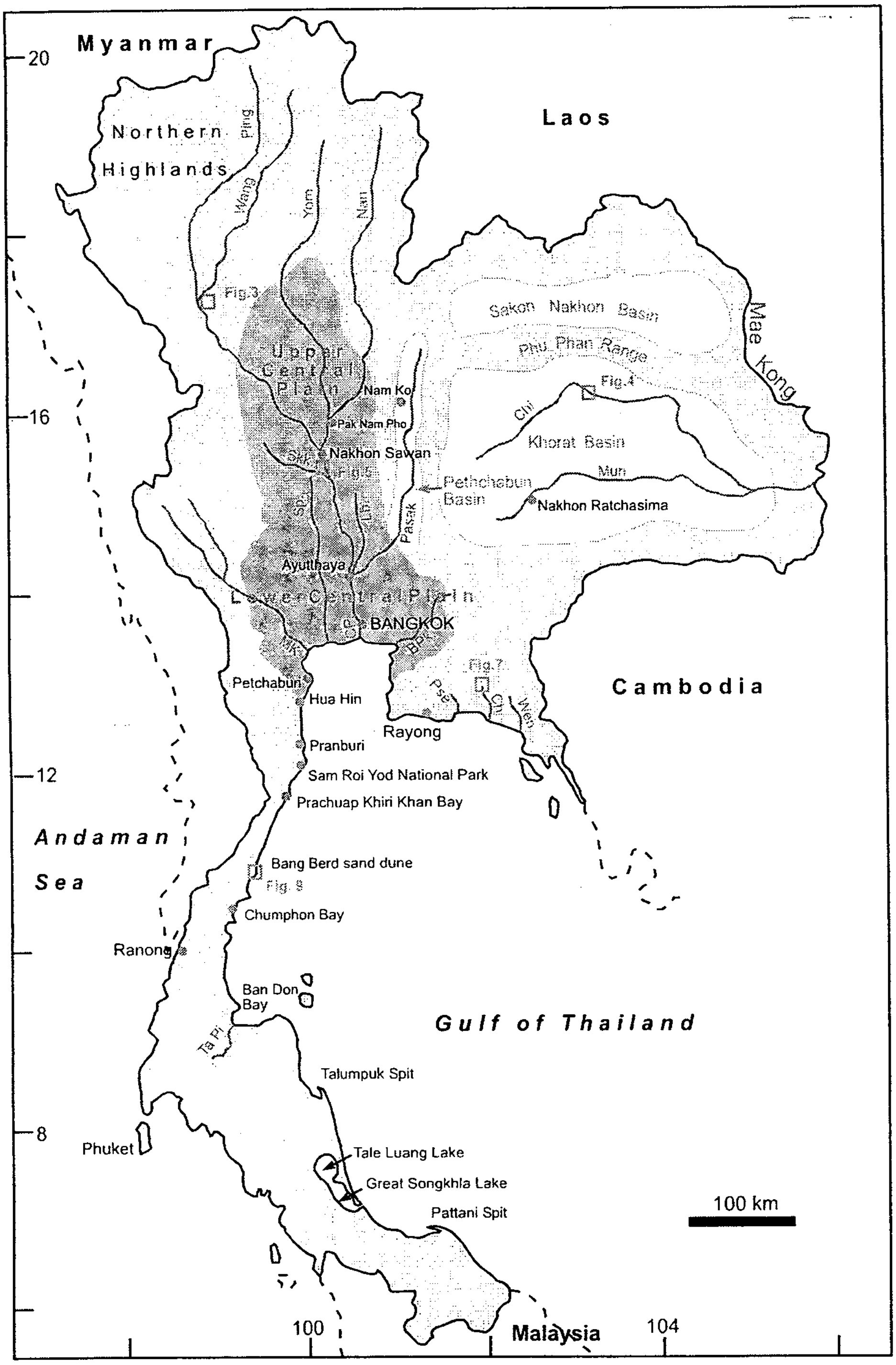

Fig. 12.1. Map showing the Quaternary provinces of Thailand and places mentioned in the text. Inset squares indicate the location of Figures 12.3–12.5, 12.7 and 12.9. Abbreviated river names are: SKK, Sakaekrang; Sp, Suphanburi; Lb, Lopburi; CP, Chao Phraya; MK, Mae Klong; BPk, Bang Pakong; Pse, Prasae; Ch, Chanthaburi.

Generally the terraces are not well preserved due to the high rate of weathering in the prevailing tropical climate, although remnants of terraces may still be distinguished from the floodplain. Commonly the terraces are preserved as undulating gravel terrains with fragments of well-preserved petrified wood in places (Fig. 12.3). Absolute dating of terrace deposits has not been carried out but, from stratigraphical considerations, they are thought to be Pleistocene (Bhongaraya 1998; Sinsakul *et al.* 2003). At Lampang, K–Ar dating of a basalt flow resting on a high-level gravel terrace yielded an age of 600 ± 200 ka (Sasada *et al.* 1987), implying a minimum age of middle Pleistocene for the gravel bed.

NE Thailand

The Khorat Plateau of NE Thailand occupies about one-third of the area of the entire country. The Plateau itself is formed of Mesozoic sandstone of the Khorat Group, but Quaternary deposits are present

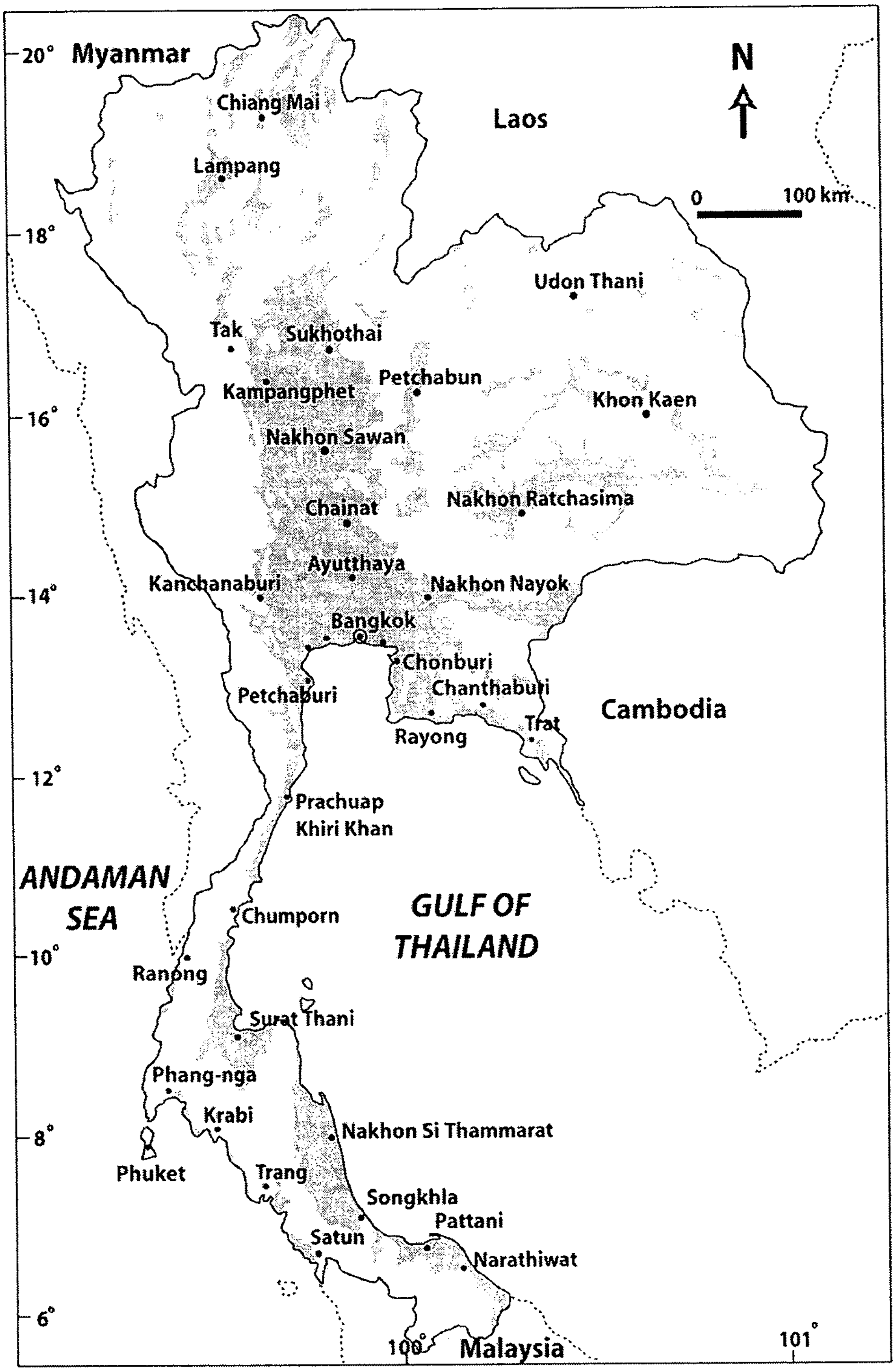

Fig. 12.2. Map showing distribution of Quaternary deposits in Thailand (compiled from the Geological Map of Thailand, Department of Mineral Resources, 2004).

in two basins: the Khorat Basin in the south and the Sakon Nakhon Basin in the north of the plateau (Fig. 12.1). Terraces and inferred aeolian (loess) deposits are the dominant Quaternary deposits in both basins. In the Sakon Nakhon Basin, the oldest Quaternary unit is preserved as a relict high-level terrace deposit close to the Phu Phan mountain range. Three terrace levels are present in the Sakon Nakhon Basin at 18, 13 and 8 m above the floodplain of the Mae Kong River (Wongsomsak 1992). In the southern Khorat Basin, the two main rivers (the Mun and the Chi) have produced extensive Quaternary fluvial landforms and deposits (Fig. 12.4). As in the Sakon Nakhon Basin, terrace deposits along the meander belt of the Mun and the Chi Rivers are characterized by the localized presence of relict gravel beds.

The terrace gravel beds are largely composed of rounded to well-rounded quartz and sandstone clasts implying local derivation from the Mesozoic sandstone basement. The age of the gravel beds

Table 12.1. *Summary of the scope of Quaternary studies (1951–2005)*

Quaternary researchers	Geomorphology	Quaternary stratigraphy	Sea-level changes	Landform evolution
Brown *et al.* (1951)	√			
Alexseev & Takaya (1967)	√	√		
Hattori (1969, 1972)	√	√		
Takaya (1968, 1971, 1972)	√	√	√	
Takaya & Thiramongkol (1982)				
Chonglakmani *et al.* (1983)		√	√	
Supajanya (1981, 1983)	√		√	
Thiramongkol (1983*a–c*)	√	√	√	
Sinsakul *et al.* (1985)		√	√	
Chaimanee (1985)		√	√	
Dheeradilok (1986, 1995)	√	√	√	
Somboon & Thiramongkol (1992)	√	√	√	
Sinsakul (1992)		√	√	
Roy (1986, 1989, 1990, 1994)	√	√	√	√
Kengkoom (1992)	√	√	√	√
Robba *et al.* (1993)	√	√	√	
Intasen *et al.* (1999)		√	√	√
Choowong (2002*a–d*)	√	√	√	√
Umitsu *et al.* (2002)	√	√	√	√
Choowong *et al.* (2004)	√	√	√	√
Horton *et al.* (2005)	√	√	√	√

is considered to be middle–upper Pleistocene, in the light of the *c.* 0.8 Ma age obtained for these sediments by workers investigating the tektites they contain (Howard 2011).

Red sandy soil is a localized feature of the Quaternary deposits of the Khorat Plateau. Its occurrence was considered by, for example, Bunopas *et al.* (1999) and Nutalaya *et al.* (1986) to be the product of aeolian processes, but that is controversial. An alternative explanation is that the red sandy soil formed *in situ* by weathering of the underlying Khorat Group sandstone in an oxidizing environment. Further research and discussion are needed to investigate the likely origin of this red sandy soil.

Upper Central Plain

The Quaternary deposits of the Central Plain of Thailand can be divided into those of the Upper and the Lower Central Plain (Takaya 1971; Sinsakul 1992). The Upper Central Plain extends south to the southern part of Nakhon Sawan Province, below the point at which the Ping and Nan Rivers join to form the Chao Phraya River. The elevation there reaches little more than 20 m above present mean sea level (MSL). Quaternary depositional environments are dominated by alluvial and fluvial landforms and the basement is shallow or, in places, forms monadnocks where it has been uplifted by movements associated with the Mae Ping Fault belt (Morley *et al.* 2007).

The main tributary of the Chao Phraya is the Sakaekrung River which enters from the west. In this area, both the Chao Phraya and the Sakaekrung exhibit the scars of abandoned meander channels and oxbow lakes. The evidence suggests three belts of avulsion to have taken place along the Chao Phraya (Fig. 12.5), probably from the Early to Mid-Holocene (Tulthaveewat *et al.* 2008).

Western and eastern parts of the Lower Central Plain

The Lower Central Plain (also termed the Chao Phraya Basin or the Southern Basin) covers an area of approximately 33 400 km^2 and extends 175 km from Chai Nat Province south to the Gulf of Thailand (Takaya 1972; Thiramongkol 1983*a*). The Chao Phraya River flows some 250 km through a flat and featureless plain until it reaches the Gulf in Samut Prakarn Province. The elevation of the plain is about 4 m above MSL at Ayutthaya and only about 2 m at Bangkok. The Quaternary landforms over this largely flat area were formed in terrestrial and transitional environments. Terrestrial morphology includes piedmont fans, peneplains, terraces and active alluvial fans in the marginal zones of the Lower Central Plain (Fig. 12.6). The northern portion of the plain shows progradation of former fluvial-dominated deltas with abandoned channels (Coleman & Wright 1971; Takaya 1972; Thiramongkol 1986; Somboon & Thiramongkol 1992; Umitsu *et al.* 2002; Tanabe *et al.* 2003). Floodplains of the Chao Phraya, Suphanburi, Lopburi, Pasak, Mae Klong and Bang Pakong Rivers dominate the central portion of the plain.

Block faulting in the Late Pliocene–Pleistocene formed horsts and grabens in the basement of the Lower Central Plain causing local accumulations up to 400 m thick of Quaternary sediments (Pradidtan & Dook 1992; Japan International Cooperation Agency 1995). Incised channel deposits have also been recognized from well log data beneath the Chao Phraya and the Suphanburi Rivers (Fig. 12.6).

Quaternary deposits of the Lower Central Plain reflect the interaction between terrestrial and transitional environments. Terrestrial depositional environments of piedmont fans and peneplains, terraces, colluvial, alluvial, modern floodplain and *in situ* saprolite are mostly observed close to the western and the eastern margins of the plain (Thiramongkol 1983*a*). Abundant alluvium was transported via valleys and small channels from the highland areas west of Lower Central Plain beyond Kanchanaburi (Choowong 2002*b*). The Quaternary terrestrial landforms and deposits of the Lower Central Plain can be classified as follows.

Piedmont fans and peneplains

Piedmont fans and peneplains occur along the eastern margin of the Lower Central Plain, including the Si Maha Phot Fan (SMPF in Fig. 12.6) and the westernmost part in the area of Kanchanaburi. They are characterized by strongly undulating surfaces with scattered hills and interfluve crests on the topmost parts of the alluvial

Fig. 12.3. Giant petrified tree trunk in terrace gravel at Tak. At 72.22 m in length, it is thought to be the longest such fossilized tree trunk in SE Asia.

fans (Thiramongkol 1983*a*). A honeycomb-textured lateritic gravel layer with a maximum thickness of 5 m is extensively observed at Kanchanaburi, which is a common characteristic of the Pleistocene peneplain deposits in the higher ground of the western Lower Central Plain (Choowong 2002*a*, *b*). Localized granite saprolites beneath the peneplain are observed in the SE part of the plain. The piedmont fans and peneplains have not been dated, but Takaya (1968) has suggested a possible correlation with the thick Pliocene–Early Pleistocene laterite from the Narmada valley in Central India.

Terraces

Terraces in the western part of the plain are the traces of meanders of the Mae Klong and Suphanburi Rivers, while terraces and outcrops of terrace deposits on the eastern side originated from the Bang Pakong River (Thiramongkol 1983*a*). No dating has been carried out but mammalian fossils (*Hippopotamus* skull, a *Bubalus* horn and an upper molar of a *Stegodon*) suggest a middle Pleistocene age (Koeningswald 1959).

Alluvial fans and floodplains

Formerly active alluvial fans as well as currently active fans occur at both marginal zones of the Lower Central Plain. The two principal formerly active alluvial fans on the western margin have been named the Mae Klong Fan and the Don Chedi Fan (Thiramongkol 1983*a*) (Fig. 12.6). The Mae Klong Fan, east of the city of Kanchanaburi, is the product of past (and to a lesser extent present) distributaries of the Mae Klong River. It has an elevation of 5–20 m above MSL and displays an undulating surface which dips gently eastwards and south-eastwards. The Don Chedi Fan, in Suphanburi Province, is an alluvial fan-terrace complex at an elevation of 15–30 m above MSL. It has an undulating surface through which

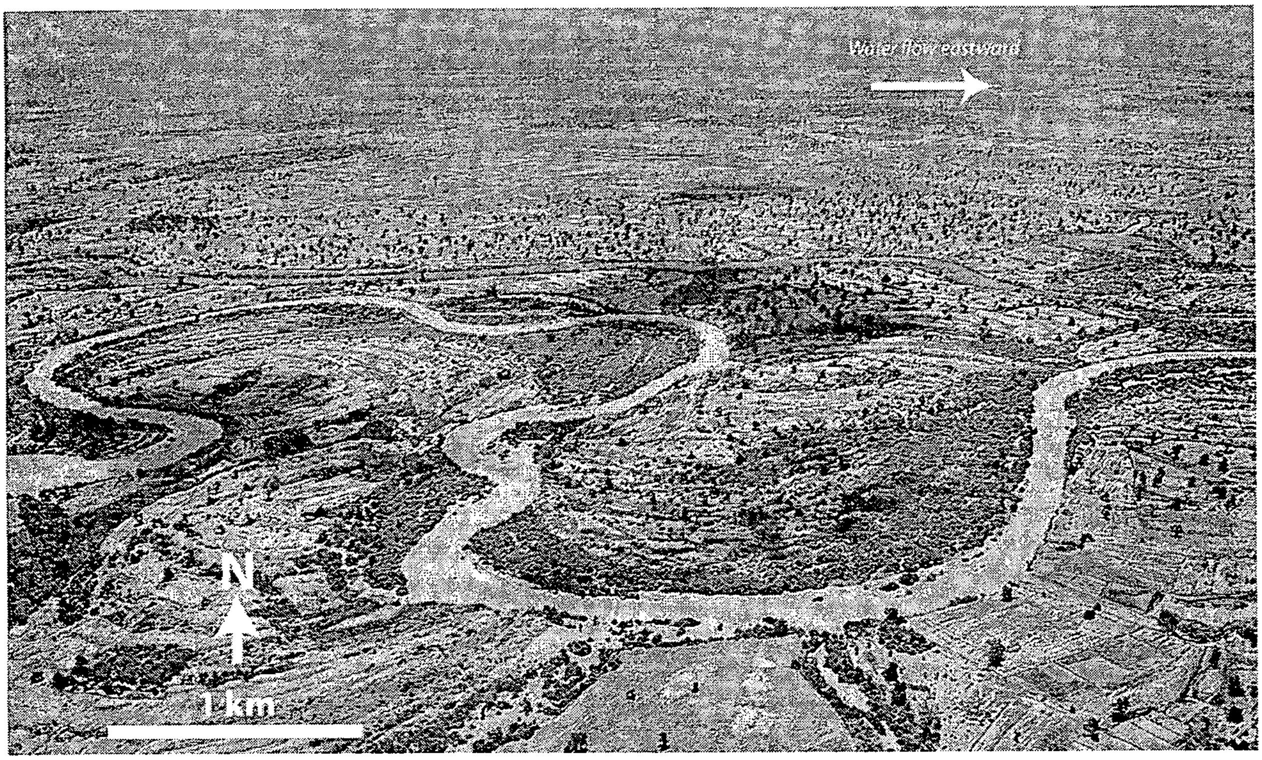

Fig. 12.4. Oblique aerial photograph of the Chi River in NE Thailand, showing abandoned channels and meander scars. Water flows east to join the Mae Kong. Swales and swells in point-bar deposits can be clearly seen.

later rivers have incised deep valleys. The Don Chedi Fan was probably formed about the same time as the formation of the middle terraces, judging by the degree of weathering of the deposits (Thiramongkol 1983*a*). The floodplain deposits of all the main rivers of the Lower Central Plain are widespread and annual flooding has produced deposits up to 2 m thick.

Quaternary transitional deposits and landforms of the Upper Gulf of Thailand

The Upper Gulf of Thailand as described here overlaps with the Lower Central Plain and includes the entire area of the eastern coast and part of the western coast southwards to Prachuap Khiri Khan Province (Fig. 12.1). The narrow coastal plain from Petchaburi Province down to the famous tourist area of Hua Hin district consists of a series of beach ridges and swales lying mostly parallel to the orientation of the coastline. Further south to Pranburi district, including Sam Roi Yod National Park, a large swampy area and a series of beach ridges overlies extensive Holocene brackish and marine deposits. A series of beach ridges is also present in the semi-enclosed bay at Prachuap Khiri Khan. Transitional environments, including tidal deltas and tidal flats, are present in the intertidal zones around the mouths of the Mae Klong, Suphanburi, Chao Phraya and Bang Pakong Rivers. Oceanographic data from coastal regions along the Gulf of Thailand are summarized in Table 12.2.

Former deltaic plain and brackish deposits in the axial part of the Lower Coastal Plain

Coleman & Wright (1971) equated the axial part of the Lower Central Plain with the Lower Chao Phraya Deltaic Plain, also calling it the 'Subaqueous Deltaic Plain'. The Lower Chao Phraya Deltaic Plain extends from the present coast as far as 40 km inland where the boundary of former tidal-influenced deposition was limited by the level of the Mid-Holocene highstand. The Lower Chao Phraya Deltaic Plain is wider than the river-dominated upper delta plain, and saltwater vegetation such as mangrove and salt marsh, together with estuarine deposits tended to prevail in this less river-dominated environment. The morphology and Quaternary depositional environments of the Lower Coastal Plain are shown in Figure 12.6.

Quaternary brackish-water deposits extend across the head and south down the coasts of the Gulf of Thailand. Their landforms generally have elevations no higher than 4 m above MSL. However, in some places in the east of the plain, elevations of up to 10 m above MSL are present and are considered to be related to movement of neotectonic faults (Thiramongkol 1986). The Pleistocene coastal deposits from the east and the west coasts of the Gulf of Thailand have been recorded at elevations up to 5 m above MSL (Choowong 2002*d*; Choowong *et al.* 2004). Older brackish deposits beneath the modern active floodplain of the major rivers at the axial part of the Lower Coastal Plain indicate a history of delta progradation during the Holocene marine transgression and regression (e.g. Umitsu *et al.* 2002; Tanabe *et al.* 2003).

Active delta and tidal flat deposits at the mouth of the Chao Phraya River

The Chao Phraya Delta is the largest active tidal delta in Thailand with an area of *c.* 11 300 km^2 (Japan International Cooperation Agency 1995); its principal characteristics are listed in Table 12.3. Although restricted laterally, the delta has prograded rapidly along the Gulf axis (Wright 1972). In its alluvial valley

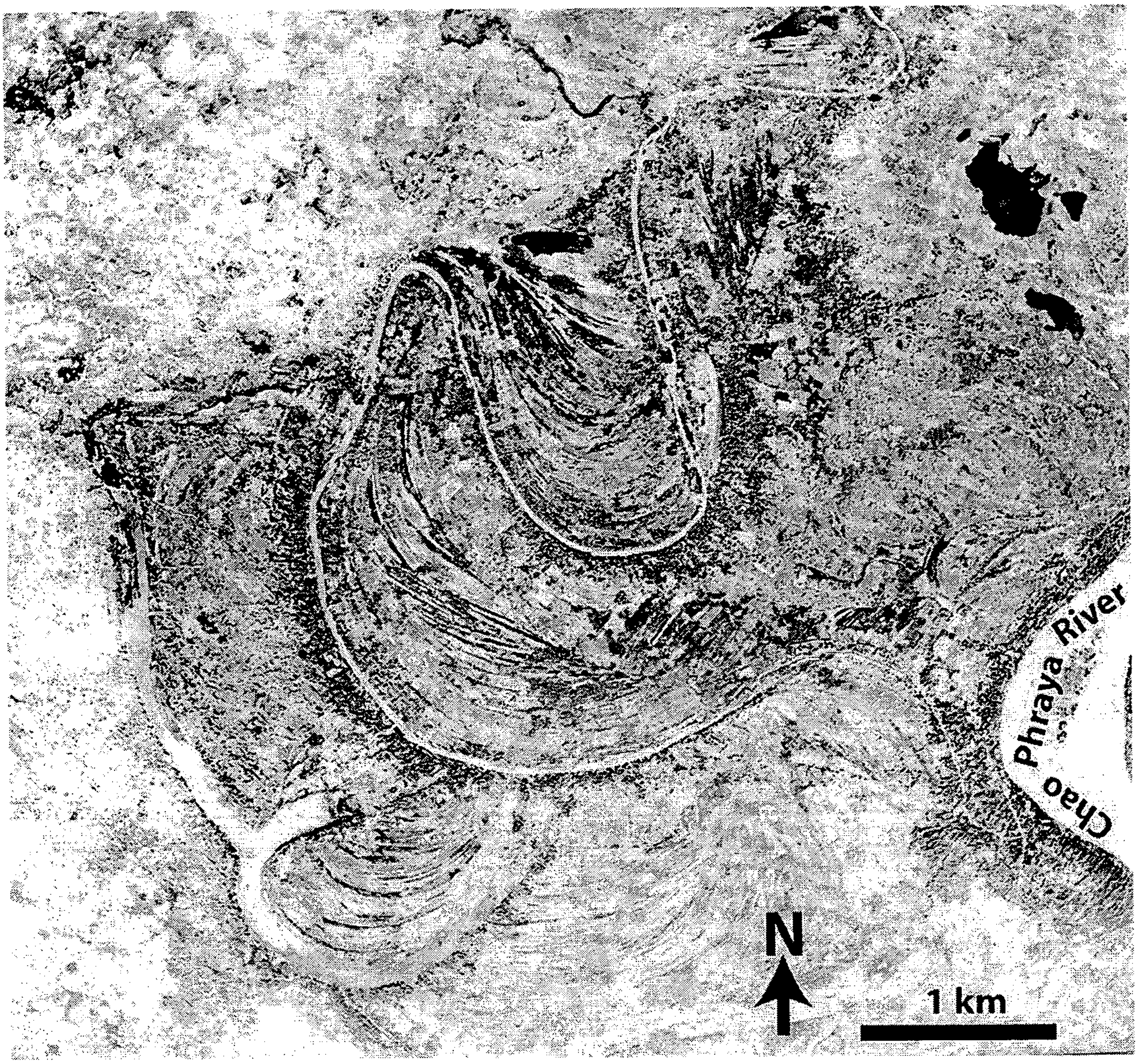

Fig. 12.5. Three meander belts of the Chao Phraya River, showing the avulsion plain that contains meander scars, oxbow lakes and swale and swell patterns within point bar deposits (from Tulthaveewat *et al.* 2008).

and the upper delta plain the sediments are fluvial-dominated, whereas sediments in the lower delta and the subaqueous portions were deposited in a tide-dominated environment (Choowong 2002*c*; Tanabe *et al.* 2003). The tidal flat deposits contain organic-rich mud (mixed with fluvial sand lenses) and mud balls (Somboon 1990).

The Subaqueous Deltaic Plain lies in the intertidal zone and is a tidal delta, dominated by the mouth of the Chao Phraya River. The sea is shallow here but becoming deeper as the sediment entering the Gulf from the river has been decreasing in recent years. As a result the intertidal zone is rapidly subsiding as compaction of the deltaic sediments occurs, a phenomenon believed to be exacerbated by isostatic adjustment, as suggested by Choowong (2002*c*). This could potentially lead to an unusual incursion of the sea onto the land, with consequent erosion of the mangrove belt (see below).

Intertidal mangroves

Mangroves are distributed extensively in the intertidal zone along the Gulf of Thailand and the Andaman Sea coast. In the Bangkok Bight, mangrove forests extend inland across the tidal flat and along the tide-influenced channels and estuaries. Mangrove forests form extensive tracts in the active deltas of the Bang Pakong, Petchaburi, Chao Phraya and Mae Klong Rivers at the head of the Gulf and along the eastern Gulf coast in Rayong, Chanthaburi and Trat Provinces. Along the latter tide-dominated stretches of the eastern Gulf coast, intertidal mangroves occupy more than 60% of the coastal plain especially in the estuaries of the Prasae, Chanthaburi and Wen Rivers (Choowong 2002*d*). Peat, sand lenses and some organic-rich mud with shell fragments are common.

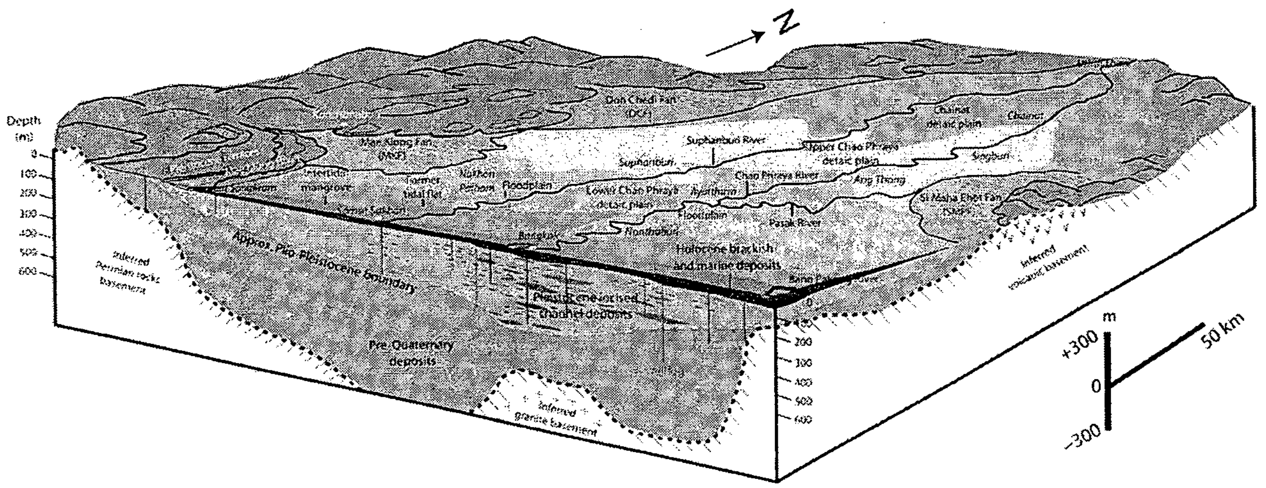

Fig. 12.6. Three-dimensional diagram of the Lower Central Plain showing distribution of landforms and Quaternary deposits (modified from Japan International Cooperation Agency 1995).

There are five major community types or zones of mangrove in Thailand (Aksornkaoe 1975; Aksornkaoe & Paphavasit 1993): (1) *Avicennia alba*, *Sonneratia griffithii* and *S. alba* occur in association with *Rhizophora mucronata* and *R. apiculata* along the seaward fringe; (2) the *Avicennia/Rhizophora* association is normally found on more arenaceous soils; (3) *Sonneratia/Bruguiera* are recognized in more argillaceous sediments; (5) *Bruguiera parviflora* and *B. gymorrhiza* in association with *Xylocarpus moluccensis*, *X. obovatus*, *Intsia bijuga*, *Excoecaria agallacha*, *Lumnitzera racemosa* and *L. coccinea* with *Ceriops roxhurghian* and *C. tagel* are found in more inland areas; and (5) *Rhizophora* forest typically extends inland along riverbanks in association with *Nypa fruticans*.

Holocene marine and brackish-water deposits

Marine and brackish-water deposits formed during the Holocene transgression and regression where the Chao Phraya River with its sediment load interacted with seawater, causing deceleration of the river's flow and rapid build-up of a delta (Umitsu *et al.* 2002; Tanabe *et al.* 2003).

In the Lower Central Plain the beds are green to greenish-grey, soft, silty clay intercalated with a few layers of fine- to very fine-grained sand; it has been called the Bangkok Clay (Thiramongkol 1983*a*). The thickness of these intertidal sediments varies from 2 m at the northern margin of the Lower Central Plain to 15–20 m in the southern part and in the upper Gulf of Thailand.

Holocene estuarine sediments are well preserved, and extend up to 3 km inland in Petchaburi Province where mangrove-lined channels have been confirmed by their characteristic brackish and marine fauna (Di Geronimo *et al.* 2002, 2005; Melis & Violanti 2006). In Chanthaburi Province on the east of the Gulf of Thailand, Holocene brackish and marine deposits have been identified as far as 15 km inland with thicknesses of 15–25 m. Organic matter in a series of three prograded beach ridges in the Prasae and Chanthaburi River estuaries have been dated using ^{14}C techniques and indicate that a gradual progradation occurred *c.* 4–2 ka (Choowong 2002*d*).

Another series of beach ridges with swales and former tidal flats in the Sam Roi Yod National Park in Prachuab Khiri Khan Province provide evidence of the change in sea level after the Mid-Holocene highstand (Choowong *et al.* 2004). Like other series of prograded beach ridges in the upper Gulf of Thailand, ^{14}C dating of organic matter shows that progradation started at *c.* 4 ka. Brackish and marine faunas preserved in the former tidal flat of Sam Roi Yod also confirmed a period of progradation after the Mid-Holocene highstand (Surakiatchai 2006).

Pleistocene relict marine landforms and deposits

Pleistocene deposits in the Lower Central Plain are mainly alluvium and fluviatile sediments and have been recognized mostly in the subsurface, below the Bangkok Clay. Borehole data suggest there are incised-channel sediments under the Bangkok Clay down to

Table 12.2. *Comparison of oceanographic data in regions of the Gulf of Thailand*

	Coastal regions of the Gulf of Thailand		
Oceanographic factors	Southern and Western	Eastern	Northern
Tidal ranges* (m) (min/max)	0.5 (0.8/1.3) Microtidal	2.0 (0.2/2.2) Mesotidal	3.6 (0.2/3.8)
Substrate gradient**	1:400 Gradient decreases →	1:900	1:10 000
Catchment basins**** (km^2)	36 926	26 353	88 900

*Tidal ranges averaged from tide data of The Royal Thai Navy from 2002 to 2006 and compiled from Siripong (1989).
**Substrate gradient calculated from bathymetry on 1:50 000 topographical map of The Royal Thai Survey Department.
***Catchment basins are the sum of sub-basins published in Roy (1994).

Table 12.3. *Components of the Chao Phraya Delta (Japan International Cooperation Agency 1995)*

Physical characteristics	Alluvial valley	Upper Delta Plain	Active Chao Phraya Delta components: Lower Delta Plain	Subaqueous Delta Plain
Elevation (m above MSL)	>20	20–5	5–0	0
Slope	*c.* 1:5	*c.* 1:10	*c.* <1:10	*c.* <1:10
Morphology	Highland	Abandoned channels Inactive alluvial fans Former delta	Young delta Tidal flat Mangrove	Tidal delta

Note: The active Chao Phraya Delta includes lower and subaqueous deltaic plains.

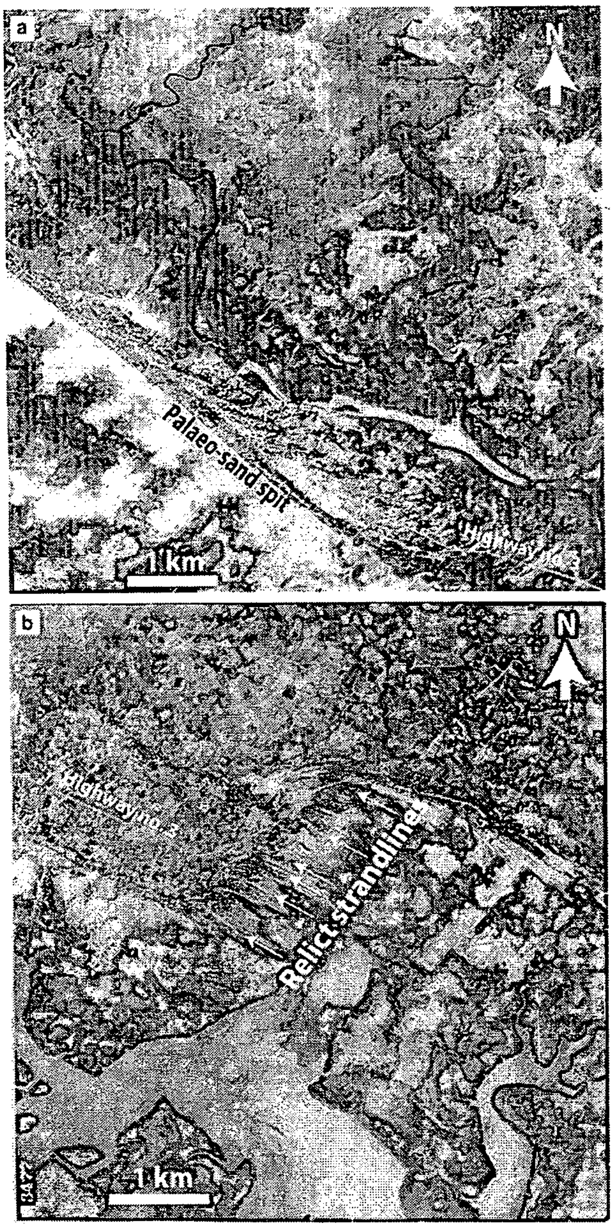

Fig. 12.7. Aerial photographs showing former landforms along Highway 3, Chanthaburi Province, possibly developed during the early Pleistocene to early Holocene marine transgression: (**a**) palaeo-sand spit 15 km inland from the present shoreline and (**b**) relict strandlines (courtesy of the Royal Thai Survey Department).

c. 400 m depth (Fig. 12.6). The top of the Pleistocene sequence is characterized by a highly oxidized stiff clay.

Laterite and lateritic soil with iron and manganese concretions are common, with intercalations of gravel, sand, silt and clay; they indicate that this fluviatile environment was probably exposed before 21 ka, while the sea level was 25 m lower than the present MSL (Hanebuth *et al.* 2000; Sathiamurthy & Voris 2006). The whole of the Gulf of Thailand as far as the South China Sea was probably a land area, which Tjia (1987) referred to as Sundaland.

Palaeo-sand spits and relict strandlines crop out as far as 15 km inland along Highway 3 in Chanthaburi Province (Fig. 12.7a, b). These former landforms and deposits are thought to have formed during the rapid marine transgression in the late Pleistocene to early Holocene (Choowong 2002*d*), although no absolute dating has been carried out on these relict landforms.

Brackish and marine deposits and landforms of the Lower Gulf of Thailand and the Andaman Sea coast

The coast of the Lower Gulf of Thailand is wave-dominated and a series of beach ridges and swales are present as far as the southernmost part of Peninsular Thailand (Fig. 12.8). The most conspicuous modern landforms are the Talumpuk and Pattani sand spits (Fig. 12.8). On the Andaman Sea coast, Holocene beach ridges are present in several small bays on the mainland and on isolated islands.

Pleistocene deposits

As mentioned earlier, Pleistocene deposits in Thailand are only rarely exposed. Most of them are recognized by their terrestrial and coastal landforms. On the Andaman Sea coast, colluvial stiff clay containing peat and wood fragments has been reported at Phuket and Phangnga. ^{14}C dating has revealed the age of the former to be 31 050 ± 280 years (Kruse 1983) and on Phangnga to be 30 430 ± 1600 years (Sinsakul *et al.* 1985). The presence of such Pleistocene stiff clay on the Andaman Sea coast is widespread and it is commonly overlain by Holocene deposits (Sinsakul *et al.* 1985). It is likely that this depositional pattern on the Andaman Sea coast correlates with a similar pattern recognized from the Quaternary sequences of the Gulf of Thailand, and may be caused by a similar history of sea-level changes. A few relict strandplains inferred to have formed during the Late Pleistocene to Early Holocene have been reported on the Surat Thani coastal plain (Roy 1994) and on Phra Thong Island in Phangnga Province (Choowong *et al.* 2008*a*).

Holocene deposits

Holocene deposits and their landforms are widespread in the coastal lowland areas along the Gulf of Thailand coast as far as the Thailand–Malaysian border, as well as on the Andaman Sea

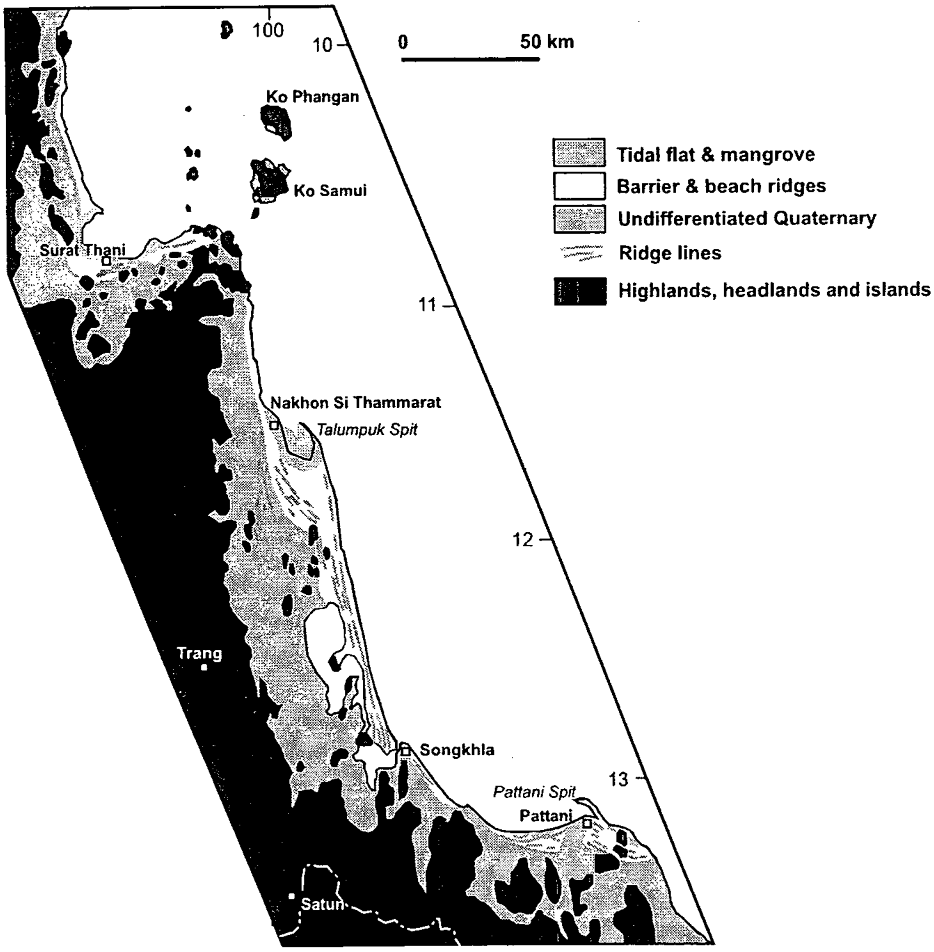

Fig. 12.8. Regional geomorphological map showing Quaternary deposits along the coastal zone of the west side of the Lower Gulf of Thailand.

coast. They show a mainly marine influence and comprise a series of beach ridges, swales and tidal lagoons. Beach ridges occur both alongshore and in pocket bays (e.g. Chumphon Bay, Fig. 12.1). The largest accumulation of Holocene deltaic sediments is in Ban Don Bay where rivers draining Surat Thani Province enter the Gulf of Thailand. Further south, the modern Talumpuk and Pattani sand spits curve slightly landward at their northern and western ends, and reflect the modern active north-westerly longshore drift.

The Thale Luang and the Great Songkhla Lake on the Lower Gulf of Thailand coast near Songkhla are brackish-water lagoons and the largest coastal lagoons in Thailand. Only a small inlet/outlet at their southern end connects them to the Gulf of Thailand. The lagoons are interconnected, elongate and parallel to the series of Holocene beach ridges and barriers which separate them from the Gulf of Thailand (Chaimanee *et al.* 1985). Horton *et al.* (2005) reported that the sedimentary sequences at the bottom of the Great Songkhla Lake are richly organic and contain palynomorph assemblages dominated by mangroves and freshwater swamp deposits. Geochronological data from the bed of the lake indicate one of the earliest mangrove environments at 8420–8190 years, which was subsequently replaced by a freshwater swamp environment at 7880–7680 years as the marine influence declined (Horton *et al.* 2005).

Aeolian sand dune deposits

Wind-blown sand dunes deposited on top of a beach-ridge plain are present over a wide area in the Bang Berd coastal area of Chumphon Province, a unique aeolian landform on this coast (Fig. 12.9). At a maximum elevation of 20 m above the present MSL, these deposits may represent repeated storm events. The geographical location of these wind-blown sand dunes is on the pathway of typhoons which, although infrequent, normally strike the Gulf of Thailand from the NW. Preliminary results of thermoluminescence (TL) and optically stimulated luminescence (OSL) datings of the sand dunes show they formed from *c.* 3000 years ago. The uppermost part of the sand dunes was deposited about 100 years ago (Prachantasen *et al.* 2008).

Correlation of Quaternary deposits and environments of Thailand

The Quaternary in Thailand has traditionally been considered as the interval of global oscillating climate (glacial and interglacial episodes) that were extensively inferred based on terrestrial and marine stratigraphic correlation (Table 12.4). The Pleistocene–Holocene and Pliocene–Pleistocene boundaries were thought to correspond to a climatic event leading to the eustatic change in sea level around 10 ka and 1.8 Ma, respectively. These boundaries were considered likely to be standardized as was originally proposed at the 8th INQUA Congress in Paris in 1969. However, the age boundaries in Thailand will need to be revised to 11.5 ka for the Pleistocene–Holocene boundary and 2.7 Ma for the Pliocene–Pleistocene boundary following the later proposals of

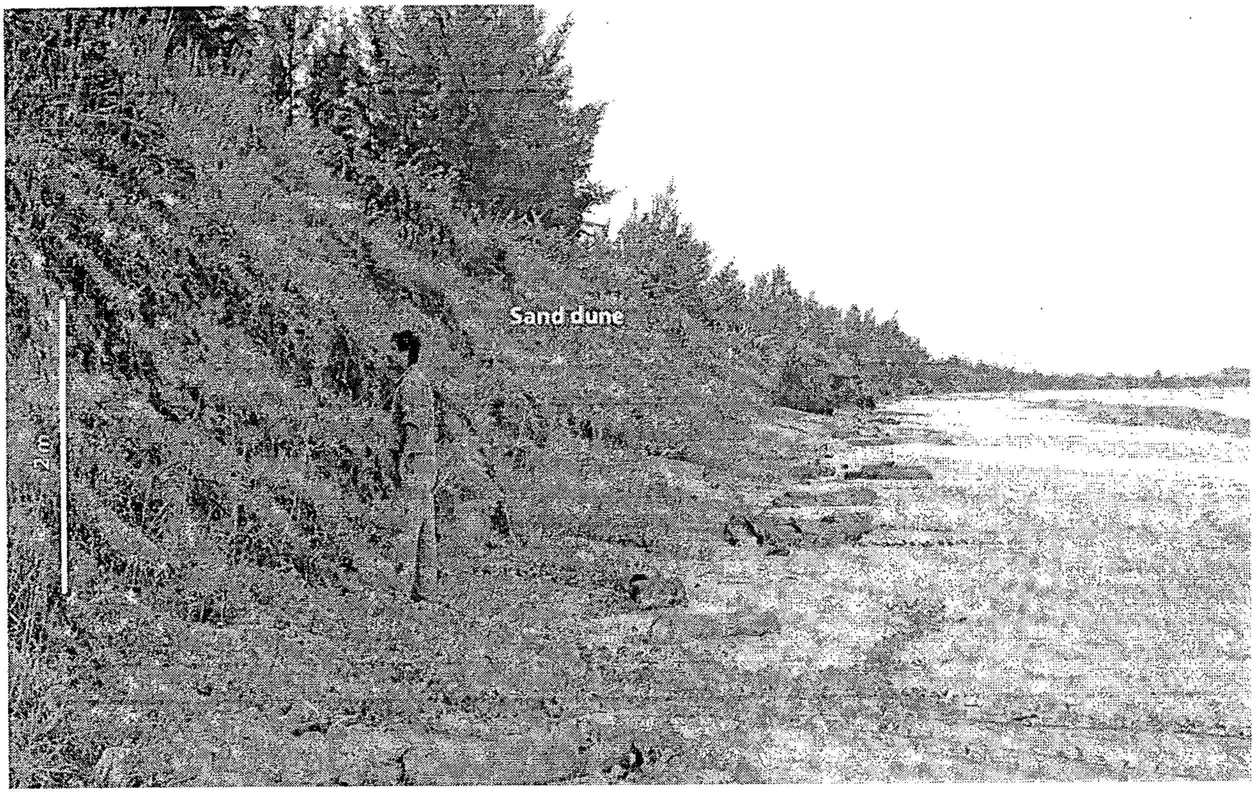

Fig. 12.9. Sand dune overlying Holocene beach deposit at the northern part of Bang Berd, Chumphon Province. Dunes here are *c.* 4–5 m above MSL and are mainly composed of very fine-grained sand which is bioturbated but otherwise structureless.

Table 12.4. *Correlation of Quaternary deposits and environments of Thailand (modified in part from Dheeradilok 1995 and Dheeradilok & Kaewyana 1986)*

Period		Northern Thailand	Northeastern Thailand		Central Thailand		Southern Peninsula
			Khorat Plateau	Lowland area	Upper Central Plain	Lower Central Plain	
Holocene		Avulsion belts Floodplain Alluvial plain	Alluvial plain Wind blown sand (loess)	Avulsion belts Floodplain	Avulsion belt Floodplain Natural levee	Floodplain Brackish intertidal deposit Active delta	Floodplain Beach ridge Lacustrine Sand dune Active delta
				Non-organic sand	Low terrace	Marine and delta	Marine and delta
Pleistocene	Upper	Fluviatile Laterite Low terrace	Fluvial organic sand	Fluvial organic sand	Alluvial fan Low to middle terrace	Estuarine Former delta Lacustrine	Marine Fluviatile
		Latest basaltic flow	Young gravel bed with tektites	Lower non-organic sand			
	Middle	Laterite Middle terrace	Older gravel bed with petrified woods	Alluvium	Fluviatile Peneplain Terrace	Fluviatile	Pediment Terrace
	Lower	High terrace (gravel bed with petrified wood)			Fluviatile	Fluviatile	Laterite
		Basaltic flow	Basalt	Saline soil			Fluviatile
Pliocene		Claystone Siltstone Semiconsolidated sandstone	Weathered Khorat Group	Weathered Mahasarakham Formation	Weathered rock basements (Granite/limestone)		Weathered older rocks

the International Commission of Stratigraphy (ICS) (Gibbard & Cohen 2008; Ogg & Pillans 2008).

Quaternary economic considerations

Mineral deposits

Quaternary deposits are utilized in several industries, either the deposit itself or the economic minerals they contain. Holocene fluvial sand is excavated extensively from abandoned river channels all around the country. Gemstone-quality sapphires have been found in Pleistocene gravel beds and in *in situ* basaltic soils in the western part of the Lower Central Plain at Kanchanaburi (Choowong 2002*b*) and in basalt-derived soils in Chanthaburi Province in SE Thailand (Vichit 1987). The Cenozoic corundum-bearing basalt in Chanthaburi Province is exposed *c.* 10 km inland and at 129 m above the present MSL, but basalt flows extend southwards into the coastal area where they are intercalated with brackish and marine mud deposits. K–Ar dating of the basalt, and hence the associated sediments, suggests an age of 0.44 $\pm$ 0.11 Ma (Chaodumrong *et al.* 1983).

Silica beach sands are an important resource for the glass industry, especially the deposits on the eastern and southern coasts of the Gulf of Thailand. Tin and its associated minerals, which over the past four decades were significant economic minerals in the country, were mined from Quaternary placer deposits along the beach areas and offshore in the Gulf of Thailand and the Andaman Sea. Other heavy minerals, also derived mainly from granite, are also found in Holocene beach and offshore sands (Roy 1989, 1990, 1991).

Quaternary changes and hazards

Sea-level changes

The first sea-level curve for Thailand was proposed by Sinsakul *et al.* (1985) and integrated into a Holocene history of sea-level changes for the wider Thai–Malay Peninsula (Tjia 1987) (Fig. 12.10). The latter shows two Holocene highstands at *c.* 5000 and 2800 ^{14}C years BP. However, the sea-level reconstruction for Thailand indicated three probable rebound phases during the Mid- to Late Holocene with highstands at 6000, 4000 and 2700 years BP (Sinsakul *et al.* 1985; Tjia 1987). Choowong (2002*a*) has sought to explain this inconsistency by pointing out that, in addition to regional eustatic sea-level changes, there were local isostatic changes which contribute to the overall history of sea-level variation. Geophysical modelling by Horton *et al.* (2005) also suggested that hydro-isostasy can account for some of the spatial variations in sea level across the Thai–Malay Peninsula. It is therefore not possible to construct a single, spatially invariable, sea-level history for the region.

A revised sea-level envelope for the Gulf of Thailand was proposed by Choowong *et al.* (2004) (Fig. 12.10) which corresponded well with the sea-level curves subsequently constructed by Horton *et al.* (2005) for the Thai–Malay Peninsula. The curves show an upward trend of rising Holocene sea level to a Mid-Holocene highstand, and then a gradual fall of sea level to the present. The average rate of sea-level rise from the Thai–Malay Peninsula was *c.* 5.5 mm per year, whereas the sea-level fall from the highstand was at about 1.1 mm per year, with no evidence of a second highstand (Horton *et al.* 2005).

Landslides and flooding

Landslides, debris flows or debris floods are now one of the country's most severe hazards. Landslides commonly occur where soil saturation limit or the surface runoff limit is exceeded, leading to rapid mass movement downslope and downstream. Landslides in Thailand are generally related to highly weathered rock basement, which might be granite or sedimentary rocks. One example was the damaging 2001 debris flow which occurred on the Nam Ko alluvial fan, located on the western margin of the Petchabun Basin in the upper part of the Upper Central Plain (Yumuang 2006). It was not the result of unusually high rainfall alone, but was caused by a combination of factors including slope gradient, the type of rock basement, volume of channel-bed sediments and modifications to the land which had taken place upstream. Such a combination of

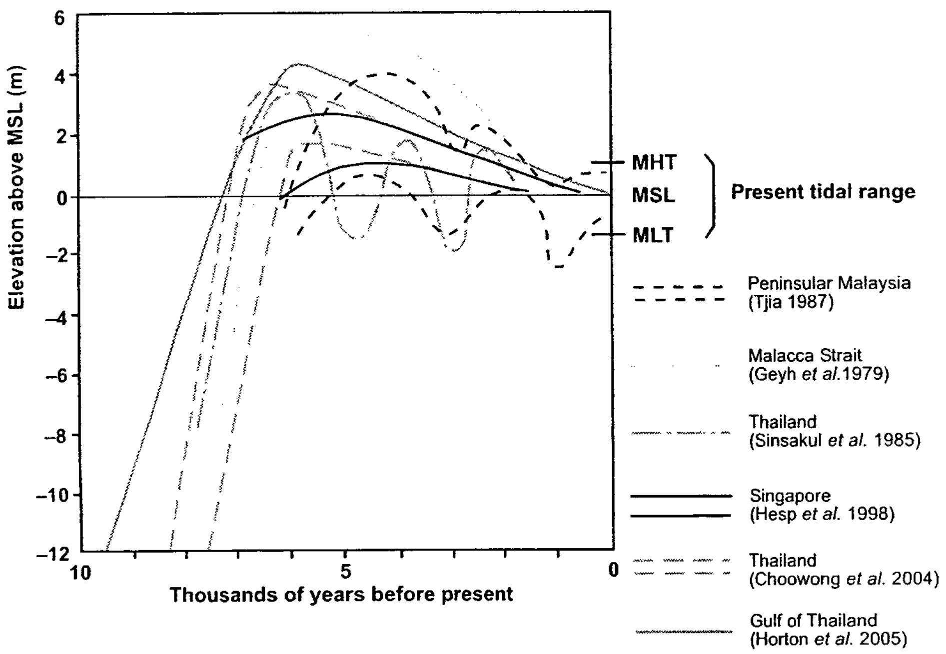

Fig. 12.10. Sea-level curves from Thailand and neighbouring countries. They show rapid transgression from the early Pleistocene to the mid-Holocene highstand, at about 3 to 4 m above present MSL. Fluctuations were reported locally from Thailand (Sinsakul *et al.* 1985) and Peninsular Malaysia (Tjia 1987) during sea-level regression after the mid-Holocene highstand.

high rainfall and other factors can be expected to trigger disasters elsewhere in Thailand in the future.

Thailand has been affected by yearly flooding throughout historical times. Whereas that has been normal on the Central Plain, it is increasingly occurring in places formerly immune from flooding, for example, in the downtown parts of Chiang Mai city in the north of the country. The severity of the flooding depends on the extent of modifications carried out on the land. Flooding seems to be most severe wherever inappropriate protective walls have been constructed on the banks of main rivers. The nature of runoff in individual subcatchments and how it has changed over time through land modifications are matters which require better understanding if future flooding is to be minimized.

Land subsidence

Subsidence of coastal areas is thought to have been occurring since the late Holocene (Choowong 2002*c*). According to the Holocene record of sea-level change from the upper Gulf of Thailand, hydro-isostatic and sedimento-isostatic subsidence may have occurred since rapid transgression started in the Late Pleistocene, resulting in a vast incursion of the sea onto the land as far as 70 km inland in the Lower Central Plain. The body of seawater may have reduced the volume of terrestrial sediment reaching the present coastline. As the column of seawater increased, the alluvium substrate became compressed and its surface subsided. During the subsequent gradual marine regression, terrestrial sediments were again supplied to the present coastline and further sediment-isostatic subsidence would have occurred. In past centuries equilibrium would have existed between sedimentation and subsidence. However, a rapid decrease of sediment supply to the coast has taken place in the last few decades after several large dams have been constructed in the catchment area of the Lower Central Plain, and equilibrium of sediment gain and loss at the coast has been affected (see further discussion below).

Land subsidence in the Lower Central Plain through groundwater extraction has become a problem in modern times (Nutalaya & Rau 1981; Nutalaya *et al.* 1984, 1996). This recent over-exploitation of groundwater depletes the aquifers beneath the urban and industrial areas of Bangkok and its vicinity, and causes non-seasonal flooding and damage to infrastructure (Phien-wej *et al.* 2006). The land surface may be flooded by the sea where subsidence has caused the land to be lower than the level of high tide (Choowong 2002*c*). This may lead to misinterpretation of the processes that actually caused the inland incursion of the sea, since it is important to distinguish land subsidence from a rise in sea level.

Coastal erosion

Changes in the position of Thailand's coastline have been studied by Vongvisessomjai (1988), Nutalaya (1996) and Sinsakul *et al.* (2003) and in places those changes have been thought to be the result of erosion. Monitoring changes in shoreline has been based on studies of topographical or hydrographical maps of different dates, aerial photographs and Landsat Thematic Mapper (TM) 1–5 images. Vongvisessomjai (1988) reported that substantial erosion has occurred at the mouth of the Bang Nara River on the southern Peninsula and at the mouth of the Chao Phraya River, and is thought to have been caused by present rising sea level (Sabhasri & Suwarnarat 1996; Sinsakul *et al.* 2003). However, tidal records from Thailand's reference datum points on Kho Lak in Prachuab Khiri Khan Province and at Sattahip in Chonburi Province during the periods 1942–1949 and 1973–1987, respectively, appear to show that the mean sea level in the Gulf of Thailand did not change during those periods (Neelasri *et al.* 1988). It is suggested that any loss of coastline through a recent rise in sea level is slight at most, and is more likely to have been caused by some natural localized isostatic adjustments (Choowong 2002*c*) or inappropriate shoreline protection structures (Nutalaya 1996). The balance in sediment budget gains and losses at the coast is also a factor that cannot be ruled out. Recently, more detailed studies of changes in the modern shoreline have been carried out.

An assessment of the yearly cycle of sedimentation/erosion balance was carried out by Songmuang (2004) in two places where Sinsakul *et al.* (2003) had considered erosion to be occurring at a moderate rate (1–5 m per year): at Pranburi and at Prachuab Khiri Khan Bay, both on the Gulf coast of the Peninsula. The position of the shoreline was measured from a series of aerial photographs taken between 1967 and 2004 and was corrected to show the shoreline at mean sea level. Shore profiles were then measured continuously over the two-year period 2003–2004. The results suggested that the shoreline in those two localities showed no significant gain or loss, although slight seasonal changes in the coastal profile were noted. Further careful monitoring of coastal changes through time is essential, and it would appear that previous estimates of Thailand's coastal erosion are likely to need revision.

Since the Mid-Holocene, land progradation seawards has steadily taken place although, as already mentioned, the net volume of sediment supply to the coast via the main river channels has decreased rapidly within the last few decades (mainly through the construction of dams). Additionally, construction of road and railway embankments parallel to the coastlines also slows surface runoff and prevents sediments from reaching the sea (Nutalaya 1996). Further research into the effect of these and associated sea walls is needed before a clear picture of sediment dynamics, tidal circulation and changes to coastal morphology since the Mid-Holocene is possible.

Earthquakes and tsunamis

Important studies of modern earthquakes and active faults are being carried out to provide a better understanding of ways to mitigate seismic hazards. Since the 26th December 2004 Sumatra earthquake and its catastrophic tsunami, a search for palaeotsunami events in the geological record has also begun. A number of studies of the 2004 tsunami deposits and post-tsunami beach surveys in Thailand have been published (Choowong *et al.* 2007, 2008*a*, *b*, 2009; Hawkes *et al.* 2007; Hori *et al.* 2007; Umitsu *et al.* 2007) and they have provided a key analogue for searching for pre-2004 tsunami deposits. To date, one such pre 2004-tsunami deposit has been reported (Jankaew *et al.* 2007, 2008) whose age from radiocarbon dating was *c.* 3000 to 600 years before the 2004 tsunami event. Further studies into pre-2004 tsunami deposits could assist in identifying other earthquake sites which could in future trigger major tsunamis, and thus enable mitigating steps to be taken.

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References

AKSORNKAOE, S. 1975. *Structure, Regeneration and Productivity of Mangroves in Thailand.* Unpublished PhD thesis, Michigan State University, East Lansing, USA.

AKSORNKAOE, S. & PAPHAVASIT, N. 1993. Effect of sea level rise on the mangrove ecosystem in Thailand. *Malaysian Journal of Tropical Geography*, **24**, 29–35.

Alexseev, M. N. & Takaya, Y. 1967. An outline of the Upper Cenozoic deposits in the Chao Phraya Basin, Central Thailand. *Southeast Asian Studies*, **5**, 106–124.

Bhongaraya, S. 1998. *Geomorphology of the Ping and the Wang River Basin, Amphoe Sam Ngao and Ban Tak area Changwat Tak*. Unpublished MSc thesis, The Department of Geology, Faculty of Science, Chulalongkorn University.

Bishop, P. 1988. Late Holocene alluvial stratigraphy and history in the Sisatchanalai area, north central Thailand. *In*: Thiramongkol, N. (ed.) *Proceedings of the workshop on Correlation of Quaternary Successions in South, East and Southeast Asia*, Bangkok, Thailand, 21-24 November 1988, 117–134.

Bishop, P. & Godley, D. 1994. Holocene palaeochannels at Si Satchanalai, north-central Thailand: ages, significance and palaeoenvironmental indications. *The Holocene*, **4**, 32–41.

Brown, G. F., Buravas, S., Charaljavanaphet, N., Johnson, W. D., Sresthaputha, V. & Taylor, G. 1951. *Geological Reconnaissance of the Mineral Deposits of Thailand*. U.S. Geological Survey Bulletin. No. **984**.

Bunopas, S., Wasson, J. T. *et al.* 1999. Catastrophic loess, mass mortality and forest fires suggest that a Pleistocene cometary impact in Thailand caused the Australian Tektite field. *Journal of the Geological Society of Thailand*, **1**, 1–17.

Chaimanee, N., Jongkanjanasoonthorn, Y., Kenvises, S. & Theerarungsikul, N. 1985. *Quaternary Geology of Sanamchai and Phatthalung area*. Technical report of the Department of Mineral Resources, Thailand, **61** (in Thai with English abstract).

Chaodumrong, P., Ukakimapan, Y., Snansieng, S., Janmaha, S., Pradidtan, S. & Sae Laow, N. 1983. A review of Tertiary sedimentary rocks of Thailand. *Proceedings of Workshop on Stratigraphic Correlation of Thailand and Malaysia*. Technical Paper, **1**, 159–187.

Chonglakmani, C., Ingavat, R., Piccoli, G. & Robba, E. 1983. The last marine submersion of the Bangkok area in Thailand. *Memorie Di Scienze Geologiche. Padova*, **36**, 35–352.

Choowong, M. 2002*a*. The geomorphology and assessment of indicators of sea-level changes to study coastal evolution from the Gulf of Thailand. *In*: Montajit, N. (ed.) *International Symposium on "Geology of Thailand"*, Department of Mineral Resources, Thailand, August 2002, 207–220.

Choowong, M. 2002*b*. Quaternary geology and sapphire deposits from the Bo Phloi gem field, Kanchanaburi province, western Thailand. *Journal of Asian Earth Sciences*, **20**, 119–125.

Choowong, M. 2002*c*. Isostatic models and Holocene relative changes in sea level from the coastal lowland area in the Gulf of Thailand. *Journal of Scientific Research, Chulalongkorn University*, **27**, 83–92.

Choowong, M. 2002*d*. Coastal sedimentary lithofacies and episodic evolution from the eastern part of Thailand. *Journal of Scientific Research, Chulalongkorn University*, **27**, 111–129.

Choowong, M., Ugai, H., Charoentitirat, T., Charusiri, P., Daorerk, V., Songmuang, R. & Ladachart, R. 2004. Holocene biostratigraphical records in coastal deposits from Sam Roi Yod National Park, Prachuap Khiri Khan, Western Thailand. *The Natural History Journal of Chulalongkorn University*, **4**, 1–18.

Choowong, M., Murakoshi, N. *et al.* 2007. Erosion and deposition by the 2004 Indian Ocean tsunami in Phuket and Phang-nga Provinces, Thailand. *Journal of Coastal Research*, **23**, 1270–1276.

Choowong, M., Murakoshi, N. *et al.* 2008*a*. Flow conditions of the 2004 Indian Ocean tsunami in Thailand, inferred from capping bedforms and sedimentary structures. *Terra Nova*, **20**, 141–149.

Choowong, M., Murakoshi, N. *et al.* 2008*b*. 2004 Indian Ocean tsunami inflow and outflow at Phuket, Thailand. *Marine Geology*, **248**, 179–192.

Choowong, M., Phantuwongraj, S., Charoentitirat, T., Chutakositkanon, V., Yumuang, S. & Charusiri, P. 2009. Beach recovery after 2004 Indian Ocean tsunami from Phang-nga, Thailand. *Geomorphology*, **104**, 134–142.

Coleman, J. M. & Wright, L. D. 1971. Analysis of major river systems and their deltas: procedures and rationale, with two examples. *Louisiana State Univ., Coastal Studies Institute Technical Report*, **95**.

Dheeradilok, P. 1986. Review of Quaternary geological mapping and research in Thailand. Progress in Quaternary Geology of East and Southeast Asia. *Proceedings of CCOP Symposium*, Bangkok, 27–30 October 1986 (Document CCOP/TP 18), 109–139.

Dheeradilok, P. 1995. Quaternary coastal morphology and deposition in Thailand. *Quaternary International*, **26**, 49–54.

Dheeradilok, P. & Kaewyana, W. 1986. On the Quaternary deposits of Thailand. *Geological Society of Malaysia Bulletin*, **19**, 515–532.

Di Geronimo, I., Sanfilippo, R. & Chaimanee, N. 2002. The Quaternary Fauna from Bam Pak Bo (Western Thailand). *In*: Montajit, N. (ed.) *Symposium on Geology of Thailand*. Bangkok, Thailand, 26–31 August 2002, 342–349.

Di Geronimo, I., Sanfilippo, R., Chaimanee, N., Robba, E. & Negri, M. P. 2005. An actuopaleontological approach to the assessment of recent changes in benthic molluscan biodiversity: preliminary result in the Northern Gulf of Thailand. *Rend. Soc. Paleontol. Ital.*, **2**, 37–68.

Geyh, M. A., Kudrass, H.-R. & Streif, H. 1979. Sea-level changes during the late Pleistocene and Holocene in the Straits of Malacca. *Nature*, **278**, 441–443.

Gibbard, P. & Cohen, K. M. 2008. Global chronostratigraphical correlation table for the last 2.7 million years. *Episodes*, **31**, 243–247.

Hanebuth, T., Stattegger, K. & Grootes, P. M. 2000. Rapid flooding of the Sunda Shelf: a Late-Glacial sea-level record. *Science*, **288**, 1033–1035.

Hattori, T. 1969. Mineral composition of clay fractions in some Quaternary deposits in the Chao Phraya Basin, central Thailand. *Center for Southeast Asian Studies*, **6**, 241–246.

Hattori, T. 1971. The Quaternary stratigraphy in the Northern Basin of the Central Plain, Thailand. *Center for Southeast Asian Studies*, **9**, 398–420.

Hattori, T. 1972. Some Properties of Brackish Sediments along the Chao Phraya River of Thailand. *Center for Southeast Asian Studies*, **9**, 522–532.

Hawkes, A., Bird, M. *et al.* 2007. Sediments deposited by the 2004 Indian Ocean tsunami along the Malaysia–Thailand Peninsula. *Marine Geology*, **242**, 169–190.

Hesp, P. A., Hung, C. C., Hilton, M., Ming, C. L. & Turner, I. M. 1998. A first tentative Holocene sea-level curve for Singapore. *Journal of Coastal Research*, **14**, 308–314.

Hori, K., Kuzumoto, R., Hirouchi, D., Umitsu, M., Janjirawuttikul, N. & Patanakanog, B. 2007. Horizontal and vertical variation of 2004 Indian tsunami deposits: an example of two transects along the western coast of Thailand. *Marine Geology*, **239**, 163–172.

Horton, B. P., Gibbard, P. L., Mile, G. M., Morley, R. J., Purintavaragul, C. & Stargardt, J. M. 2005. Holocene sea levels and palaeoenvironments, Malay–Thai Peninsula, Southeast Asia. *The Holocene*, **15**, 1–15.

Howard, K. T. 2011. Tektites. *In*: Ridd, M. F., Barber, A. J. & Crow, M. J. (eds) *The Geology of Thailand*. The Geological Society, London, 573–591.

Intasen, W., Tepsuwan, T. & Seritrakul, S. 1999. Seismic facies, stratigraphy and evolutionary model of the late Quaternary deposits in the Lower Central Plain of Thailand. *Proceedings of the Thai–Japanese Geological Meeting: Comprehensive Assessments on Impacts of Sea-Level Rise*, Petchaburi, Thailand, November 30–December 4, 1999, 108–124.

Jankaew, K., Choowong, M. *et al.* 2007. A pre-2004 tsunami deposit in Thailand. *Eos Trans. AGU*, **88**, 23.

Jankaew, K., Atwater, B. F., Sawai, Y., Choowong, M., Charoentitirat, T., Martin, M. E. & Prendergast, A. 2008. Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand. *Nature*, **455**, 1228–1231.

Japan International Cooperation Agency. 1995. *The study on management of groundwater and land subsidence in the Bangkok Metropolitan area and its vicinity*. Final report, March 1995, Kokusai Kogyo Co. Ltd.

Kengkoom, S. 1992. Quaternary sea-level fluctuations in the coastal area of eastern Thailand: a synoptic view in relation to mineral resources exploration. *Journal of Southeast Asian Earth Sciences*, **7**, 39–51.

Koeningswald Von, G. H. R. 1959. A Mastodon and other fossil mammals from Thailand. Department of Mineral Resources of Thailand. Report of Investigation, **2**, 25–28.

Kruse, G. A. M. 1983. Carbon 14 data from tin mines on Phuket island, Thailand. *CCOP Newsletter*, **10**, 19–20.

MELIS, R. & VIOLANTI, D. 2006. Foraminiferal biodiversity and Holocene evolution of the Petchaburi coastal area (Thailand Gulf). *Marine Micropaleontology*, **61**, 94–115.

MORLEY, C. K., SMITH, M., CARTER, A., CHARUSIRI, P. & CHANTRAPRASERT, S. 2007. Evolution of deformation styles at a major restraining bend, constraints from cooling histories, Mae Ping fault zone, western Thailand. *In*: CUNNINGHAM, W. D. & MANN, P. (eds) *Tectonics of Strike-Slip Restraining and Releasing Bends*. Geological Society, London, Special Publications, **290**, 325–349.

NEELASRI, C., PUNPUK, V. & RADOK, R. 1988. An investigation of mean sea level change in the Upper Gulf of Thailand. *Proceedings of an International Symposium on Sea Level Rise*, Bangkok.

NUTALAYA, P. 1996. Coastal erosion in the Gulf of Thailand. *GeoJournal*, **38**, 283–300.

NUTALAYA, P. & RAU, J. J. 1981. Bangkok: The Sinking Metropolis. *Episodes No. 4*, 3–8.

NUTALAYA, P., CHANDRA, S. & BALASUBRAMANIAN, A. S. 1984. Subsidence and its control in Bangkok. *International Symposium on Geotechnical Aspects of Mass and Material Transportation*. Bangkok, 479–500.

NUTALAYA, P., VELLA, P., BUNOPAS, S. & WORAKOON, K. 1986. Quaternary process in Thailand. *Proceedings of the Workshop on Economic Geology, Tectonics, Sedimentary Processes and Environment of the Quaternary in Southeast Asia*, Haad Yai, Thailand, 3–7 February 1986, 35–44.

NUTALAYA, P., YONG, R. N., THONGCHAI, C. & BUAPENG, S. 1996. Land subsidence in Bangkok during 1978–1988. *In*: MILLIMAN, D. J. & HAQ, U. B. (eds) *Sea-Level Rise and Coastal Subsidence; Causes, Consequences and Strategies*. Kluwer Academic Publishers, London, 105–130.

OGG, J. G. & PILLANS, B. 2008. Establishing Quaternary as a formal international Period/System. *Episodes*, **31**, 230–233.

PHIEN-WEJ, N., GIAO, P. H. & NUTALAYA, P. 2006. Land subsidence in Bangkok, Thailand. *Engineering Geology*, **82**, 187–201.

PRACHANTASEN, N., CHOOWONG, M., PAILOPLEE, S. & PHANTUWONGRAJ, S. 2008. Sedimentary characteristics of sand dune from Bang Berd, Chumporn Province, western Thailand. *Bulletin of Earth Sciences of Thailand*, **1**, 28–34.

PRADIDTAN, S. & DOOK, R. 1992. Petroleum geology of the northern part of the Gulf of Thailand. *National Conference on Geologic Resources of Thailand: Potential for Future Development. DMR*, Bangkok, Thailand, 17–24 November 1992, 235–246.

ROBBA, E., CHAIMANEE, N., DHEERADILOK, P., JONGKANJANASOONTHORN, Y., PICOLLI, G. & BOYL, A. P. 1993. Late Quaternary molluscan communities from the Bangkok Clay, Thailand. *Proceedings of International symposium on Biostratigraphy of Mainland Southeast Asia; Facies and Palaeotology*, Chiang Mai, 427–437.

ROY, P. S. 1989. *Offshore Mineral Exploration in the Gulf of Thailand. Quaternary Geology: a methodology for marine minerals exploration using lithofacies concepts*. United Nations (DTCD) Mission Report, 1 March–28 April 1989.

ROY, P. S. 1990. *Offshore Minerals Exploration in the Gulf of Thailand; review of Quaternary geology of the coast and offshore seabed in exploration area 2*. UN/DTCD Mission Report, March 1990.

ROY, P. S. 1991. *Offshore Minerals Exploration in the Gulf of Thailand. Description of the Quaternary coastal geology in Exploration Area 3 and a review of factors controlling placer mineralization in the Gulf of Thailand*. United Nations (DTCD) Mission Report, May 20–June 20 1991.

ROY, P. S. 1994. *Offshore Minerals Exploration in the Gulf of Thailand: the geology, stratigraphy and mineral prospectivity of inshore parts of the Gulf of Thailand: a preliminary assessment of drilling results*. UN/DDMS Mission Report, April 18–May 18 1994.

SABHASRI, S. & SUWARNARAT, K. 1996. Impact of sea level rise on flood control in Bangkok and vicinity. *In*: MILLIMAN, D. J. & HAQ, U. B. (eds) *Sea-Level Rise and Coastal Subsidence; Causes, Consequences and Strategies*. Kluwer Academic Publishers, London, 343–356.

SASADA, M., RATANASTHIEN, B. & SOPONPONGPIPAT, P. 1987. New K-Ar ages from the Lampang basalt, northern Thailand. *Bulletin of the Geological Survey of Japan*, **39**, 13–20.

SATHIAMURTHY, E. & VORIS, K. H. 2006. Maps of Holocene Sea Level Transgression and Submerged Lakes on the Sunda Shelf. *The Natural History Journal of Chulalongkorn University*, **5** (Suppl. 2), 1–44.

SINSAKUL, S. 1992. Evidence of Quaternary sea level changes in the coastal areas of Thailand: a review. *Journal of Southeast Asian Earth Sciences*, **7**, 23–37.

SINSAKUL, S., SONSUK, M. & HASTING, P. J. 1985. Holocene sea levels in Thailand: evidence and basis for interpretation. *Journal of Geological Society of Thailand*, **8**, 1–12.

SINSAKUL, S., TIYAPAIRACH, S., CHAIMANEE, N. & ARAMPRAYOON, T. 2003. Coastal change along the Andaman Sea coast of Thailand. Bangkok. *Technical report of the Department of Mineral and Resources, Thailand* (in Thai with English abstract).

SIRIPONG, A. 1989. The cause of circulation in the Gulf of Thailand. *Paper presented at the Association of Southeast Asian Marine Scientists. General Assembly and Symposium*. Manila, Philippines, 6–7, February 1989.

SOMBOON, J. R. P. 1990. *Geomorphology of the Chao Phraya Delta, Thailand*. Unpublished PhD thesis, Kyoto University, Japan.

SOMBOON, J. R. P. & THIRAMONGKOL, N. 1992. Holocene highstand shoreline of the Chao Phraya Delta, Thailand. *Journal of Southeast Asian Earth Sciences*, **7**, 53–60.

SONGMUANG, R. 2004. *Evaluation of Shoreline Changes and Coastal Erosion Hazards from Prachuap Khiri Khan*. Unpublished MSc thesis, Department of Geology, Faculty of Science, Chulalongkorn University, 110.

SUPAJANYA, T. 1981. Delineation of the regression shorelines in the lower Chao Phraya Plain. *Proceedings of the Seventeenth Session, Committee for Coordination of Joint Prospecting for Mineral Resources*, 232–237.

SUPAJANYA, T. 1983. Tentative correlation of old shorelines around the Gulf of Thailand. *First Symposium on Geomorphology and Quaternary Geology of Thailand*, Bangkok, Thailand, October 1983, 96–105.

SURAKIATCHAI, P. 2006. *Classification of gastropoda and bivalvia fossils from the Khao Sam Roi Yod National Park, Prachuap Khiri Khan Province, Thailand*. Unpublished MSc thesis, Department of Geology, Faculty of Science, Chulalongkorn University.

TAKAYA, Y. 1968. Quaternary outcrops in the Central Plain of Thailand. *Reports on Research in S.E. Asia, Natural Science Series No. 3, The Center for S.E. Asian Studies*, Kyoto University, 7–68.

TAKAYA, Y. 1971. Two brackish clay beds along the Chao Phraya River of Thailand. *Center for S.E. Asian studies*, Kyoto University, **9**, 46–57.

TAKAYA, Y. 1972. Physiography of rice land in peninsular Thailand. *Center for S.E. Asian studies*, Kyoto University, **10**, 422–432.

TAKAYA, Y. & THIRAMONGKOL, N. 1982. Chao Phraya of Thailand, Asian Rice-Land, Investory. *S.E. Asian Studies*, Kyoto University, **1**, 138 (map).

TANABE, S., SAITO, Y., SATO, Y., SUZUKI, Y., SINSAKUL, S., TIYAPAIRACH, S. & CHAIMANEE, N. 2003. Stratigraphy and Holocene evolution of the mud-dominated Chao Phraya delta, Thailand. *Quaternary Science Reviews*, **22**, 789–807.

THIRAMONGKOL, N. 1983*a*. Quaternary stratigraphy of Thailand. *Workshop on Stratigraphy Correlation of Thailand and Malaysia*. Haad Yai, Thailand, September 1983, 188–203.

THIRAMONGKOL, N. 1983*b*. Geomorphology of the lower Central Plain, Thailand. *Third Meeting of the Working Group on Geomorphology and Quaternary Geology of Thailand*, Bangkok, Thailand. October 1983, 13–25.

THIRAMONGKOL, N. 1983c. Reviews of geomorphology of Thailand. *First Symposium on Geomorphology and Quaternary Geology of Thailand*, Bangkok, Thailand, October 1983, 6–23.

THIRAMONGKOL, N. 1986. Neotectonism and rate of uplift in the eastern margin of the lower Central Plain of Thailand. *Proceedings of the Workshop on Economic Geology, Tectonics, Sedimentary Processes and Environment of Southeast Asia*, Haad Yai, Thailand, 3–7 February 1986, 3–22.

TJIA, H. D. 1987. Changes of sea level in the southern South China Sea area during Quaternary times. *Proceedings of Symposium on Quaternary Geology of the Malay-Indonesian Coastal and Offshore Areas (CCOP Report, CCOP/TP.5)*, 11–36.

TULTHAVEEWAT, R., CHABANGBON, A. & CHOOWONG, M. 2008. Avulsion of the Chao Phraya River from part of Nakhon Sawan Province, Thailand. *Bulletin of Earth Sciences of Thailand*, **1**, 40–43.

UMITSU, M., TIYAPAIRACH, S., CHAIMANEE, N. & KAWASE, K. 2002. Late Holocene sea-level change and evolution of the Central Plain, Thailand. *Symposium on Geology of Thailand.* Bangkok, Thailand, 26–31 August 2002, 196–200.

UMITSU, M., TANAVUD, C. & PATANAKANOG, B. 2007. Effects of landforms on tsunami flow in the plains of Banda Aceh, Indonesia, and Nam Khem, Thailand. *Marine Geology*, **242**, 141–153.

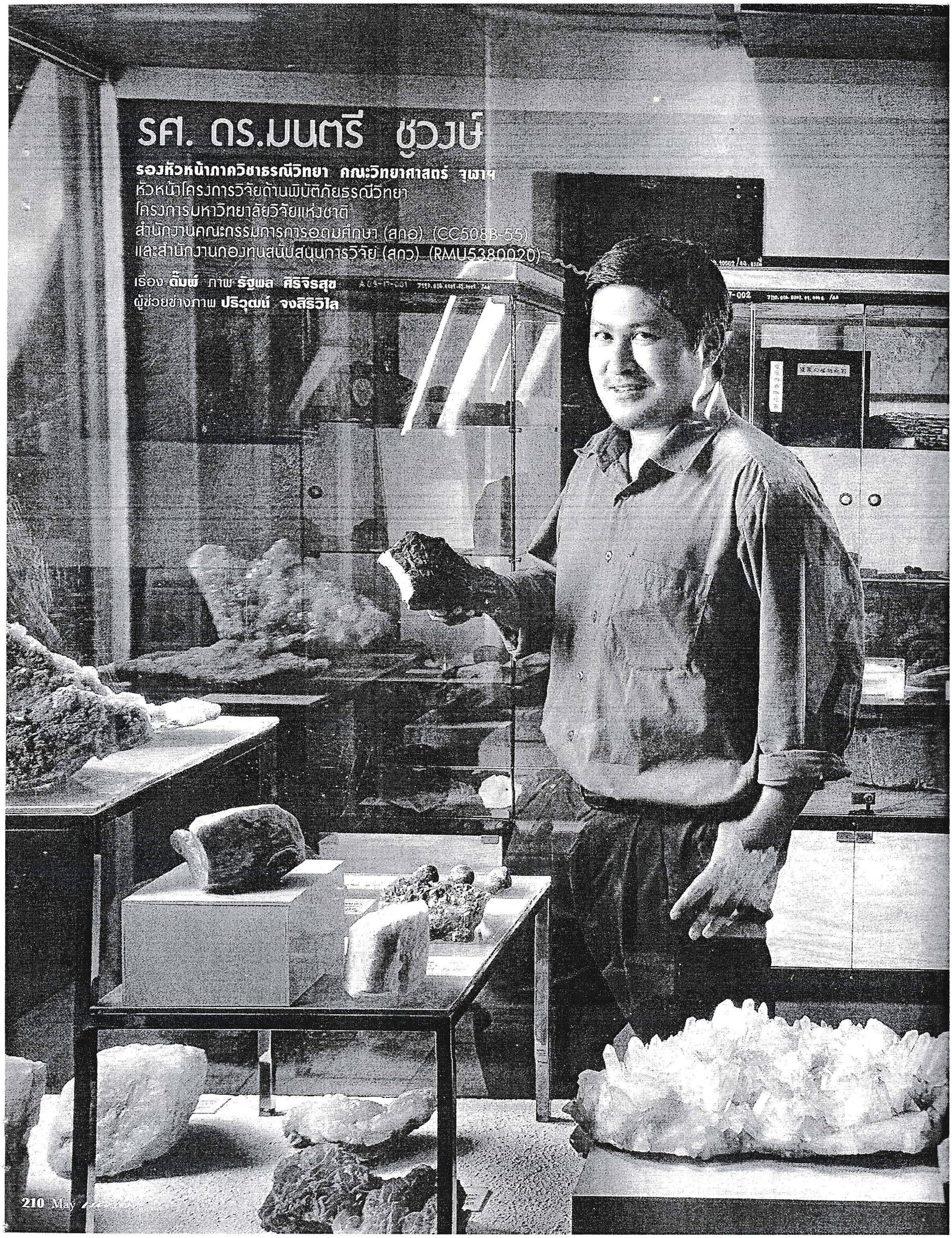
VICHIT, P. 1987. Gemstone in Thailand. *Journal of Geological Society of Thailand*, **9**, 108–233.

VONGVISESSOMJAI, S. 1988. Coastal Erosion – A Case Study for Coastal Area of Thailand. *Proceedings of an International Symposium on Sea Level Rise*, Bangkok.

WONGSOMSAK, S. 1992. Preliminary investigation on Mekong terraces in Nakhon Phanom Province: Distribution, characteristic, age and implication. *Proceedings of a National Conference on Geologic Resources of Thailand: Potential for future Development*, Department of Mineral Resources, Bangkok, 326–331.

WRIGHT, L. D. 1972. River delta morphology: wave climate and the role of the subaqueous profile. *Science*, **176**, 282–284.

YUMUANG, S. 2006. 2001 debris flow and debris flood in Nam Ko area, Phetchabun Province, central Thailand. *Environmental Geology*, **51**, 545–564.



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หัวหน้าโครงการวิจัยด้านพิบัติภัยธรณีวิทยา
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สำนักงานคณะกรรมการการอุดมศึกษา (สกอ) (CC508B-55)
และสำนักงานกองทุนสนับสนุนการวิจัย (สกว) (RMU5380020)

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"ประเทศไทยนับถอยหลังเผชิญหน้า 3 ภัยพิบัติ"

เขาคืออาจารย์ด้านธรณีวิทยาคนแรก ที่ศึกษาเรื่อง "สึนามิ" อย่างถ่องแท้ จนได้ดีกรีปริญญาเอก รวมทั้งศึกษาเกี่ยวกับสภาพภูมิประเทศในแต่ละพื้นที่ และแม่น้ำสายต่างๆ ของประเทศไทยอย่างละเอียด เราจึงขอให้เขาวิเคราะห์ข้อมูลทางวิทยาศาสตร์ ถึงแนวโน้มภัยพิบัติต่างๆ ที่อาจเกิดขึ้นในปีนี้และปีต่อไป

รู้ไว้เพื่อตื่นตัว ช่วยกันรักษ์โลก และเตรียมพร้อมรับมือทุกสถานการณ์ที่อาจเกิดขึ้น

ได้เวลา "ปรับสมดุลโลก"

รศ. ดร.มนตรีอธิบายว่า โลกเราเกิดมา 4,500 ล้านปีแล้ว และมีวิวัฒนาการที่ทำให้เกิดการเปลี่ยนแปลงทางกายภาพตลอดเวลา แต่ยุคที่เห็นการเปลี่ยนแปลงชัดเจนที่สุด เกี่ยวข้องกับทุกชีวิตทั้งพืชและสัตว์ คือ ยุคไดโนเสาร์สูญพันธุ์เมื่อ 65 ล้านปีมาแล้ว อย่างไรก็ตาม จะเห็นว่าโดยกระบวนการทางธรรมชาติของโลก มีการปรับตัวเองตลอดเวลา เหมือนร่างกายคนเรา ตอนเป็นไข้ ตัวร้อน เหงื่อออก บางคนอาเจียนออกมา โลกเองก็ต้องปลดปล่อยพลังงานออกมาในรูปของแผ่นดินไหวบ้าง มีการหมุนเวียนสับเปลี่ยนสภาพภูมิอากาศ ความร้อนและเย็น การเปลี่ยนแปลงของโลกปัจจุบัน จึงถือเป็นการปรับสมดุลครั้งสำคัญทั้งภายในโลก พื้นผิวโลก และชั้นบรรยากาศ บวกกับปัจจุบันเรามีเทคโนโลยีสื่อสารดีขึ้น ทำให้เรารับรู้ตลอดเวลาว่า เกิดภัยพิบัติอะไรที่ไหนบ้าง

"เมื่อโลกปรับตัวจนได้สมดุลแล้ว ทุกอย่างจะเบาลงและนิ่ง หรือโลกอาจไม่หยุดการปรับตัวเลยก็ได้ ยังไม่มีใครฟันธงว่าจะเกิดภัยพิบัติแบบนี้เรื่อยๆ หรือไม่ แต่กิจกรรมหลายอย่างของมนุษย์ เช่น การใช้พลังงานและทรัพยากรที่ไม่สมดุล ไม่มีการควบคุม โดยเฉพาะเชื้อเพลิงหรือสิ่งที่ใช้แล้วหมด หาใหม่ไม่ได้ เช่น ถ่านหิน น้ำมัน ก๊าซธรรมชาติ ฯลฯ มีการปล่อยก๊าซเรือนกระจกมาตั้งแต่ยุคปฏิวัติอุตสาหกรรม จนทุกวันนี้ยังไม่หยุดปล่อย บางประเทศถึงขนาดซื้อคาร์บอนเครดิตด้วยซ้ำ เพื่อจะได้ปล่อยคาร์บอนมากน้อยตามที่ซื้อ หรือขณะที่บอกให้ช่วยกันปลูกป่า แต่ก็ยังมีการตัดต้นไม้ ทั้งหมดนี้กระตุ้นให้โลกผิดสมดุล ถ้าเรายังไม่หยุดหรือลดพฤติกรรมเหล่านี้ ก็เหมือนกระตุ้นโลกให้ต้องปรับตัวตลอดเวลาไม่หยุดนิ่ง"

รับมือ Climate Change - อุณหภูมิโลกผันแปร

"ถ้าถามว่า นับจากนี้ไปเรามีโอกาสเจอภัยพิบัติอะไรบ้าง คงต้องแยกวิเคราะห์ตามการเกิดแต่ละกระบวนการ ซึ่งทางธรณีวิทยาแบ่งโลกและบรรยากาศเป็น 3 ส่วน ส่วนแรกคือ การเปลี่ยนแปลงที่เกิดในชั้นบรรยากาศ ส่งผลกระทบกับส่วนที่ 2 คือ พื้นผิวโลก และส่วนที่ 3 คือ การเปลี่ยนแปลงที่เกิดขึ้นใต้พื้นผิวโลกและส่งผลบนพื้นผิวโลกเช่นกัน

"ถ้าพูดถึงภัยพิบัติที่เกิดขึ้นตั้งแต่พื้นผิวโลกขึ้นไปชั้นบรรยากาศ แน่นอนว่าเรื่องไคลเมตเชนจ์ หรือการผันแปรสภาพภูมิอากาศทั่วโลก เป็นสิ่งที่ทุกคนยอมรับว่าอุณหภูมิโลกเพิ่มสูงขึ้น เพียงแต่ยังไม่มีตัวเลขชัดเจนว่าสูงขึ้นกี่องศา ที่ไหนบ้าง อย่างปีนี้เมืองไทยร้อนมาก แต่ประเทศแถบยุโรปและจีน หนาวติดลบ 30 - 40 องศา ซึ่งไม่เคยเกิดมานานแล้ว ภาวะที่เกิดขึ้นจึงไม่ใช่แค่โลกร้อนอย่างเดียว แต่สภาพอากาศทั่วโลกผันแปร เป็นผลมาจากการปรับตัวของโลก โดยมีการเปลี่ยนแปลงในวัฏจักรของน้ำเป็นปัจจัยสำคัญ เพราะกว่า 71 เปอร์เซ็นต์ของพื้นผิวโลกคือน้ำ แผ่นดินมีแค่ 20 กว่าเปอร์เซ็นต์ ดังนั้นถ้าเราไม่ปรับเปลี่ยนพฤติกรรม ก็ต้องทำใจและปรับตัวให้ได้ตามสภาพอากาศ"

น้ำท่วมปีนี้มาอีกแน่...แต่เชื่อว่า "เอาอยู่"

"เครื่องมือทางวิทยาศาสตร์บันทึกข้อมูลชัดเจนว่า ภัยพิบัติบางอย่างคาดการณ์ได้ว่าอาจเกิดขึ้น เช่น น้ำท่วม และถ้ารู้ว่าจะเกิดเรื่อยๆ แทนที่จะเสียหายมากเหมือนปีที่ผ่านมา เรานำจะรู้จักปรับตัวเพื่อบรรเทาความสูญเสียได้

"อย่างในปีนี้ น้ำท่วมอีกแน่นอน แต่คงไม่เสียหายมากเหมือนปีที่แล้ว ซึ่งกว่า 80 เปอร์เซ็นต์จะเกิดน้ำท่วมในพื้นที่เดิมที่เคยน้ำท่วมซ้ำซากมาตั้งแต่อดีต ตัวผมเองเรียก 'ภัยพิบัติซ้ำซาก' เช่น จังหวัดที่อยู่ติดแม่น้ำปิง วัง ยม น่าน และเจ้าพระยา อย่างอำเภอบางระกำ พิษณุโลก บางอำเภอในนครสวรรค์ เรื่อยมาสิงห์บุรี อ่างทอง ถึงอยุธยา ปทุมธานี รังสิต นนทบุรี กรุงเทพฯ อย่าลืมว่าโดยภูมิประเทศเดิมของที่ราบภาคกลางในอดีต เป็นดินดอนสามเหลี่ยมปากแม่น้ำเก่าและบางแห่งเคยเป็นทะเลมาก่อน แสดงให้เห็นว่าพื้นที่นี้เป็นแอ่งรองรับตะกอนดินที่ไหลพัดพามาจากที่สูงในภาคเหนือและภาคตะวันตกเป็นส่วนใหญ่ผ่านทางแม่น้ำ ทับถมกันมาเรื่อยๆ จนแผ่ออกไปเป็นดินดอนสามเหลี่ยมปากแม่น้ำในอดีต และปัจจุบันเป็นที่ราบลุ่มน้ำท่วมถึง (Floodplain)

"ดังนั้น ถ้าเข้าใจว่าภาคกลางตอนล่างของบ้านเราตั้งอยู่ในพื้นที่น้ำท่วมถึงโดยธรรมชาติอยู่แล้ว ก็ทำใจได้ น้ำมาทุกปีแน่ เพียงแต่จะมากหรือน้อย เตรียมตัวรับมือได้เลย และอยู่กับน้ำให้ได้ ส่วนพื้นที่ที่ไม่เคยถูกน้ำท่วม และถูกน้ำท่วมแบบผิดธรรมชาติเมื่อปีที่แล้ว น่าจะอยู่ในความควบคุมได้ เพราะเรามีบทเรียนแล้ว และด้วยระบบการจัดการที่ทุกหน่วยงานช่วยกันอย่างเต็มที่

"นอกจากนี้ต้องระวังเรื่องดินโคลนถล่ม น้ำป่าไหลหลาก ส่วนพายุฤดูร้อน ลูกเห็บตก เกิดขึ้นทุกปีอยู่แล้ว ผมประเมินว่าคงไม่เกิดถี่ขึ้น แต่อาจเปลี่ยนจุดที่เกิดไปเรื่อยๆ ขึ้นอยู่กับสภาพพื้นที่"

แผ่นดินไหวเกิดถี่ขึ้น

"ส่วนภัยพิบัติที่เกิดใต้พื้นผิวโลกคือแผ่นดินไหว เมื่อไรก็ตามที่ภายในเปลือกโลกมีการขยับ พลังงานที่อยู่ในรูปของพลังงานความร้อนที่ถูกสะสมไว้ใต้พิภพจนอุณหภูมิสูงขึ้นและแรงเค้นที่สะสมไว้นานๆ ต้องหาทางระบายพลังงานเหล่านั้นออกมา ง่ายที่สุดก็คือปล่อยตามรอยต่อของแผ่นเปลือกโลก เปรียบเทียบเหมือนหนังลูกฟุตบอลเย็บต่อกันหลายๆ แผ่น รอยตะเข็บที่เย็บเปรียบเหมือนรอยต่อแผ่นเปลือกโลก ส่วนรอยเลื่อนต่างๆ ที่พูดถึงกันบ่อยๆ ทั้งมีพลังและไม่มีพลัง ก็อยู่บนแผ่น

เปลือกโลกแต่ละแผ่นอีกที รอยเลื่อนสำคัญในประเทศเราก็มีหลายรอยเลื่อนที่น่าจับตา เช่น รอยเลื่อนเจดีย์สามองค์ รอยเลื่อนศรีสวัสดิ์ รอยเลื่อนคลองมะรุ่ย รอยเลื่อนระนอง ฯลฯ

"ดังนั้นถ้าเกิดแผ่นดินไหวรุนแรงในโซนรอยต่อของแผ่นเปลือกโลกตั้งแต่เทือกเขาหิมาลัยลงมาทางใต้ หรือที่เรียกว่าโซนแนวการมุดตัวสุมาตรา - อันดามัน โอกาสที่สึนามิจะมาปะทะประเทศไทยมีแน่ แต่หลังจากเหตุการณ์สึนามิปี 2547 มีการคาดการณ์ทางธรณีวิทยาว่าโอกาสที่จะเกิดแผ่นดินไหวขนาด 9 ริกเตอร์ขึ้นไปจนเกิดสึนามิเหมือนปี 2547 จะเกิดอีกครั้งอย่างเร็วที่สุดคืออีกกว่า 140 ปีนับจากปี 2547 เพราะฉะนั้นในช่วงชีวิตเราไม่น่าเจอสึนามิขนาดที่สร้างความเสียหายเท่าปี 2547 อีก แต่มีความเป็นไปได้มากที่อาจเกิดสึนามิขนาดเล็กถึงปานกลาง ดังกรณีเมื่อวันที่ 11 เมษายน ที่ผ่านมา

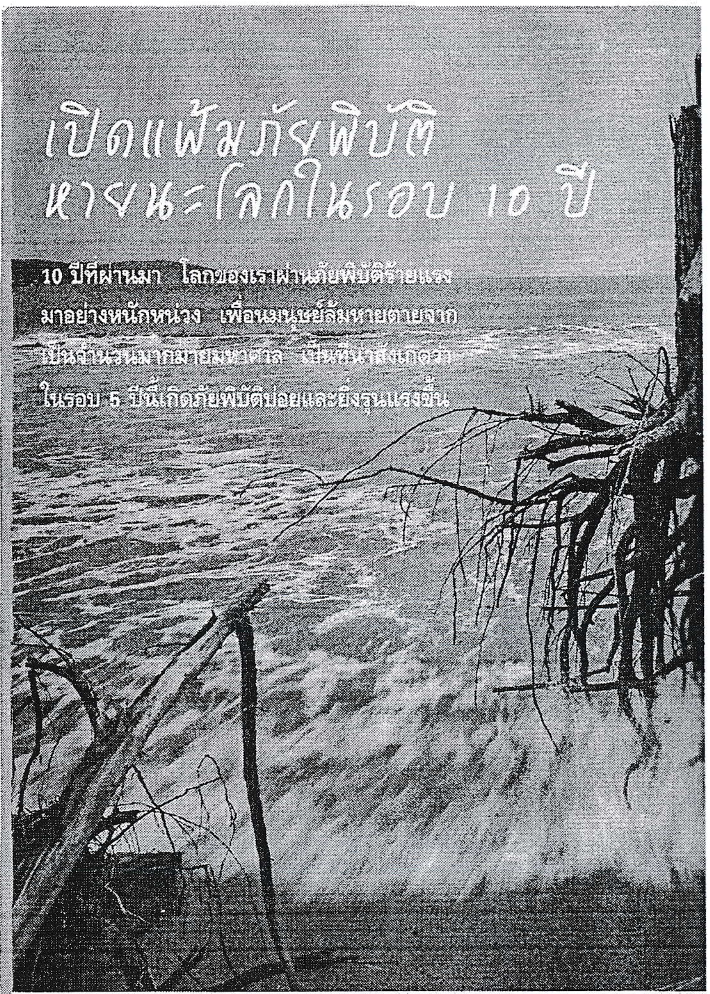
"จากข้อมูลการไหวสะเทือนที่บันทึกได้ ทำให้นักธรณีวิทยาและวิศวกรคาดการณ์ได้ว่า นับจากนี้ไปหากเกิดแผ่นดินไหวเกิน 5 ริกเตอร์ในประเทศของเรา จะทำให้อาคารสูงประมาณว่าตั้งแต่ 10 ชั้นขึ้นไปโดยเฉพาะในกรุงเทพฯ สามารถโคลงและโอนเอนได้ ถ้าเป็นอาคารรุ่นใหม่ที่สร้างหลังปี 2540 ส่วนใหญ่สามารถรองรับการสั่นไหวได้ แต่ก็ไม่ได้หมายความว่าจะปลอดภัยร้อยเปอร์เซ็นต์ ควรระวังและตรวจสอบอาคารอย่างจริงจัง

"แต่ถ้าเกิดแผ่นดินไหวในพื้นที่ใกล้เคียง เช่น พม่า ที่เราจับตากันมากคือ ในโซนรอยเลื่อนสะแกง ซึ่งมีบันทึกว่า เคยเกิดแผ่นดินไหว 7 - 8 ริกเตอร์มาแล้ว และถ้าเกิดอีก จะส่งผลต่อแขนงรอยเลื่อนที่พาดผ่านประเทศไทย เกิดความเสียหายในประเทศไทยได้ โดยเฉพาะจังหวัดในโซนตะวันตกของไทย ตั้งแต่กาญจนบุรี อุทัยธานี ตาก แม่ฮ่องสอน รวมถึงภาคเหนือ เตรียมตัวรับมือได้ สำหรับกรุงเทพฯก็ควรระวังไว้เพราะคลื่นแผ่นดินไหวมาถึงได้ จึงควรตรวจสอบตัวเองว่าอยู่ในพื้นที่หรืออาคารที่เตรียมป้องกันแผ่นดินไหวหรือเปล่า หากรู้สึกมึนๆหรือข้าวของในอาคารหล่นเสียหายเพราะตึกโอนไปเอนมา ก็ควรตั้งสติและหาทางป้องกันตัวเอง

"เมื่อรู้อย่างนี้แล้ว เราควรช่วยกันเปลี่ยนพฤติกรรมเพื่อช่วยรักษาโลก เริ่มจากศึกษาค้นคว้าข้อมูลต่างๆ เปิดรับข่าวสารและให้ความสนใจกับภัยธรรมชาติที่เกิดขึ้น อย่าหลงเชื่ออะไรง่ายๆ อย่างเช่นปี 2012 มีคนเชื่อว่าโลกจะเกิดภัยพิบัติรุนแรง หรือถึงขั้นโลกแตก แต่ในทางวิทยาศาสตร์ ณ ข้อมูลปัจจุบัน ที่เกี่ยวข้องทางธรณีวิทยา ผมพูดได้เต็มปากว่า ไม่มีหลักฐานหรือข้อมูลใดบ่งชี้ว่าโลกจะแตก

"แต่ถามว่าความถี่ของเหตุการณ์ภัยพิบัติในอนาคตจะเกิดขึ้นมากไหม นักวิทยาศาสตร์หลายคนสรุปแนวโน้มตรงกันว่า มีโอกาสเกิดถี่ขึ้นและอาจเพิ่มความรุนแรงเป็นลำดับ เช่น กรณีสภาพผันผวนของอากาศ ซึ่งเมื่อรุนแรงถึงระดับหนึ่งแล้วทุกอย่างก็จะกลับเข้าสู่สมดุล ผลกระทบอาจจะลดลงก็เป็นได้ แต่ท้ายที่สุด ทุกอย่างต้องเป็นไปตามวัฏจักรธรรมชาติ

"เพราะฉะนั้นอย่าขวางและรบกวนธรรมชาติ ป้องกัน เตรียมตัว และมีสติ ดีที่สุด"



เปิดแฟ้มภัยพิบัติ หายนะโลกในรอบ 10 ปี

10 ปีที่ผ่านมา โลกของเราผ่านภัยพิบัติร้ายแรงมาอย่างหนักหน่วง เพื่อนมนุษย์ล้มหายตายจากเป็นจำนวนมากมายมหาศาล เป็นที่น่าสังเกตว่าในรอบ 5 ปีนี้เกิดภัยพิบัติบ่อยและยิ่งรุนแรงขึ้น

ปี 2545 น้ำท่วม...โคลนถล่มภาคเหนือ

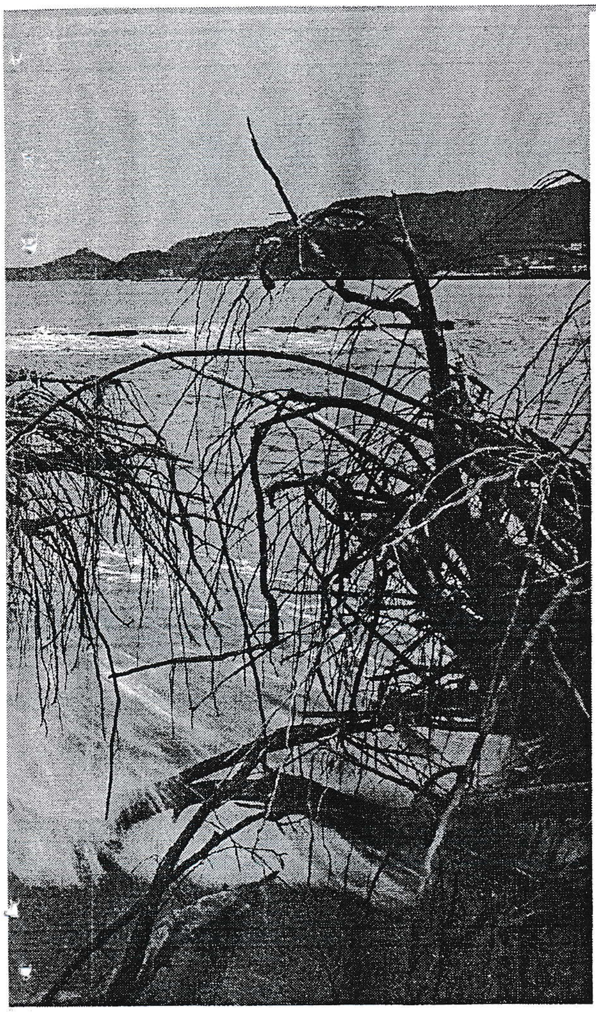
เกิดฝนตกหนักในหลายพื้นที่ เกิดน้ำท่วมเป็นบริเวณกว้างในบริเวณภาคเหนือ ภาคกลาง ภาคอีสานบางส่วน รวม 58 จังหวัด ชาวบ้านได้รับความเดือดร้อนกว่า 900 ครัวเรือน มูลค่าความเสียหาย 6,200 ล้านบาท

ปี 2546 น้ำท่วมอ่วมทั่วประเทศ

เกิดฝนตกหนักในจังหวัดเชียงราย เป็นผลให้น้ำท่วมหลายจังหวัดทางภาคเหนือ ต่อเนื่องไปถึงภาคอีสาน จนถึงกบินทร์บุรีและพระนครศรีอยุธยา ปิดท้ายปลายปีด้วยพายุดีเปรสชั่นพัดถล่มเพชรบุรีและประจวบคีรีขันธ์ เกิดฝนตกหนักติดต่อกัน น้ำท่วมขังหลายพื้นที่ รวมทั้งหาดใหญ่ และอิทธิพลคลื่นลมในทะเลและมรสุมตะวันออกเฉียงเหนือยังทำให้เกิดน้ำท่วมหนักในหลายอำเภอของจังหวัดสุราษฎร์ธานี

ปี 2547 หายนะของธุรกิจประกันภัยทั่วโลก

เกิดเหตุการณ์ผิดธรรมชาติต่างๆ มากมายในรอบ 1 ปี เช่น ร้อนสุด หนาวสุด ฝนตกหนักสุด แล้งสุด ภูเขาไฟปะทุขึ้นพร้อมกัน จนบริษัทมิวนิก รี บรรษัทธุรกิจประกันภัยเสริมรายใหญ่สุดของโลกระบุในรายงานชื่อ "ภัยพิบัติทางธรรมชาติ" ว่าเป็นปีหายนะของธุรกิจประกันภัยทั่วโลก จากภัยธรรมชาติที่เกิดขึ้นทั้งปีกว่า 560 ครั้ง มีมูลค่ารวมทั้งสิ้นไม่ต่ำกว่า 5 ล้านล้านบาท ไม่รวมเหตุการณ์สึนามิใน 14 ประเทศรวมถึงประเทศไทย ที่มีผู้เสียชีวิตมากกว่า 230,000 คน มูลค่าความเสียหายประมาณ 2,800 ล้านดอลลาร์



หนึ่งเดือนต่อมา บริเวณหมู่เกาะโซโลมอนตะวันตกเกิดแผ่นดินไหวขนาด 8.0 ริกเตอร์ จนเกิดคลื่นสึนามิผลาญชีวิตผู้คนไปมากกว่า 50 คน

ปี 2551 ภัยพิบัติมาครบ

เวนิส ประเทศอิตาลี เกิดพายุฝนหนักสุดในรอบกว่า 20 ปี ส่งผลให้น้ำท่วมสูงถึง 1.56 เมตร เช่นกันกับเวียดนามที่เผชิญน้ำท่วมเฉียบพลันจากฝนตกหนักสุดในรอบ 35 ปี ไต้หวัน เฮติ พม่า สหรัฐอเมริกา ก็ถูกพายุกระหน่ำจนอ่วมอรทัย ขณะที่จีนเกิดทั้งแผ่นดินไหวและพายุหิมะถล่มรุนแรงที่สุดในรอบ 50 ปี

ปี 2552 โศกนาฏกรรมหมู่ในเอเชีย

พายุกิสนาถล่มฟิลิปปินส์ - เวียดนาม - ลาว เกิดฝนตกรุนแรงสุดในรอบกว่า 40 ปี กวาดเรียบกว่า 500 ศพ ถัดจากนั้น 4 วันเกิดแผ่นดินไหวที่เมืองปาดัง ประเทศอินโดนีเซีย ฝังกลบชาวบ้านกว่าหนึ่งพันคน สามวันต่อมาฟิลิปปินส์ถูกพายุป้าหม่าถล่มซ้ำ จนแผ่นดินถล่มหลายสิบครั้ง คร่าชีวิตผู้คน 712 คน

ปี 2553 พสุธากัมปนาท

เปิดปีด้วยแผ่นดินไหวที่กรุงปอร์โตแปรงซ์ เมืองหลวงของเฮติ ขนาด 7.0 ริกเตอร์ มีผู้เสียชีวิตเกือบ 3 แสนราย เดือนถัดมาเกิดแผ่นดินไหวที่บริเวณชายฝั่งตะวันตกของชิลี ขนาด 8.8 ริกเตอร์ มีผลให้แกนโลกขยับจากเดิม 8 เซนติเมตร สองเดือนต่อมา เกิดภูเขาไฟระเบิดทางภาคตะวันตกเฉียงใต้ของไอซ์แลนด์ ส่งผลให้อุตสาหกรรมการบินเลวร้ายยิ่งกว่าวินาศกรรม 911 จนถึงเดือนตุลาคม เกิดน้ำท่วมทั่วทั้งภาคอีสานและภาคกลางของประเทศไทยรุนแรงที่สุดในรอบ 50 ปี

ปี 2554 เผชิญหน้าพายุสุริยะ

เกิดปรากฏการณ์พายุสุริยะรุนแรงที่สุดในรอบ 10 ปี ซึ่งเป็นสัญญาณบอกเหตุก่อนเกิดภัยพิบัติเป็นเวลา 1 - 3 วัน ไม่ว่าสึนามิที่ญี่ปุ่น น้ำท่วมภาคใต้ และมหาอุทกภัยในกรุงเทพฯ

ปี 2555

ผ่านครึ่งปีแรกกับภัยแล้งรุนแรงที่มณฑลยูนนานของจีน ในเวลาใกล้กันก็เกิดพายุหิมะครั้งรุนแรง กับพายุทอร์นาโดถล่มหลายรัฐในสหรัฐอเมริกา มีผู้เสียชีวิตหลายสิบราย

หากมนุษย์ยังไม่หยุดทำลายโลก โอกาสที่ทุกคนจะเผชิญกับภัยพิบัติจะสูงกว่านี้

ปี 2548 แผ่นดินไหวในเอเชีย

วันที่ 8 ตุลาคม ที่เขตอาซาด แคชเมียร์ ทางทิศตะวันออกเฉียงเหนือของปากีสถาน ใกล้ชายแดนอินเดีย เกิดแผ่นดินไหวโดยมีจุดศูนย์กลางอยู่ใกล้เมืองมูซัฟฟาราบัด เมืองหลวง และมียอดผู้เสียชีวิต 79,000 คน มีผู้เสียชีวิตเพิ่มเติมในแคว้นชัมมูและกัศมีร์ของอินเดียอีก 1,400 คน รวมทั้งเกิดแผ่นดินไหวขนาด 8.6 ริกเตอร์ที่เกาะเนียส ประเทศอินโดนีเซีย มีผู้เสียชีวิตอย่างน้อย 900 คน

ปี 2549 ธรณีพิโรธที่อินโดนีเซีย

27 พฤษภาคม เกิดแผ่นดินไหวขนาด 6.3 ริกเตอร์ในเขตยอกยาการ์ตา ประเทศอินโดนีเซีย มีผู้เสียชีวิต 6,000 ราย และอีก 1.5 ล้านคนไร้ที่อยู่อาศัย

ถัดมาอีก 2 เดือน เกิดแผ่นดินไหวขนาด 7.7 ริกเตอร์ ซ้ำบริเวณใต้ทะเลของเกาะชวา ประเทศอินโดนีเซีย ก่อให้เกิดคลื่นยักษ์สึนามิที่คร่าชีวิตผู้คนไป 596 ราย บาดเจ็บมากกว่า 9,500 คน

ปี 2550 แผ่นดินไหวและสึนามิ

6 มีนาคม เกิดแผ่นดินไหวซ้ำที่เกาะสุมาตรา ประเทศอินโดนีเซีย ขนาด 6.3 ริกเตอร์ ส่งผลให้อาคารบ้านเรือนพังหลาย มีผู้เสียชีวิต 70 คน