# ลักษณะเฉพาะทางตะกอนวิทยาของชั้นตะกอนคลื่นซัดล้นฝั่งที่เกิดจากพายุเขตชายฝั่งทะเลจังหวัดประจวบคีรีขันธ์ถึงนครศรีธรรมราช ประเทศไทย

นายสุเมธ พันธุวงค์ราช

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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ปีการศึกษา 2555

# SEDIMENTOLOGICAL CHARACTERISTICS OF STORM-INDUCED WASHOVER DEPOSITS ALONG THE COASTAL ZONE OF CHANGWAT PRACHUAP KHIRI KHAN TO NAKHON SRI THAMMARAT, THAILAND

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A Dissertation Submitted in Partial Fulfillment of the Requirements
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Faculty of Science
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| Thesis Title | SEDIMENTOLOGICAL CHARACTERISTICS OF STORM-INDUCED WASHOVER DEPOSITS ALONG THE COASTAL ZONE OF CHANGWAT PRACHUAP KHIRI KHAN TO NAKHON SRI THAMMARAT, THAILAND |
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| Thesis Co-advisor | Professor Ken-ichiro Hisada, Ph.D. |

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สุเมธ พันธุวงค์ราช: ลักษณะเฉพาะทางตะกอนวิทยาของชั้นตะกอนคลื่นซัดล้นฝั่งที่เกิดจากพายุเขตชายฝั่งทะเลจังหวัดประจวบคีรีขันธ์ถึงนครศรีธรรมราช ประเทศไทย.(SEDIMENTOLOGICAL CHARACTERISTICS OF STORM-INDUCED WASHOVER DEPOSITS ALONG THE COASTAL ZONE OF CHANGWAT PRACHUAP KHIRI KHAN TO NAKHON SRI THAMMARAT, THAILAND) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร.มนตรี ชูวงษ์, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม : Prof. Ken-ichiro Hisada, Ph.D., 127 หน้า.

การวิเคราะห์ตะกอนคลื่นซัดล้นฝั่งที่เกิดจากพายุในปัจจุบันและอดีตจากบริเวณชายฝั่งทะเลภาคใต้ด้านอ่าวไทยมีวัตถุประสงค์เพื่อหาลักษณะเด่นทางตะกอนวิทยาในการพัฒนาความเข้าใจเรื่องกระบวนการสะสมตัวของตะกอนประเภทนี้ โดยมีพื้นที่ศึกษาอยู่ในบริเวณที่เคยได้รับผลกระทบจากเหตุการณ์คลื่นซัดล้นฝั่งในปัจจุบันจากจังหวัดประจวบคีรีขันธ์ถึงนครศรีธรรมราช ตะกอนคลื่นซัดล้นฝั่งที่เกิดจากพายุพบสะสมตัวอยู่บริเวณที่ลุ่มต่ำด้านหลังหาดทราย ที่ราบน้ำท่วมถึงบริเวณเขตน้ำขึ้นน้ำลง และสันทรายจะงอย โดยแยกตามรูปร่างและสัณฐานของตะกอนที่พบได้เป็นสามประเภท คือ เป็นรูปพัด เป็นลานตะพัก และเป็นผืนทรายขนาดใหญ่ที่มีแนวเส้นตรงที่พื้นผิวด้านบน พื้นที่สะสมตัวของตะกอนคลื่นซัดล้นฝั่งที่เกิดจากพายุในปัจจุบันอยู่ในระยะ 100 เมตรจากชายฝั่งทะเล ขณะที่ตะกอนคลื่นซัดล้นฝั่งที่เกิดจากพายุในอดีตพื้นที่สะสมตัวอยู่ในระยะ 400 เมตรจากชายฝั่งทะเลโบราณ

ผลการศึกษาพบลักษณะเฉพาะทางตะกอนวิทยาของตะกอนคลื่นซัดล้นฝั่งที่เกิดจากพายุโดยสามารถแบ่งได้เป็นสองชนิด คือ ชั้นทรายขนาดหนาหลายชั้นที่มีการเรียงตัวของเม็ดตะกอนในแนวดิ่งแบบผกผันจากขนาดเล็กไปใหญ่ และชั้นทรายขนาดปานกลางหลายชั้นที่มีการเรียงตัวของเม็ดตะกอนในแนวดิ่งแบบปกติจากขนาดใหญ่ไปเล็ก การสะสมตัวของชั้นตะกอนมีความหนาตั้งแต่ 1-80 เซ็นติเมตร โดยความหนาจะลดลงในทิศทางจากชายฝั่งเข้าสู่แผ่นดิน ด้านล่างของแต่ละชั้นทรายย่อยมักพบลักษณะชั้นบางของเม็ดทรายขนาดกลางหรือเปลือกหอยวางตัวขนานกับชั้นทราย ที่บริเวณส่วนปลายสุดของชั้นทรายมักพบลักษณะโครงสร้างทางตะกอนแบบ foreset bedding/lamination ตะกอนคลื่นซัดล้นฝั่งที่เกิดจากพายุแสดงการเอียงเทของชั้นตะกอนในทิศทางเข้าสู่แผ่นดิน การเปลี่ยนรูปของโครงสร้างตะกอนที่เกิดขึ้นหลังการสะสมตัวพบว่าเกิดจากการชอนไชของรากพืช เกิดจากการรบกวนผิวตะกอนโดยลม และเกิดจากการกัดเซาะโดยคลื่นซัดล้นฝั่งที่เกิดจากพายุครั้งถัดไป

ภาควิชา……ธรณีวิทยา……ลายมือชื่อนิสิต…………………………………………………………

สาขาวิชา.….ธรณีวิทยา……ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก…………………………………

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KEYWORDS: STORM SURGE / WASHOVER DEPOSIT / STORM DEPOSIT / THAILAND

SUMET PHANTUWONGRAJ: SEDIMENTOLOGICAL CHARACTERISTICS OF STORM-INDUCED WASHOVER DEPOSITS ALONG THE COASTAL ZONE OF CHANGWAT PRACHUAP KHIRI KHAN TO NAKHON SRI THAMMARAT, THAILAND. ADVISOR: ASSOC.PROF. MONTRI CHOOWONG, Ph.D., CO-ADVISOR : PROF. KEN-ICHIRO HISADA, Ph.D., 127 pp.

Modern and ancient storm surge washover deposits from Thailand generated by several storm surge events along the southern coast of the Gulf of Thailand side were analyzed aiming to improve the understanding in the typical sedimentary features within the washover deposit. The studies sites were focused where there have been affected by modern storm surges at Prachuap Khiri Khan, Chumphon, Surat Thani, and Nakhon Sri Thammarat Provinces. Washover storm deposits were found in a swale behind beach, tidal floodplain, and sand spit. Washover deposits were characterized into three types including, perched fan, washover terrace, and sheetwash lineations. These depositional patterns were found within a distance 100 m and 400 m far inland from shoreline for modern and ancient deposits, respectively. The investigations in sedimentary structures were performed in both lateral and horizontal variations.

As a result, the modern 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. Washover deposits show landward dipping of horizontal to subhorizontal layers with the bottom sharp contact to the underlying buried surface. The thickness ranges from 1-80 cm and commonly decreases inland. Multiple grading layers of normal and reverse graded sand (up to 12 layers) were identified and can be used as typical feature of washover storm deposit for this study. At the lower part of each storm depositional layer, laminae of medium to coarse sand and shells were observed. Foreset bedding and lamination are common at the distal part of washover margin. Inclination of bedding was recognized only in unidirectional side from seaward to landward. Post modifications of the deposit by bioturbation from root plants, aeolian process, and erosion by the latter storm surge were also recognized. Dark organic layer of burial vegetation and small grain sand layer reworked by aeolian process between sand successions is one characteristic that can be used as sedimentological clue to distinguish the two different storm depositional events.

Department : .............Geology........... Student's Signature ..........................................................
Field of Study : ...........Geology......... Advisor's Signature ..........................................................
Academic Year : ...........2012............. Co-advisor's Signature .....................................................

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# CHAPTER I

# INTRODUCTION

## 1.1 Rational

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 (Phantuwongraj et al, 2013).

In fact, the sedimentary characteristics and physical properties of storm-induced washover deposits have been published since the 1960's. 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). 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 (Schwatrz, 1975; 1982; Deery and Howard, 1977; 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, 2008a, 2008b; Morton et al., 2007; 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 (Phantuwongraj et al, 2013).

Although, Thailand has experienced storm surges at least four times recently from tropical storms (“Harriet” in 1962, “Ruth” in 1970, 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.

Apart from the storm events, the storm surge generated by temporary strong NE wind during northeast (NE) monsoon season is also causing the erosion and also contribute the washover deposits to the coastal zone along the southern Thailand in the GOT side as stated by Phantuwongraj and Choowong (2012) and Phantuwongraj et al (2013). According to the frequency of its occurrence, at least once a year, washover deposits resulting from temporary strong NE wind are found to be more in number than the washover deposits induced by storm. Therefore, such a more frequent coastal hazard as this kind of storm surge should be one to take into consideration to which it usually affects the people in the coastal zone probably in every monsoon season.

Nott and Hayne (2001) suggested that storms have also been predicted to increase in magnitude and possible more frequency in occurrence. They also introduced the linkage between the frequency of storm occurrence and the effect of recent enhanced greenhouse climate. It is definitely clear that in the area that has records of coastal storm events, the prediction of storm attack frequency or recurrence period is possible. If this is a case, storm potential hazard map can be created consequently. However, storm record may not persist in all coastal areas. In the areas where the written historical record is limited or absent, like Thailand, the geological evidences of storm events such as washover deposits is likely valuable.

Therefore, a concrete research on this kind of washover deposits becomes necessary. All these washover deposits are the best key indicator of storm surge events in the coastal area which can used to create storm surge hazard map. Therefore, apart from the increasing of a geological importance from this storm surge washover deposits research, the result of finding a historical record of storm surge events can be extended to further the appropriate mitigation or even the warning system.

## 1.2 Objectives

In this study, the sedimentary characteristics of storm washover deposits from different geomorphic conditions are mainly focused. The different of topographical and flow conditions from the individual and geological settings related to washover sediment features are also concerned. This study aims to present the first detail of storm deposits from Thailand which also can be used as a modern analog for storm deposits from other areas. The main objectives of this study are as follow.

1. To examine the sedimentological characteristics of the wind driven-current washover deposits.
2. To correlate and establish the wind driven-current washover depositional stratigraphy.

**1.3 Scope and limitation**

This thesis focused on the sedimentological analysis in the washover storm deposits found from the coastal zone of the Gulf of Thailand. Representative provinces are at Prachuap Khiri Khan, Chumphon, Surat Thani, and Nakhon Si Thammarat. The recognition and reconstruction of hydraulic conditions of the storm surge flow will be based solely on the observation made from washover sand sheet characteristics, not in mathematic calculation.

**1.4 Assumption**

Recently, based on the literatures review, there are not any scientific report mentioned that the coastal plain of southern peninsular at the Gulf of Thailand (GOT) side has been experienced tsunami hazard. Additionally, the tsunami source zones are commonly concentrated in the subduction zone (Department of Geology, 2005) such as the 2004 Sumatra tsunami that was triggered by a magnitude 9.1-9.3 earthquake along the Indian – Australian subduction zone off the northern coast of Sumatra (Lay et al., 2005; Okal and Titov, 2007) and the 2011 Sendai tsunami triggered by a magnitude 9 earthquake at the megathrust off the Pacific coast of Tohoku, Japan (Lay et al., 2011). This feature of tectonic setting is found at the Andaman sea side but not at the GOT side. At the GOT side, the high possibility tsunami generated source zone is located further away at Manila trench in Philippines (Ruangrassamee and Saelem, 2009). According to the study of Ruangrassamee and Saelem (2009) the earthquake $M_w$ 9.0 at Manila trench can generated possible tsunami high 65cm at the southernmost coastline at the GOT side. However, the damage from this 65 cm height tsunami seem to be lower than the annually storm surge induced by temporary NE strong wind. Thus, we can rule out the deposition of sand sheet induced by tsunami from the coast of the Gulf of Thailand. Consequently, unusual sand sheet deposited onshore between layers of peaty mud are as a result of other high energy processes like storm surge.

## 1.5 Outputs

This research will be the first to provide sedimentological clues of wind driven current washover deposits induced by storm and temporary strong NE wind from the southern peninsular of Thailand. The major expectation is to understand the characteristics of washover deposits as the key analogue leading to identifying and distinguishing it from other sediments deposits. Expected results are as follows:

1. Sedimentological characteristics of the wind driven current washover deposits.
2. The correlation and establishment of washover depositional stratigraphy in the study area.
3. Flow conditions model of the individual washover event.

## CHAPTER II

## LITERATURE REVIEWS

### 2.1 Washover deposits in regional scale

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. 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. (Phantuwongraj et al., 2013).

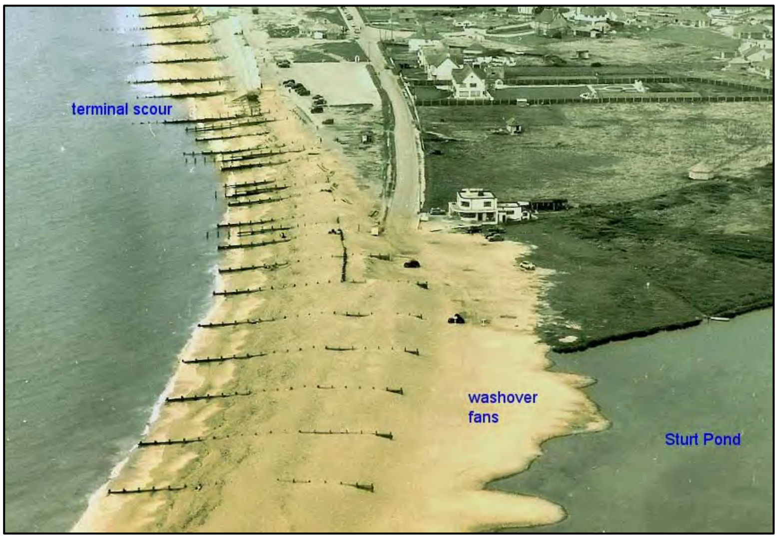


Figure 2.1 Oblique photo showing washover sediments penetrated into a pond at the coastline of Hurst Spit, Milford on Sea, Southern England in 1958.
(http://www.soton.ac.uk/~imw/jpg-Hurst/6HS-1958-Milford.jpg)

In addition, washover deposit also contributes to the sediment budget of a barrier island, and overwash flow is sometimes a driving process in the migration of barrier islands landward as stated by Donnelly et al. (2004). Furthermore, washover deposits also play an important role in a coastal hazard management as a geological indicator of the high-energy deposits of the extreme overwash event. The recurrence period of the storm surge events, calculated from paleo-storm sand sheets, can revealed us the frequency of the storm surge events in the past which may related to the present storm event. This information may useful for the decision making for land planning management in the coastal area.

**2.1.1 Processes**

Washover deposit is one of the most commonly observed depositional responses to extreme events such as storm and tsunami that was a result of overwash flow as mentioned above, the processes of washover deposits are describe here in detail. In this study we focus only the washover deposits from wind-driven current, so the washover sediments from tsunami generated are not explain here.

Overwash is the flow of water and sediment over a beach crest that does not directly return to the water body (ocean, sea, bay, or lake; hereafter, ocean) where it originated (Donnelly et al., 2004). It begins when the runup level of waves, usually coinciding with a storm surge, exceeds the local beach or dune crest height (Figure 2.2). Significant overwash usually occurs as a result of tropical storms, typhoon, and temporary strong NE wind during the northeast (NE) monsoon in Thailand.

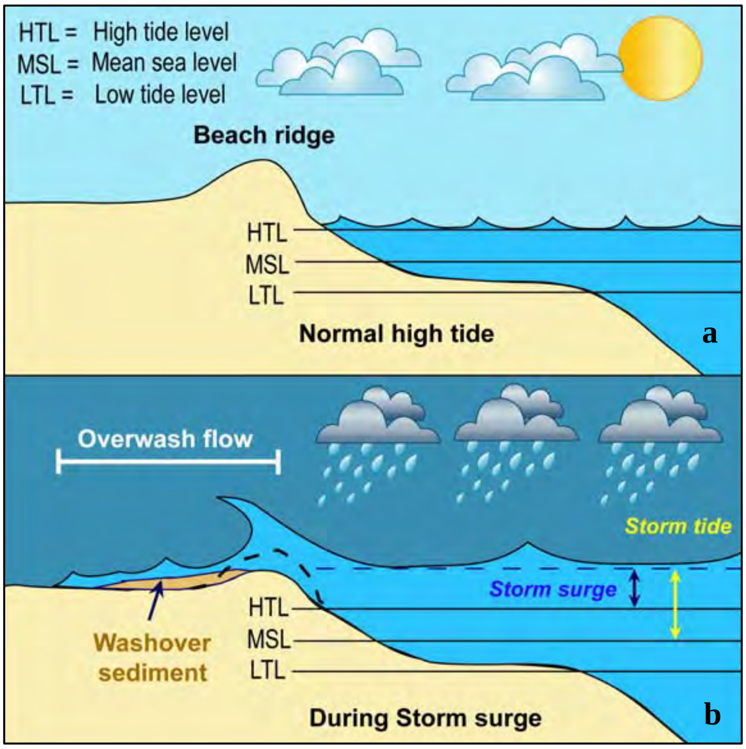


Figure 2.2 Cross-section model of beach showing the sea water level during the fair weather and storm weather period. a) Water level is stay lower beach ridge during fair weather condition. b) During storm condition, water level is raising high over beach ridge and causing overwash flow that eroded beach sand and result in washover sediment deposits.

### 2.1.2 Intensity of overwash

Severe overwash primarily occurs in association with a large storm or a hurricane. As stated that overwash flow usually coincided with the tropical storm, typhoon, and winter cold fonts, so the major factors that influence the intensity of overwash flow are including the storm's intensity and coastal topography. The storm intensity scale is namely Saffir-Simpson wind scale which is categorizes a damage potential of property resulting from hurricane into five scale base on its sustained wind speed (Table 2.1). However, there is no relationship between wind speed and high of storm surge because there are other factors that control high of sea water level as reported by NOAA (2012). For example, hurricane Katrina, a category 3 at landfall in Louisiana, produced catastrophic damage with a 28-ft. storm surge. Hurricane Ike, a category 2 at landfall in Texas, also produced catastrophic damage with a 20-ft. storm surge. Finally, hurricane Charley, a category 4 hurricane at landfall in Florida, produced a storm surge of 6 to 8 ft.

In reality, storms that cause the greatest morphological changes and the most destruction are the systems with high sustained wind speeds, large radii of maximum winds, and high storm surges that remain stationary for several days or move slowly onshore before making landfall as mentioned by Morton (2002).

| Category | Sustained Winds | Types of Damage Due to Hurricane Winds |
|---|---|---|
| 1 | 74-95 mph, 64-82 kt, 119-153 km/h | Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roof, shingles, and vinyl siding and gutters. |
| 2 | 96-110 mph, 83-95 kt, 154-177 km/h | Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof and siding damage. |
| 3 | 111-129 mph, 96-112 kt, 178-208 km/h | Devastating damage will occur: Well-built framed homes may incur major damage or removal of roof decking and gable ends. |
| 4 | 130-156 mph, 113-136 kt, 209-251 km/h | Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. |
| 5 | 157 mph or higher,137 kt or higher, 252 km/h or higher | Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. |

Table 2.1 Saffir-Simpson hurricane wind scale (modified from NOAA, 2012).

Sallenger (2000) proposed that, the impact of a storm on the coastal area is not depend only on the magnitude of storm characteristics, such as storm surge and waves, but also on the elevation of the coastal topography at landfall.

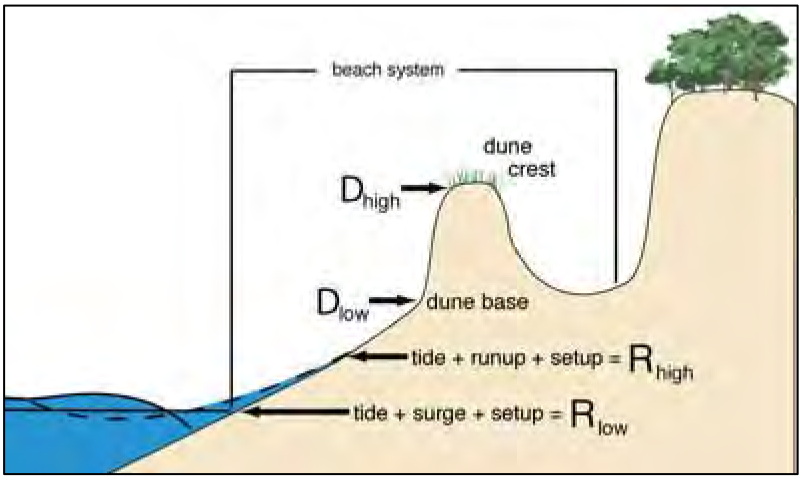


Figure 2.3 Definition sketch showing $R_{high}$ $R_{low}$, $D_{high}$ and $D_{low}$.
The dashed lines represent the swash excursion about wave setup (solid line).
(Source http://coastal.er.usgs.gov/hurricanes/impact-scale/index.php )

From the study of USGS (2011) show that the potential vulnerability of a particular stretch of coast can be assessed using a conceptual model that scales the impacts of storms on barrier islands as proposed by Sallenger, (2000). Within the model (Figure 2.3), the elevation of storm-induced water levels ($R_{high}$ and $R_{low}$), including storm surge, astronomical tide, and wave runup, are compared to measurements of local dune morphology such as the elevation of the dune crest and toe, ($D_{high}$ and $D_{low}$).

The hurricane-induced water levels ($R_{high}$ and $R_{low}$) are the highest reaches of the waves on the beach during the storm. By considering these water levels relative to coastal elevations $D_{high}$ and $D_{low}$, the crest and base of the dune, four storm impact regimes can be defined for a specific area of the coast (Figure 2.4 and 2.5).

Swash; total water levels are lower than the dune toe ($R_{high} < D_{low}$). During storms, the foreshore typically erodes and sand is transported offshore (Figure 2.4a). Collision; total water levels exceed the dune toe ($D_{low} < R_{high} < D_{high}$). The collision forces sand to be eroded from the dune and transported offshore or longshore (Figure 2.4b). Overwash; total water levels exceed the dune crest ($R_{high} > D_{high}$). Sand is transported landward (tens to hundreds of meters) contributing to the net migration of the barrier beach landward (Figure 2.4c). Inundation; storm surge and tide exceed the dune crest ($R_{low}$ > $D_{high}$). Massive net onshore transport occurs with landward migration of sand bodies on the order of 1 km (Figure 2.4d).Within each of these regimes, the nature and magnitude of coastal change are expected to be unique.

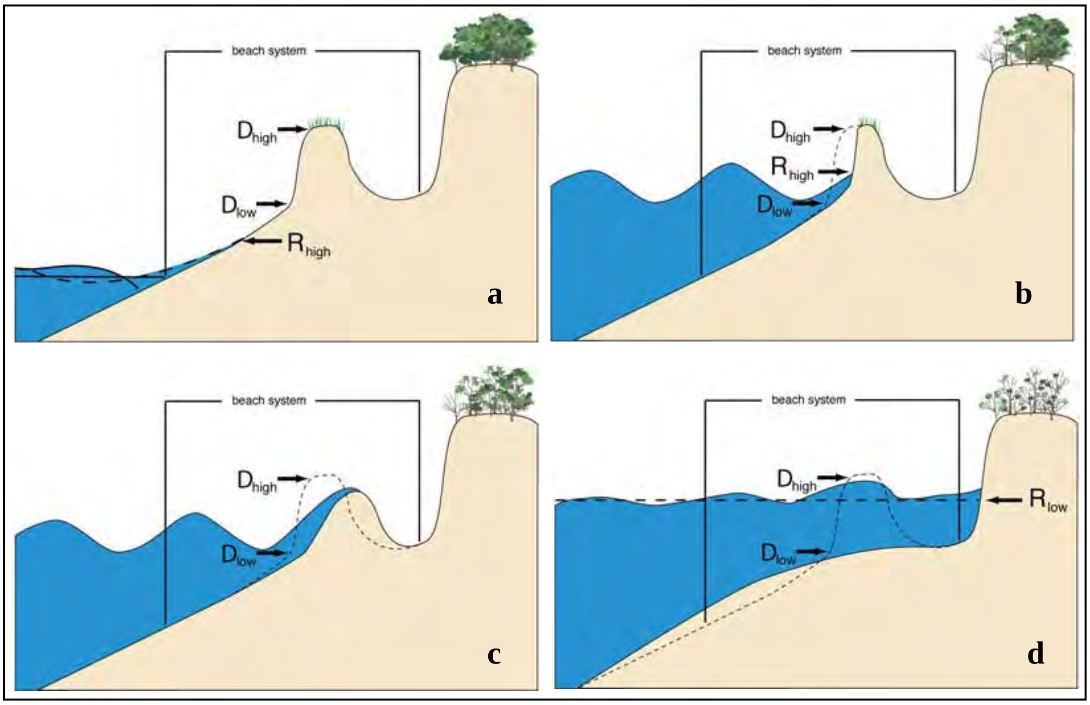


Figure 2.4 Definition sketch showing four wave attack regime at shoreline during storm condition; including a)swash, b)collision, c)overwash, and d)inundation regime. (Source http://coastal.er.usgs.gov/hurricanes/impact-scale/ )

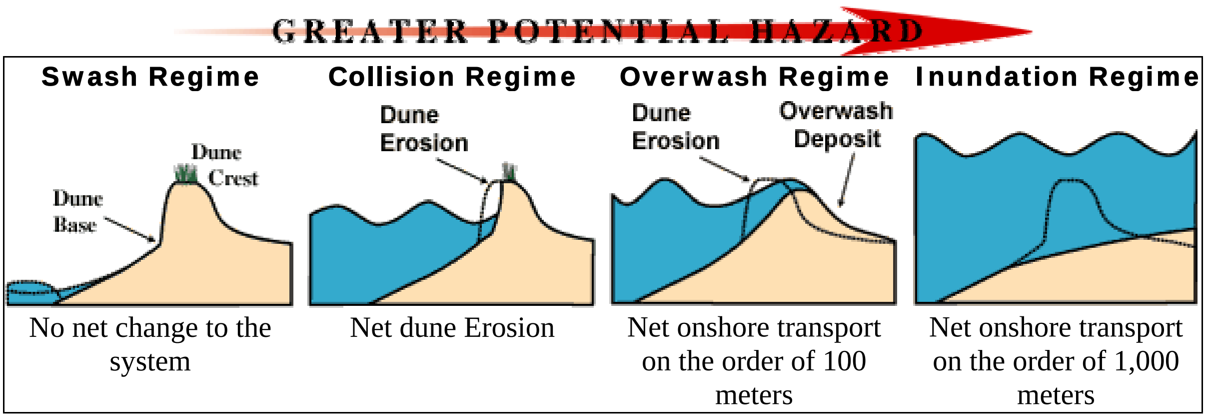


Figure 2.5. Four storm impact regimes for a specific area of the coast

(Source http://coastal.er.usgs.gov/hurricanes/impact-scale)

### 2.1.3 Beach response morphology after overwash

After the storm event the coastal area usually exhibited the response morphology both erosional and depositional feature from overwash flow associated storm surge. Severe overwash primarily occurs in association with a large storm or a hurricane.

Donnelly et al., (2004) stated that overwash can be a precursor to breaching by initiating erosion of the beach face, lowering the crest elevation of the beach profile, and transporting sediment from the beach and back beach into the bay (Kraus et al., 2002; Kraus and Wamsley, 2003).

The sediment that was left behind by overwash flow we call washover deposits (Figure 2.6) which is one of the most commonly observed depositional responses to extreme storm events (Morton and Sallenger, 2003; Wang and Horwitz, 2007). The first observed of post-storm attack event in the affected area are a change in beach morphology so the study of geomorphological response after the event is very famous (Hayes, 1967; Wright et al., 1970; Schwartz, 1975; Morton, 1976; 1978; 1979; Kahn and Roberts, 1982; Morton and Paine, 1985; Gayes, 1991; Thieler and Young, 1991; Stone and Wang, 1999).

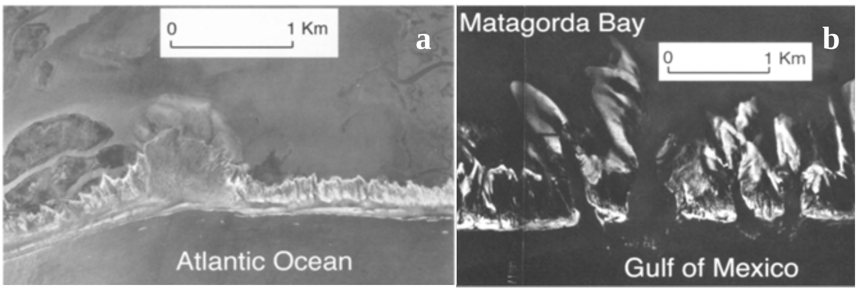


Figure 2.6 a) Washover terrace and fan on Cedar Island, Virginia constructed by the 2.5 m surge of an extratropical storm (Ash Wednesday 1962). b) Incised channels and flame-shaped washover fans constructed on Matagorda Peninsula, Texas by the 3 m surge of a category 4 hurricane (Carla in 1961) (From Morton, 2002)

From the morphology of washover deposits the geologist can interpret the intensity of storm and flow condition which results in different shape of deposits as mentioned above. The good examples of the washover deposit morphology are the study of Morton, 2002 and Morton and Sallenger, 2003 which stated in the part of beach response morphology from overwash flow after extreme storm event.

From the study of Morton and Sallenger (2003), change of coastal landform after the storm event can be classify into two type of features, the erosional and the depositional, based on its forming processes (Figure 2.7). Dune scarp erosion, channel incision, and washout are the feature of the former process whereas perched fan, washover terrace, and sheet wash are the result of the latter process. The characteristic and forming process of each feature are described here follow to the study of Morton (2002) and Morton and Sallenger (2003).

Erosional features

*Dune scarp erosion* (Figure 2.7a) occurred when the storm surge and wave runup is substantially higher than the backbeach, but lower than the height of the dunes or bluff. The runup will collide with the dune causing erosion and dune retreat.

*Channel incision* (Figure 2.7b) commonly occurred when the storm surge and superimposed wave heights exceed heights of the primary dunes, then the entire headland or barrier island is inundated and the response is commonly sheetwash, or for barrier islands, incision of washover channels through the barrier core.

*Washout* (Figure 2.7c) involves channel erosion across the beach and foredunes as a result of floodwaters flowing from the lagoon to the ocean. The term washout is used because the process is opposite to that of overwash (Morton and Paine, 1985). This relatively rare phenomenon occurs where the lagoon is higher than the ocean and also higher than the foredunes (Elashry and Wanless, 1968; Pierce, 1970).

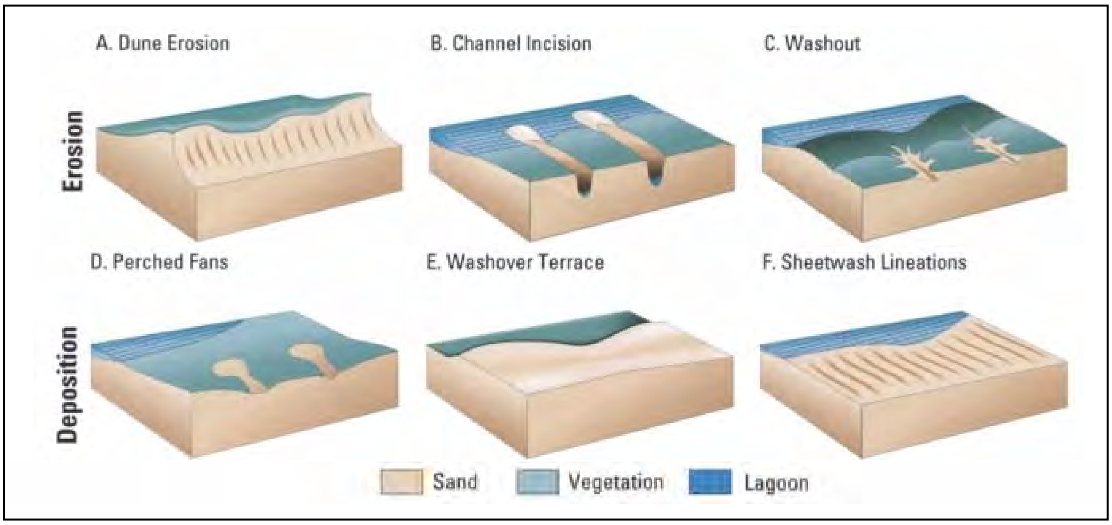


Figure 2.7 Types of erosional and depositional features produced by extreme storms. (From Morton and Sallenger, 2003)

Depositional features

*Perched fans* (Figure 2.7d) are small lobate to elongate washover features that are oriented perpendicular to the shore which constructed when wave runup superimposed on the storm surge exceeds the lowest dune elevations, but elsewhere the surge is blocked by higher dune elevations. Morphological criteria that favor construction of regularly spaced fans include a narrow barrier island, low dunes, and minor alongshore differences between dune gaps and dune crests. At some locations, perched fans are so closely spaced that they merge to form a washover terrace (Morton, 2002).

*Washover terraces* (Figure 2.7e) are elongate deposits oriented parallel to the shore (Schwartz, 1975; Morton and Paine, 1985). Terraces form where land elevations are relatively uniform alongshore and lower than the maximum storm surge. They may form a uniformly wide band, or their landward margins may be highly irregular, depending on the interactions between breaking waves and currents during washover deposition.

*Sheetwash* (Figure 2.7f) involves laterally unconfined flow where sediment transport is continuous across the barrier island. Sheetwash may result in either deposition of sand eroded from the adjacent beach/dune system or redistribution of sand eroded locally. Common bedforms resulting from sheetwash are narrow elongate zones of erosion and deposition that form lineations parallel to the direction of flow.

### 2.1.4 Sedimentary characteristics

Within the literature, the sedimentary characteristics and bedform surfaces of storm-induced washover deposits that have been characterized have included normal grading, reverse grading, laminaset, horizontal bedding, foreset bedding/laminae, antidune, rhomboid bedform and current ripples (e.g., Andrews, 1970; Frey and Mayou, 1971; Deery and Howard, 1977; Leatherman and Williams, 1977; Leatherman and Williams, 1983; Morton, 1978, Morton et al., 2007; Schwartz,1982; Davis Jr et al., 1989; Nanayama et al., 2000; Sedgwick and Davis, 2003, Wang and Horwitz, 2007; Komatsubara et al., 2008; Phantuwongraj et al., 2008; Spiske and Jaffe, 2009).

Sedgwick and Davis, 2003 studied the twelve modern washover deposits in Florida, USA to develop a reliable method of identifying washover deposits in the stratigraphic record. The typical modern washover stratigraphy displays landward-dipping plane beds comprised of well-sorted sand with distinct laminae of shells and heavy minerals. Sedgwick and Davis (2003) reported the five subfacies including, stratified sand, reverse-graded sand, normal-graded sand, bioturbated muddy sand, and undifferentiated washover sediments, in the modern washover deposits in Florida, USA which representing the variability in flow conditions and post-depositional reworking that presents throughout the washover sediments.

Sedwick and Davis (2003: 33) mentioned that the stratigraphy of washover deposits reflects both the overwash processes and subsequent reworking. The washover sediments usually show horizontal bedding, but sometime, foreset bedding are recognize as a result of sediment prograded into a pond or lagoon (Figure 2.8). Sedwick and Davis (2003: 33) stated that "foreset bedding/lamination may occur on the distal margins of the fan, depending on the water level at the time of deposition as reported by Schwartz (1975) and Davis et al. (1989). However, these foresets bedding are not universal and depend upon subaqueous deposition of the distal portion of the washover. Other sedimentary structures, such as convolute bedding, soft-sediment deformation, and fluid escape structures, have all been mentioned in washover stratigraphy as mentioned by Morton (1978) and Ritchie and Penland (1988)".

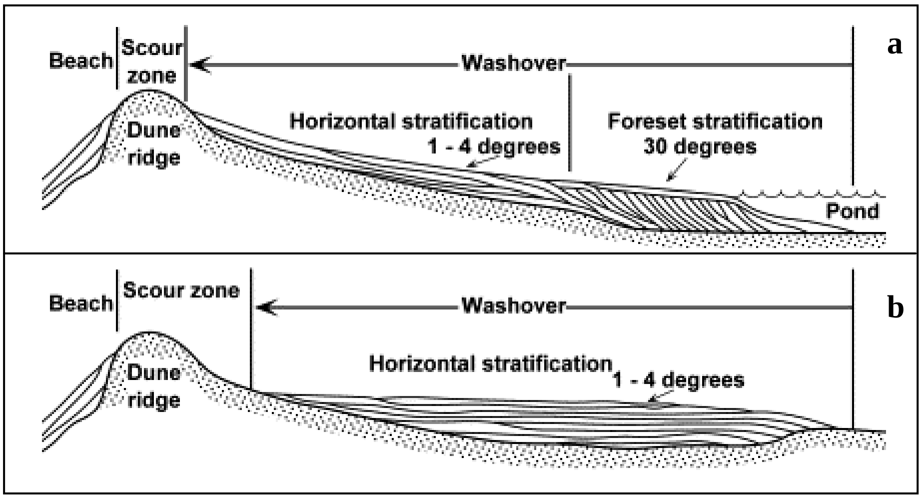


Figure 2.8 Generalized washover fan stratigraphy showing a) foreset laminae during subaqueous deposition and b) planar-laminated sand in supratidal washover fans (from Schwartz, 1975 in Sedgwick and Davis, 2003)

Morton et al. (2007: 204) reported that “the physical attributes that strongly favor a washove deposit by storm origin are: a moderately thick (average >30 cm) sand bed which composed of numerous subhorizontal planar laminations organized into multiple laminasets (Figure 2.9). Maximum bed thickness is near the shore, and landward thinning of the deposit is commonly abrupt. Additional, the types of stratification also associated with bed-load transport (foresets, climbing ripples, backsets), numerous thin (mm to a few cm) laminasets of alternating coarse and fine textures indicative of high frequency waves”.

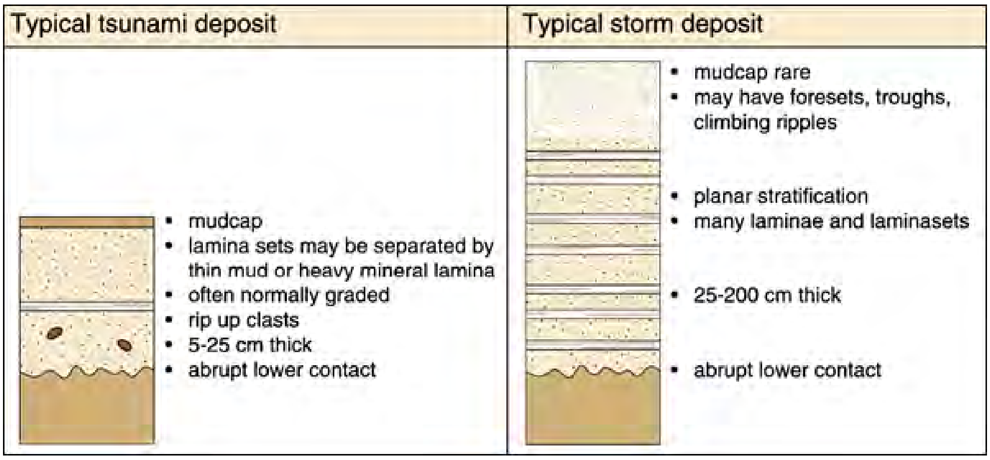


Figure 2.9 Composite characteristics of typical sandy tsunami and storm deposits. (from Morton et al., 2007)

Sedwick and Davis (2003: 32) also stated that “the composition of washover sediments are vary due to differences in local source material, however in general, they consist of horizontal bedding, alternating layers of terrigenous sand, shell fragments, and heavy minerals which reflect changing in hydraulic condition and tidal variations during storm event as described by Kochel and Dolan (1986)”.

### 2.1.5 Preservation potential

The preservation potential of individual storm units and the washover facies depends on many factors, including rate of bioturbation, frequency of overwash, thickness of the units, and the magnitude and rate of sea-level change as described by Sedwick and Davis (2003). Post-depositional modification also plays a significant role in recognition of washover deposits. Sedwick and Davis (2003: 33) reported that

"…modification can be either by organisms and/or vegetation through bioturbation (Frey and Mayou, 1971) or by physical reworking from wind, waves or subsequent overwash events (Andrews, 1970 and Fisher and Stauble, 1977). Colonization by blue-green algal mats is also common in ponded water or in intertidal zones, and provides a good marker bed when interpreting stratigraphy (Leatherman and Williams, 1977). The frequency of overwash events is a major factor in determining the amount of reworking of a deposit. Rapid burial will lead to decreased biological and physical reworking, but subsequent storm events may destroy or rework previous deposits through scour (Leatherman and Williams, 1977).

The rate and magnitude of sea-level change are perhaps of greatest importance in assessing the long-term preservation of washovers (Deery and Howard, 1977). Although overwash can occur during regression, it is much more common under transgressive sea-level conditions. Under this circumstance the constant landward migration of the barrier island associated with slowly rising sea level may obliterate the stratigraphic signatures of washover facies (Reinson, 1992). Conversely, if rates of sea-level rise are rapid, reworking is minimized and preservation is enhanced by submergence of the barrier system" as stated by Sedwick and Davis (2003).

### 2.1.6 A geological record evidence of storm events

As mentioned above that one of the major morphologic impacts on beaches of powerful storm is overwash and the resulting washover deposits (Wang and Horwitz, 2007). Therefore, we can use these deposits as a key indicator of storm impact event in the coastal area.

Additionally, storms have also been predicted to increase in magnitude and possibly frequency under an enhanced greenhouse climate (Nott and Hayne, 2001). In the area that has records of coastal storm events, the prediction of storm attack frequency or recurrence period is possible and storm risk map can create. Unfortunately, not all of the coastal areas have the data of storm record. In the areas where the historical record is limited or absent the geological evidence of storm events such as washover deposits is valuable.

Switzer and Jones (2008a) stated that one popular method of extending the record of extreme events such as tsunami or storm surges beyond that of written history is to investigate the stratigraphic record of coastal systems for sedimentary evidence of washover events (Nott, 2004; Scheffers and Kelletat, 2003; Morton et al., 2007). If several washover sand layers of storm deposits were found the recurrence period of storm attack can be calculated. In addition, the intensity of storm can be interpreted from the geometry of washover deposit. If the thickness and the width (continuity) of layer are very thick and very wide the intensity of storm is high.

## 2.2 Washover deposits in Thailand

In Thailand, from the Andaman coast, the catastrophic event from 2004 tsunami had generated the large washover sand sheet along the coast and exhibited bed form structure of modern tsunami deposits (Choowong et al., 2007; Choowong et al., 2008a). Furthermore, the unusual deposit of sand sheets in muddy environment has recently been classified as paleo-tsunami deposits at Phrathong Island, Phang-Nga (Jankaew et al., 2008). However, at the Gulf of Thailand side, there is no historical record of tsunami event; on the other hand, the storm events occurred frequently.

As mentioned that overwash flow, which is cause of washover deposit, is usually coincided with the tropical storm, typhoon, and winter cold fonts, the coast of Thailand also been damaged by storms surge for many times. Although, southern peninsular of Thailand has experienced storm surges generated by tropical storm and typhoon at least four times (Figure 2.10) recently, only a few reports on the storm deposits have been officially published (e.g. Roy, 1990).

After typhoon Nargis hit the west coast of Myanmar in 2008, the awareness of storms has spread to the Indian Ocean societies. Clearly, a lack of relevant research on storm records in Thailand makes this research trend become one of the geological research challenges. Consequently, the studies of storm surge washover deposits induced by tropical storm and high velocity NE wind during NE monsoon season in Thailand are beginning as seen from the study of Phantuwongraj et al. (2008), (2010), (2013), and Phantuwongraj and Choowong (2012).

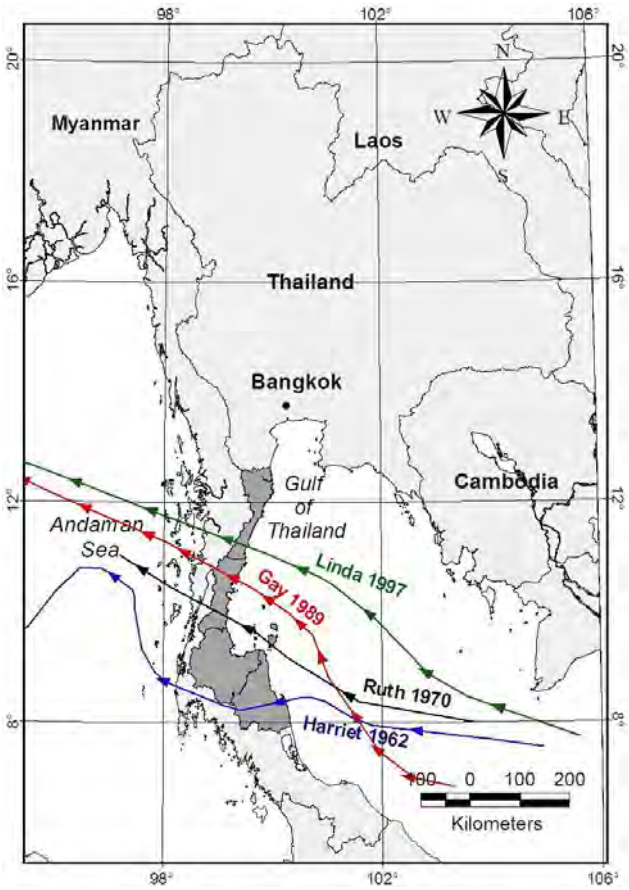


Figure 2.10 Storm tracks of the four catastrophic events in Thailand. Dark grey color refer to the study area in four provinces.

Phantuwongraj et al. (2008) have 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 up northwards along this coastline to Chumphon where Phantuwongraj et al. (2010) found multiple layers of paleo-storm sand sheets in the swale located 1 km inland and far away from the present shoreline. However, a more detailed study of the sedimentary characteristics, topographical and flow conditions of the washover deposits induced by storms are still required.

### 2.2.1 Review of overwash events

#### 2.2.1.1 Strom surge induced by tropical storm and typhoon

From the historical records of coastal disasters in the southern peninsular Thailand, our country has experienced at least four events of storm surge in the coastal area along the Gulf of Thailand (GOT) which induced by typhoon and tropical storm. In the night of 25th October 1962, the tropical storm ‘‘Harriet’’, with a wind speed 97 km/h, has generated an unusual surge high 7-8 meters at Laem Talumphuk (LT) sand spit in southern peninsular of Thailand. Vongvisessomjai (2009) reported that its devastating winds causing 800 deaths, 252 injured, and left over 10,000 homeless. The village, school, and temple also destroyed as a wind stress and storm surge attack (Figure 2.11 and 2.12). Then in 1970, tropical storm Ruth caused damage to Ko Samui, Surat Thani, Chumphon and Prachuap Khiri Khan (Vongvisessomjai, 2009).

After that in 1989 on the 4th November, typhoon Gay hit the Chumphon coast with a maximum wind speed of 185 km/h and caused a storm surge flood over the northern part of the Chumphon coastal plain especially at Pathio and Tha Sae district. The transportations in the affected area were almost destroyed such as road, bridge, and railway (Figure 2.13). Before landfall, typhoon Gay causing the Unocal oil drilling ship name Seacrest which moored in the Gulf of Thailand to capsize shortly after it passing. The estimated wave height at Seacrest is about 6-11 m which 91 seamen were killed and only 2 survivors were rescued as reported by Vongvisessomjai (2009). Finally, in November 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 GOT. Vongvisessomjai (2007) reported that 30 people were dead while 102 people also missing and more than 400,000 rai of agricultural land were destroyed. The damage from typhoon Linda are also similar to the last two events which including flash flood, coastal erosion, and transportation problems (Figure 2.14).


Figure 2.11 Damage from Tropical storm Harriet in 1962 at Laem Talumphuk sand spit. Picture a, b show destroyed houses and coconut tree along the shoreline of LT sand spit. (pictures from http://paipibat.com and http://www.gotonakhon.com)


Figure 2.12 Comparing pictures of school's building "before and after" which resulted from Harriet in 1962. Picture a) showing the two floors building before the storm event and b) the collapsed building after the storm event. c) Students are removing the desks out of the collapsed building and d) the official's governments are surveying the damage from Harriet. (pictures from http://www.gotonakhon.com)


Figure 2.13 Pictures showing damage from typhoon Gay in 1989 at Chumphon province. After typhoon Gay event, many damages were left behind as seen from the following pictures as a) the coconut trees were bended, b) the bridge was destroyed, c) the garbage at the shoreline, and d) the sinking boats near the pier. (pictures from http://www.oknation.net/blog/print.php?id=519439)


Figure 2.14 Damage from typhoon Linda in 1997 at Prachuap Khiri Khan province. a) The coconut trees were bended due to the strong wind and b) a village was flooded as a result of heavy rain fall. (pictures a) from http://www.tmd.go.th/info /info.php?FileID=70 and picture b) from http://www.stock2morrow.com/showthread.php? t=183&page=1)

**2.2.1.2 Strom surge induced by temporary NE strong wind**

Apart from the storm, the temporary increasing of monsoonal wind velocity above its usual speed for a few successive days during NE monsoon season is also causing the storm surge high 1.25-2.5 m to the low-lying coastal area (Phantuwongraj et al., 2013). This storm surge can cause the erosion to the beach and also contribute the washover deposits to the coastal zone along the coast of southern Thailand in the GOT side. According to the frequency of its occurrence, at least once a year, washover deposits resulting from temporary NE strong wind are found to be more in number than the washover deposits induced by tropical storm.

In December 2007, the temporary NE strong wind during NE monsoon season with maximum velocity speed of 20-22 knots, measured at Surat Thani province, has generated the extreme surge along the coastline of Chaiya district, Surat Thani province. According to the study of Phantuwongraj et al. (2013), at Ban Takrop, Surat Thani, the inundation distance from overwash flow is 100-300 m from shoreline. The area was flooded by sea water, 40 cm depth, for a few days and subsequently drained out through the tidal channel. Beach erosion feature was found at the shoreline and damage from overwash flow also destroyed small house at the coast.

Then, at the middle of January 2009, storm surge was occurred along the shoreline of Nakhon Si Thammarat and Songkhla province due to the strong wind from NE monsoon. Overwash with flow depth 60 cm was observed at Songkhla province (Figure 2.15a) and reported of washover deposits were found at Laem Talumphuk, Nakhon Si Thammarat (Figure 2.15b).

Subsequently, in November 2009, the high velocity NE wind during NE monsoon season, with maximum velocity speed of 20-22 knots, has generated the storm surge along the coast of Nakhon Si Thammarat province again. At Laem Talumphuk, the eyewitness said the coastal was flooded by overwash flow for many hours. Beach erosion, as result of wave attacked, was found along the shoreline of Laem Talumphuk. More than 30 pine trees along the shoreline were knocked down due to the erosion of beach sand. Many houses in Laem Talumphuk village were damage from wave attacked. Washover sediments were found deposited into the shrimp pond along the shoreline. The thickness of washover deposits at Laem Talumphuk village were thick about 80-90 cm.

After that, at the middle of March-early April 2011, the low pressure system has generated the strong wind and heavy rain fall in the southern part of Thailand. Storm surge also generated along the southern shoreline in the GOT side from Chumphon to Pattani province (Figure 2.16, 2.17, and 2.18). The heavy rain fall was concentrated in Surat Thani and Nakhon Si Thammarat provinces which both areas were seriously damage from flash flood and landslide trigger by heavy rainfall. At coastal area in Khao Mai Ruak, Prachuap Khiri Khan, the overwash flow had flooded the coastal area far inland up to 100 m. Amount of beach sand was eroded away from the beach in a distance of 1 km along the shoreline as stated by Phantuwongraj et al. (2013). Many scours from overwash erosion were found scattered along the beach, at least 35 cm thick of pre-storm surface sediments depth were eroded.

Seven months afterward, during 23-25 November 2011, Laem Talumphuk, Nakhon Si Thammarat province, was attacked again by storm surge high 4-5 m (Figure 2.19). Village and road near the shoreline was damage from strong wave attacked. Root of coconut trees were exposed about 60 cm due to the eroded of beneath sand beach.


Figure 2.15 Damage from storm surge during 15-16 January 2009. a) Boat’s owner standing in the flooding area with depth 60 cm at the beach of Songkhla province. b) Water tanks near a house at Laem Talumphuk, Nakhon Si Thammarat province were buried by washover sediments. (pictures from http://www.manager.co.th)

Figure 2.16 People are moving a boat which wrecked by wave high 3-4 m at Sai Ree beach, Chumphon province on 17 March 2011. (pictures from http://www.thairath.co.th)


Figure 2.17 Damage from storm surge at Laem Talumphuk, Nakhon Si Thammarat province on 29 and 30 March 2011. a) A man was frightened to see the strong wave which going to destroy his house. b) Wave high 4-5 m attacked the seawall. c) Prime minister Abhisit Vejjajiva is investigating the damage at the LT village. d) Root of coconut trees were exposed due to the erosion of beach sand. (pictures from http://www.oknation.net/blog/singslatan)


Figure 2.18 Picture a) and b) showing the destroyed road along the shoreline at Yaring district, Pattani province by strong wave from storm surge on 1 April 2011. (pictures from http://www.thairath.co.th)


Figure 2.19 Storm surge high 3-4 m during 23-25 November 2011 flooding the coastal area of Laem Talumphuk, Nakhon Si Thammarat province. Pictures a), b), and c) showing the surges are flooding into the LT village. (picture a) from http://www.thairath.co.th and picture b), c) from http://www.manager.co.th)

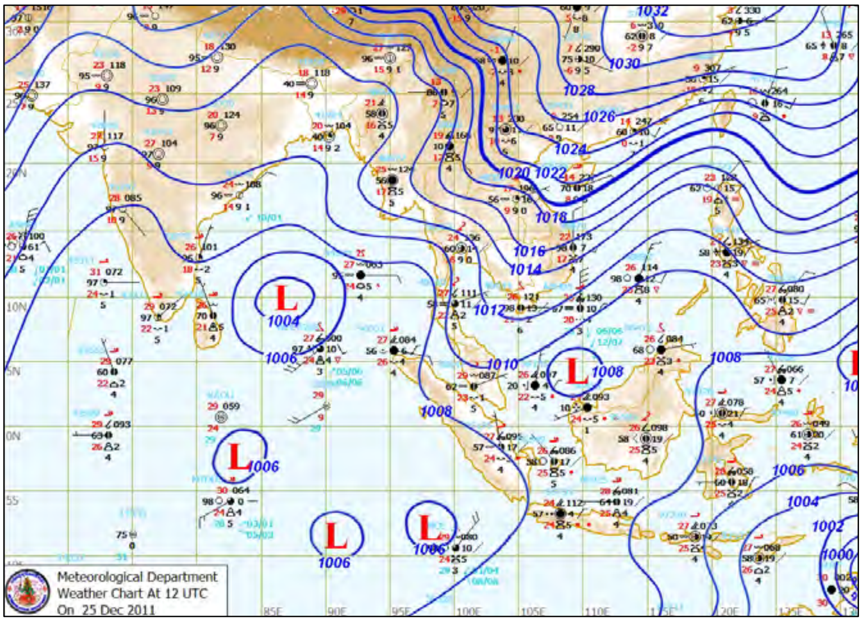


Figure 2.20 Surface map of isobar at 12 UTC on the 25th December 2011 showing the strong high pressure from mainland China pushing into Thailand that caused the strong winds and generated 4 m high waves in the GOT (modified from Thai Meteorology Department).


Figure 2.21 Storm surge during 25-26 December 2011 at Prachuap Khiri Khan Province. (picture a) from http://www.krobkruakao.com, b) from http://www.thairath.co.th, c) and d) from http://www.manager.co.th)


Figure 2.22 Storm surge at Hua Hin beach, Prachuap Khiri Khan province on 25-26 December 2011. a) Breaking waves are heading to Hua Hin beach. b) and c) Overwash flow are flooding into the market along the beach. d) Government officers are investigating the damage from storm surge. (pictures from http://www.manager.co.th)


Figure 2.23 Overwash flow and storm surges at Chumphon province on 25 December 2011. (picture a) and b) from http://www.manager.co.th, c) and d) from http://www.krobkruakao.com)


Figure 2.24 Storm surge and overwash flow at Laem Talumphuk, Nakhon Si Thammarat province on 25 December 2011. a) Wave splashing high 6-7 m during the attack at the seawall. b) Destroyed road and house along the shoreline. c) and d) Overwash flows are flooding in to the village near shoreline. (picture a), c), and d) from http://www.mana ger.co.th, b) from http://www.oknation.net/blog/nn1234/2012/01/02/entry-1)


Figure 2.25 Washover deposits and damage from storm surge at Laem Talumphuk, Nakhon Si Thammarat province on 25 December 2011. a) Washover deposit thick 60cm in the village and b) washover sediment deposit far 50m from shoreline. c) and d) Destroyed house and road . (pictures from http://www.oknation.net/blog/nn1234/2012/01/02/entry-1)

Lastly, during the 24-26 December 2011, the strong NE wind during NE monsoon season (Figure 2.20) has generated the unusual surge high 3-4 m along the coastal zone of the southern Thai peninsular from Prachuap Khiri Khan to Songkhla province (Figure 2.21, 2.22, 2.23, 2.24, and 2.25). This storm surge caused the overwash flow across beach or dune and resulting in flooding at the backshore area. Beach erosion was also reported from every affected area. Road and house along the shoreline were almost destroyed from strong wave attacked. Washover sediments were found at the backshore along the coastal lowland of the affected area in a distance of 50 -100 m from shoreline. Phantuwongraj et al. (2013) found the washover deposits from this storm surge as a perched fan and washover terrace at Prachuap Khiri Khan and Surat Thani province, respectively.

## 2.3 The study area

In this research, the study sites were selected by focusing on the affected area of storm surge induced by the last four catastrophic storm and temporary NE strong wind during the years 2005 to 2011 along the GOT which located in the four provinces including, Prachuap Khiri Khan, Chumphon, Surat Thani, and Nakhon Si Thammarat as showed in Figure 2.26.

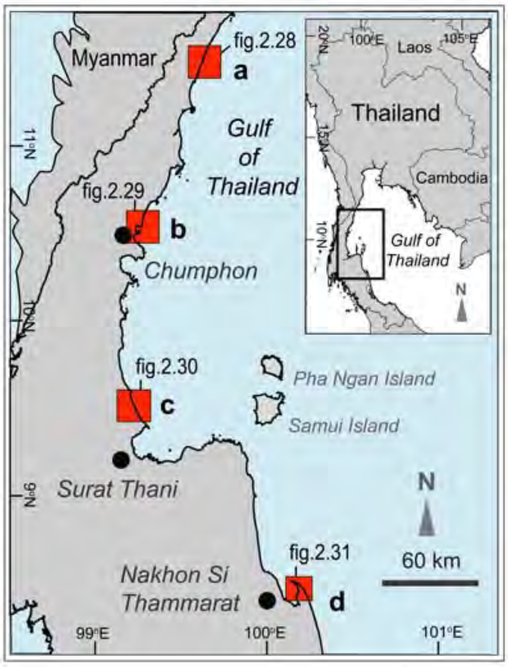


Figure 2.26 Map of the site study locations which located in four provinces; including, a) Prachuap Khiri Khan, b) Chumphon, c) Surat Thani, and d) Nakhon Si Thammarat.

During the temporary strong NE wind in NE monsoon season from 2007-2011, the maximum wind speed measured from three weather stations closer to each study site was ranging from 20 to 22 knots. The potential heights of storm tide were at 2.30-2.96 m high above MSL calculated from tide gauge data and significant wave high data at each study site. (Figure 2.27).

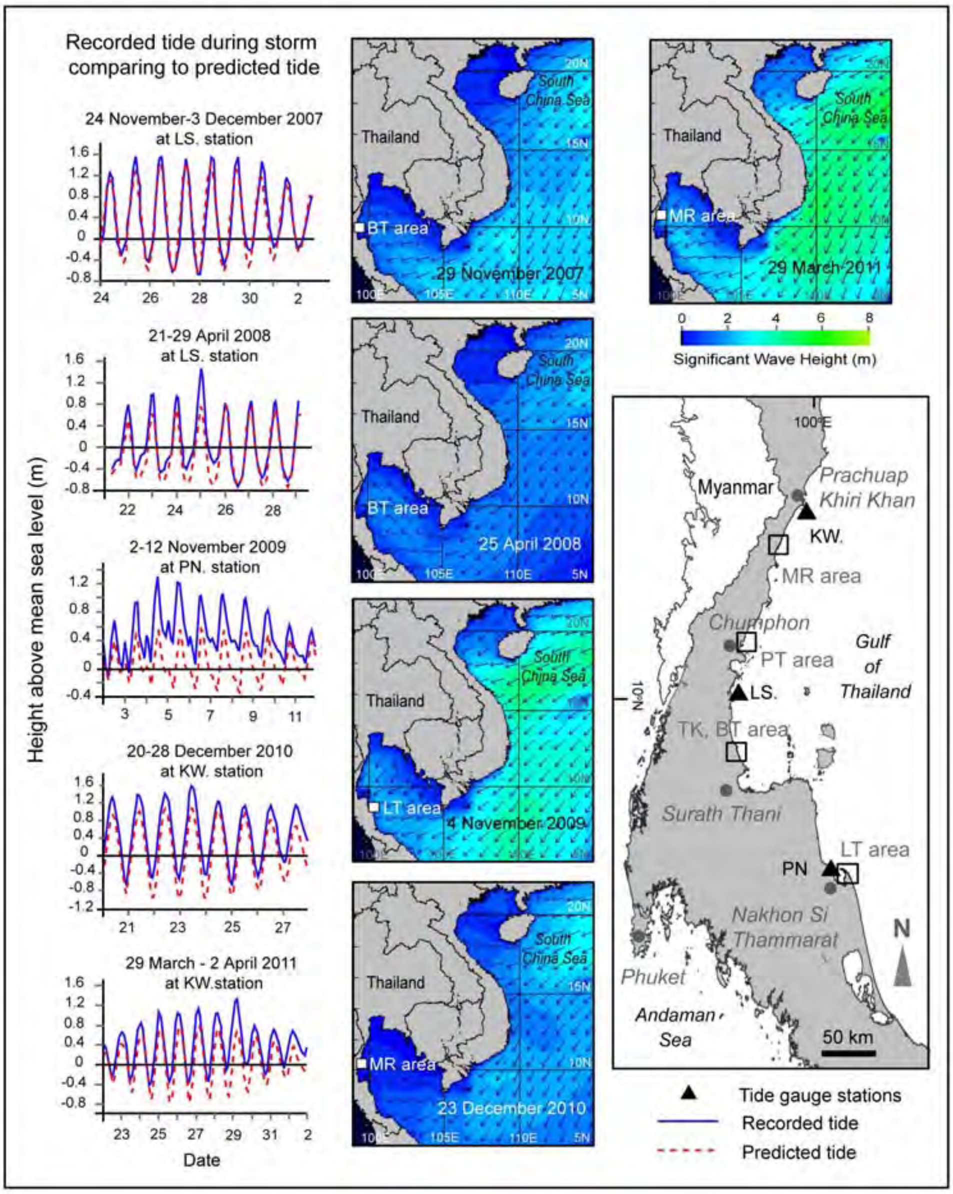


Figure 2.27 Records of tide during storm surge from 2007-2011 in the study sites from the nearby tide gauge stations (left). Significant wave height and wave direction map in the South China Sea and the GOT during the 2007-2011 overwash events (middle). Location of tide gauge stations and the study sites (right). Recorded tide and predicted data; from Hydrographic Department, Royal Thai Navy. Significant wave height and wave direction data from Oceanweather, Inc and www.thaiwater.net.

**2.3.1 Khao Mai Ruak (MR), Prachuap Khiri Khan**

The first location is the Khao Mai Ruak (MR) in Prachuap Khiri Khan Province which is located at the northernmost of the four areas. Its topography exhibits the sand barrier which developed in front of the tidal channel (Figure 2.28). At the northern part, the shrimp farm is developed in the tidal floodplain and marsh area whereas the southern part is still undisturbed. The old washover deposits which cover by vegetation can be recognized from satellite image as a fan lobe at the southern part of area near the inlet tidal. Roy (1990) found the washover deposits from typhoon Gay in 1989 at Khao Huai Khrok, Thap Sakae which located at the southern part of MR area. Additionally, MR is also affected from storm surge induced by high velocity NE wind and low pressure system in 2010 and 2011. Modern washover deposits from storm surge 2010-2011 were found at the backside of sand barrier as reported by Phantuwongraj et al. (2013). Furthermore, the geological evidence of former washover deposits were also found behind the outer sand barrier as mentioned by Roy (1990) and Phantuwongraj et al. (2013).


Figure 2.28 High resolution satellite image at Khao Mai Ruak (MR) area in Thap Sakae, Prachuap Khiri Khan Province. White polygon is the study area. Satellite image from PointAsia; acquisition period: May 2003.

### 2.3.2 Phanang Tak bay (PT), Chumphon

The second site is Ban Hua Tha, Phanang Tak bay (PT), Chumphon province. Based on the interpretation from satellite image, the coastal plain of PT bay exhibited the series of relict sandy ridge in the north-south trend parallel to the bay shape. These relict sand ridges were result of the prograded of sand barrier at estuary's mouth during the regressive sea level about 2,000-1,500 year ago as mentioned by the Phantuwongraj et al. (2010). At the middle part of PT bay behind the relict sand ridge, the large swale shape-liked lagoon was recognized (Figure 2.29). Many sand layers of possible ancient storm deposit were found in the large muddy swale which located far about 1 km inland from the present shoreline as reported by Phantuwongraj and Choowong (2012). Generally, this swale in not effected from storm surge generated by temporary strong NE wind due to the distance from swale to shoreline is quiet far. However, in November 1989 when Typhoon Gay was landfall at Chumphon province, PT bay, including this swale, was flooded by storm surge for a few days.


Figure 2.29 High resolution satellite image showing the large swale and relict sandy ridge at Ban Hua Tha, Phanang Tak bay (PT), Chumphon province. Satellite image from PointAsia; acquisition period: December 2005.

### 2.3.3 Ban Pak Nam Tha Krachai (TK), Tha Chana and Ban Takrop (BT) Chaiya, Surat Thani

The third area is located in Tha Chana and Chaiya district, Surat Thani province. At Ban Pak Nam Tha Krachai (TK) in Tha Chana district, the study area is located in the delta plain beach ridge near the tidal channel Khlong Taling Thao (Figure 2.30a). The relict strand lines are obviously seen from the satellite image which shows the prograded of strand plain along the Khlong Tha Chana delta. Washover deposit were found as a single sand sheet between muddy layers in a small swale behind the outer beach ridge (Figure 2.30a1) at Tha Chana as reported by Phantuwongraj et al. (2008). Village's people indicate that, normally, this swale is rarely flooding from overwash even in a high tide period.


Figure 2.30 High resolution satellite images showing the site study locations in Surat Thani province.a) Strand plain along the Khlong Tha Chana delta. a1) Swale at Ban Pak Nam Tha Krachai (TK) near Khlong Taling Thao. b) Paleo sand spit at Chaiya district. b1) Relict strand lines at Ban Takrop (BT). Blue polygon indicated the study sites.Satellite image from PointAsia; acquisition period is not available.

However, during the end of December 2011, the temporary strong NE wind during NE monsoon season has generated the storm surge that caused the overwash flow to the coastal lowland of the Surat Thani province which including this area too.

Whereas at Ban Takrop (BT) in Chaiya district, the area displays as prograded shoreline which is composed of relict strand lines oriented in the northwest-southeast direction. 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. Then, the geomorphology is transform to the strand plain of paleo-sand spit which exhibited the series of relict strand lines that indicated the paleo-longshore current in north-south direction (Figure 2.30b). During 2007-2012, BT area was affected from the storm surge induced by temporary NE strong wind that causing the overwash flow and flooding the coastal area up to 200 m inland. Here, modern washover fan lobes were found behind the outer beach ridge (Figure 2.30b1) as a result of overwsh flow by storm surge during 2007-2011 as reported by Phantuwongraj et al. (2013).

### 2.3.4 Laem Talumphuk (LT), Nakhon Si Thammarat

The last location is located in Laem Talumphuk (LT), Nakhon Si Thammarat province. Laem Talumphuk is an active sand spit, 6 km long and 500-700 m wide with a south-north trending orientation that corresponds to the recent majority longshore current. The spit itself developed from an east-west orientation of a series of former beach ridges. Now, the distal part of the spit is re-curving to the west (Figure 2.31).

Behind the outer beach ridge, many shrimp pounds were situated along the shoreline of sand spit. These coastal shrimp farm are one of the important factors that induced the rate of shoreline erosion in this area so faster. Additionally, when the storm surge occurred, the damage from scour and breach are higher than the other area. In 1962 when tropical storm Harriet landfall at LT, it generated storm surge high at least 4 m which causing the damage to the LT sand spit area. Apart from 1962 event, LT is annually affected storm surge generated by high velocity NE wind. Phantuwongraj et al. (2008) reported the washover sediments deposits found at LT. In 2009, LT area also effected by NE monsoon surge again and many washover deposits were found behind beach along the shoreline of LT as reported by Phantuwongraj et al. (2013).

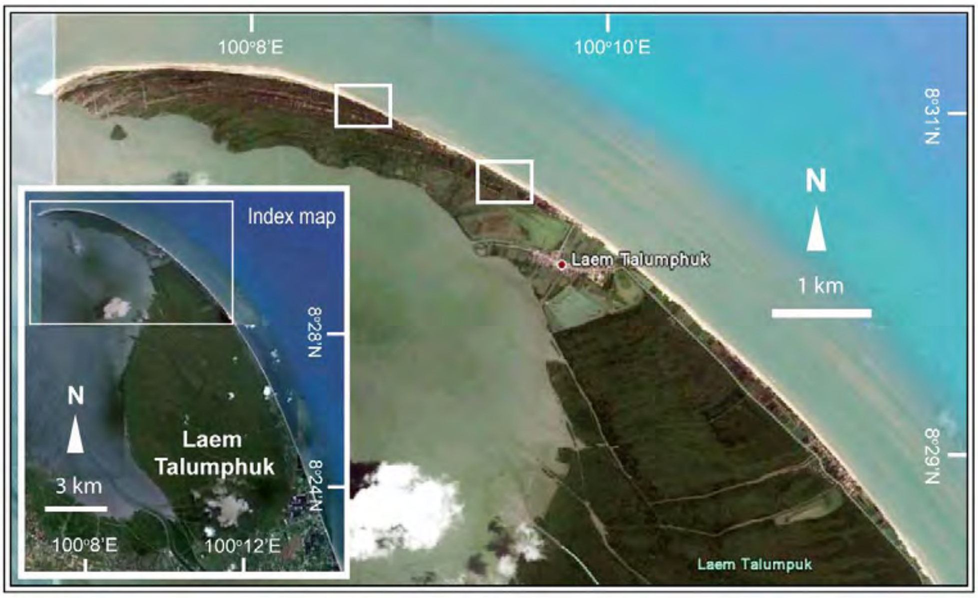


Figure 2.31 High resolution satellite image showing Laem Talumphuk sand spit, Nakhon Si Thammarat province. White polygon indicated study areas. Satellite image from Google Earth; acquisition date: 4 May 2009.

**2.4 Monsoonal wind**

The climate variation of Thailand is under the influence of two main monsoon winds of seasonal character, being the southwest (SW) monsoon and NE monsoon (Figure 2.32). The SW monsoon in May-October brings a stream of warm moist air from the Indian Ocean towards the Thai peninsular resulting in an abundance of rain over the country. Subsequently, the NE monsoon in October-February originally forms as the 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 peninsular. NE monsoon wind also forcing sea water in the South China Sea to moving downward in the southwest direction, which some part of this sea water also flowing into the GOT. Consequently, as the volume of sea water in the GOT was increasing, thus the sea water level in the GOT is also increasing too (Figure 2.32a).

The increasing of wind speed during the NE monsoon period also generated the wave set up, strong wind pushing the surface of sea water, that causing the wave height in the GOT is increasing (Figure 2.32b).

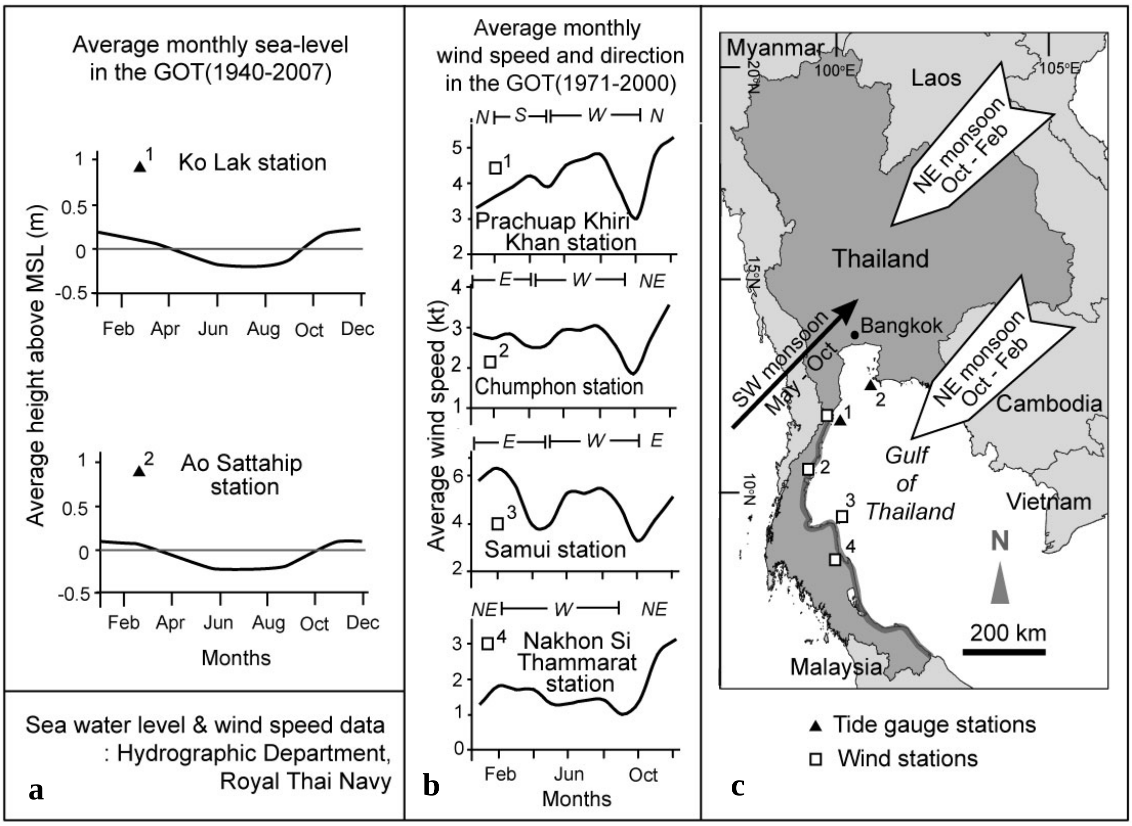


Figure 2.32 (a) Average monthly sea-level in the Gulf of Thailand (GOT) from 1940-2007. (b) Average monthly wind speed and direction from 1971-2000 from the nearest weather stations to the three study sites. (c) Map demonstrates usual NE and SW monsoon directions in Thailand and location of tide gauge stations and weather stations. Bold line bounds the areas commonly affected by overwash flow by storm surge.

This wind driven-current from the NE monsoon is usually creates a 2-3 m high wave (above the normal sea level) that often induces the overwash flow across the beach ridge in low-lying coastal areas. This phenomenon of storm surge induced by temporary NE strong wind usually occurs during the November to January as it is a highest period of sea level rise of the year in the GOT side. The storm surge induced by temporary NE strong wind during NE monsoon season also found in Singapore as reported by Tkalich et al. (2013).

Additionally, during November – December, the eastern side of southern Thai peninsular is usually affected from depression or tropical storm and sometime typhoon that were generated in the South China Sea, Pacific Ocean, and sometime in the GOT as well. The tropical storm or depression will moving from the east to the west, and finally landfall at the southern Thai peninsular at the GOT side as Tropical storm Harriet, Typhoon Gay, and Typhoon Linda attacked the Nakhon Si Thammarat, Chumphon, and Prachuap Khiri Khan province, respectively.

**2.5 Tides**

The tidal patterns in the four study sites are characterize as diurnal type and mixed type, prevailing diurnal (Figure 2.33). The different in tide patterns were resulted from the different topographic location and current in the ocean. The diurnal type which has only one high and one low tide each day is belong to the upper two study sites at Prachuap Khiri Khan and Chumphon provinces. Subsequently, the mixed type, prevailing diurnal is belong to the lower two area at Surat Thani and Nakhon Si Thammarat provinces. This mixed type, prevailing diurnal has temporarily only one high water and low water daily, but temporarily also two high waters and two low waters, which differ much in high and high water time as described by Wyrtki (1961).

During the NE monsoon season, sea level in the GOT is normally raising higher than the average mean sea level (MSL) (Figure 2.32a) due to the movement of seawater from South China Sea moving downward and then flowing into the GOT corresponded to the prevailing wind from northeast direction. In contrast, in SW monsoon season, the prevailing wind blown to the opposite side which leading the seawater moving out of the GOT, thus the seawater level in the GOT is decreased lower than the average MSL. The average change of seawater level in the GOT causing by monsoon wind change is 0.4 m. (Figure 2.32a).

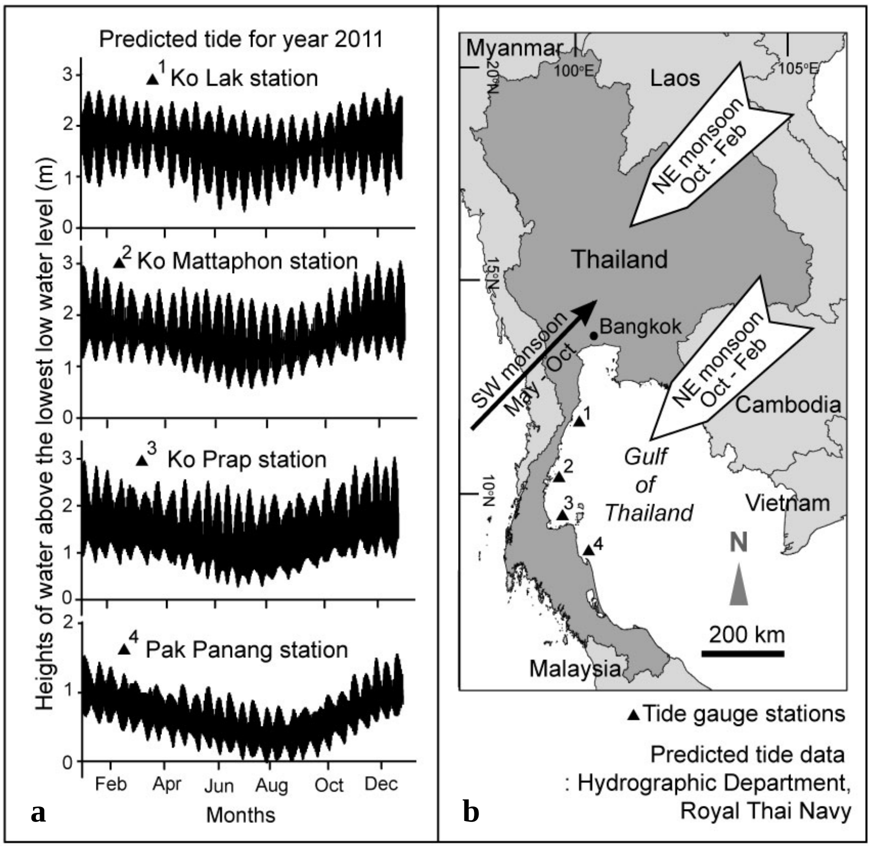


Figure 2.33 Predicted tide data for year 2011 from four tide gauge stations nearby the site study area.

The average tidal range values in the study area show the high value at the north and slightly change to the low value toward to the south. At MR area in Prachuap Khiri Khan Province which located at the northernmost of four areas, the average tidal range is 1.12 m. The second area at PT in Chumphon province the different between high and low tide in average value is 1.04 m. Then, the third area at TK and BT in Surat Thani Province yields the average tidal range at 1.09 m. Finally, the last site at LT area in Nakhon Si Thammarat provinces the average interval of high and low tide is 0.5 m. The different in average tidal range values may result from the different of coastal topography, tidal pattern, and ocean current at each area.

# CHAPTER III

# METHODOLOGY

This study is approach mainly in four steps, including 1) Literature review and remote sensing interpretation, 2) Regional survey, 3) Sample collection, 4) Beach profile measurement, and 5) Laboratory analyses (Figure 3.1). The establishments of sedimentary characteristics of washover deposit models in different environmental setting will show the spatial and stratigraphical relationships between the coastal topography and washover sediments.

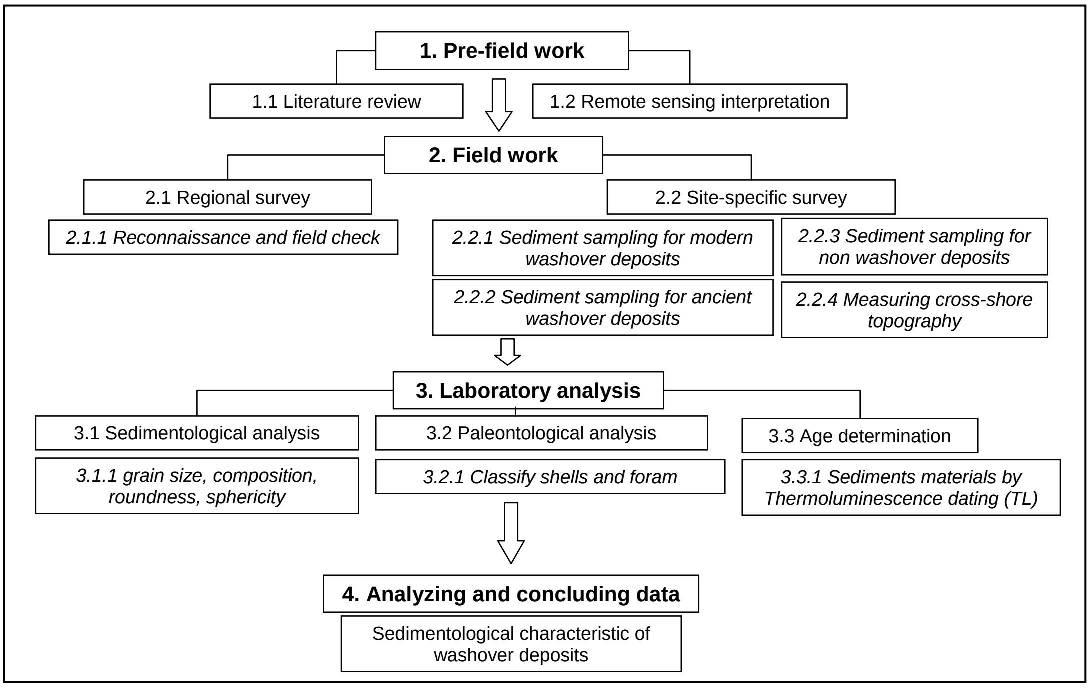


Figure 3.1 Flow chart showing methodology using in this research study.

## 3.1 Literature review and remote sensing interpretation.

Literature studies related to high-energy sediments deposits such as storm and tsunami were reviewed. The storm genesis, NE monsoon condition, and coastal storm hazard in Thailand were also studied. Carefully interpretation of satellite images and aerial-photographs were performed which aiming to locate precise localities for detail pitting and trenching for detecting washover deposits successions, especially in storm and NE monsoon path way areas. Lastly, coastal geomorphology map and tidal range database particularly along the Gulf of Thailand also summarized.

## 3.2 Regional survey

After the potential study sites of washover deposits were specified by remote sensing interpretation, the reconnaissance and field check in the areas where the geomorphology are suitable for trapping the washover deposits were carried out carefully together with hand auger (Figure 3.2). Basically, hand auger is first use for the investigation of stratigraphy of possible washover layer and to recognize other subsurface stratigraphy in the target area. After that, mapping coastal geomorphology in a regional scale (1:50,000 base) and in a local scale (1:4,000 base) for site-specific areas were performed.


Figure 3.2 Pictures showing regional survey by using hand auger in several environment including; a) swamp, b) swale behind beach ridge, c) tidal channel, and d) paleo-lagoon which aiming to investigate the burial washover sediment and subsurface coastal profile.

## 3.3 Sample collection

When the possible modern or ancient washover deposits were found the systematic collecting data will be performed as follows:

### 3.3.1 Sediment sampling for modern and ancient washover deposits

The systematic collection is carry out by making test pits and/or long trench (Figure 3.3) to obtain sedimentological data such as sedimentary structures, geometry of each observed sedimentary structure, organic matters, and the other related physical properties of sediments. Samples are collected separately by lunch-box (Figure 3.4a) (Nanayama et al., 2000; Choowong et al., 2008a), and bulk sampling (Figure 3.4b) techniques. Lunch box technique is the best way that we can bring sediment samples back to the laboratory without the disturbance for the sedimentary analysis and also useful when the target layer is thin and difficult to collect from the pit wall.

The washover sediments were sampling systematically layer by layer from top to bottom. At washover deposits layer the samples are collected at every 5 mm for thin layer (thickness <10 cm) or 1 cm for thick layer (thickness >10 cm) in a vertical distance (Figure 3.5a) for observing the change during the deposition time. Additionally, hand auger is commonly use for collecting the sediments samples for ancient washover deposits (Figure 3.5b) which can go down deeply about 4 meters from ground surface in case of trenching and pitting is not possible.


Figure 3.3 Trenching a), b), and c) and test pit d), e), and f) were made to observe the physical characteristics and continuity of burial washover sediment and also for collecting sediment samples


Figure 3.4 Lunch box a) and bulk sample b) technique using in this study.


Figure 3.5 a) Sediment sampling at every 1 cm for washover deposit layer form test pit and b) core sampling form hand auger.

### 3.3.2 Sediment sampling for non washover deposits

For non washover sediments such as beach, dune, flood tidal delta, and swampy area, bulk sample (500 g/sample) and systematically layer by layer were assigned for comparing the sedimentary properties to the washover sediments.

## 3.4 Beach profile measurement

The coastal surface profiles from site-specific areas are carrying out by high precision digital topographic survey camera (Figure 3.6). Beach profiles were measuring during the low tide time for acquiring the widest and deepest part of the coastal area. Optionally, coastal subsurface profiles will relatively be done by comparing with the result of stratigraphical depth from hand augers. The maximum expectation of depth is approximately 4 meters depending on sediment properties and geological setting of each area. This coastal surface profile ascribes the condition of topography whether it is likely suitable for the preservation of washover deposits while sedimentary data from subsurface profile can disclose the evolution of the coastal area.

Figure 3.6 Digital survey camera using for beach profile measurement at the coastal area.

## 3.5 Laboratory analyses

### 3.5.1 Sedimentological analysis

Once washover deposits were collected, careful laboratory analyses are compulsory. Grain size analyses are performing by a sieve analysis at department of Geology, Chulalongkorn University and Camsizer (Figure 3.7) at Geological Survey of Japan (GSJ) Tsukuba, Japan and Department of Earth Evolution Sciences, University of Tsukuba for investigating grain size distribution and sorting. Basically, physical properties of sediments such as roundness, sphericity, and sediments compositions will be analyzed carefully under binocular microscope. Comparison chart of roundness and sphericity purposed by Power (1953) and comparison chart for estimating percentage composition proposed by Fritz and Moore (1988) are use in this study.


Figure 3.7 Camsizer, a particle analysis by digital image processing method, at GSJ using in this study.

### 3.5.2 Paleontological analysis

Although, the zone of washover sediment deposits are usually located beyond the beach area, in order to confirm whether washover deposits were transported by storm or any other environmental settings of coastal deposits, paleontological analysis is necessary. In general, most of the bioclasts in washover sediments are reworked from the beach; nevertheless, if some fauna that found frequently only in deep water area were present in the washover deposit it can use as a criteria to indicate the high intensities processes of overwash flow such as storm surge. The careful classification of organic matters, particularly benthic fauna are done by binocular microscope. The living zone of these burial fauna can presumably tell us all about their living environment such as swampy area, tidal zone, foreshore, backshore, back-barrier, shoreface, and deep marine. As well as it resemble the source and processes of sediment deposits in each layer.

### 3.5.3 Age determination

The most informative data we needed to see from sediment deposit is the age of the deposition, especially how old of washover depositional layer. The determination in age of the coastal deposits employed for this research is done by Thermoluminescence dating (TL). TL dating technique is applied to sediment sample which collected from the relict strand line or former beach ridge.

Notable, 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) as described in Chapter II. The flood regime, including the overwash regime and inundation regime, followed the conceptual model of storm impact regime originally proposed by Sallenger (2000) which mentioned in the Chapter II. Terminology used for differentiating the thickness of beds and laminae followed that of Campbell (1967). The term “modern washover deposits” is refer to the washover sediments resulting from storm surge during the years 1960-2012, whereas “ancient washover deposits” is refer to the washover sediments resulting from storm surge since a hundred year ago from year 2012.

# CHAPTER IV

# RESULTS

## 4.1 Washover deposits from Prachuap Khiri Khan

In 1989, the southern part of Prachuap Khiri Khan was affected from storm surge generated by typhoon Gay which its trace of storm deposits was found at Amphoe Thap Sakae as reported by Roy (1990). Subsequently, in 1997 typhoon Linda was landfall at Thap Sakae which caused seriously damage to the city. However, the washover deposit from typhoon Linda has never reported. In this study, washover deposits in Prachuap Khiri Khan are mainly results of storm surge which generated by temporary strong NE wind during the NE monsoon season in 2010 and 2011. During the NE monsoon season, the coastal area of Prachuap Khiri Khan was suffered from strong wave attacked the shoreline and flooding from overwash that occurred in the low-lying coastal area. The coastal erosion from strong wave attacked was mainly focus in the area where dam, seawall, or shoreline protection is not available. However, washover deposits were found only in some places. In the sight seeing area where resort and hotel is dominated at the coastline the washover deposits are rare. Washover sediments were found in the coastal lowland which height of beach ridge is not exceeding 2.5 m from mean sea level. For this study, the study site was selected at the non-human activity area which located in Thap Sakae district.

### 4.1.1 Description of Khao Mai Ruak (MR) area

The first location is at the Khao Mai Ruak (MR) in Prachuap Khiri Khan Province which is the northernmost of the four areas. Its topography exhibits the sand barrier which developed in front of the tidal channel (Figure 4.1). 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 (Figure 4.2). 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. The typical sediment deposit at tidal floodplain and marsh here is mud and silt. These fine particles were transported by overbank flood process from tidal channel during high tide or heavy rain fall. At the southern part of Khao Mai Ruak, the tidal channel is flow parallel to the shoreline as the boundary between alluvial plain and supratidal plain (Figure 4.1).

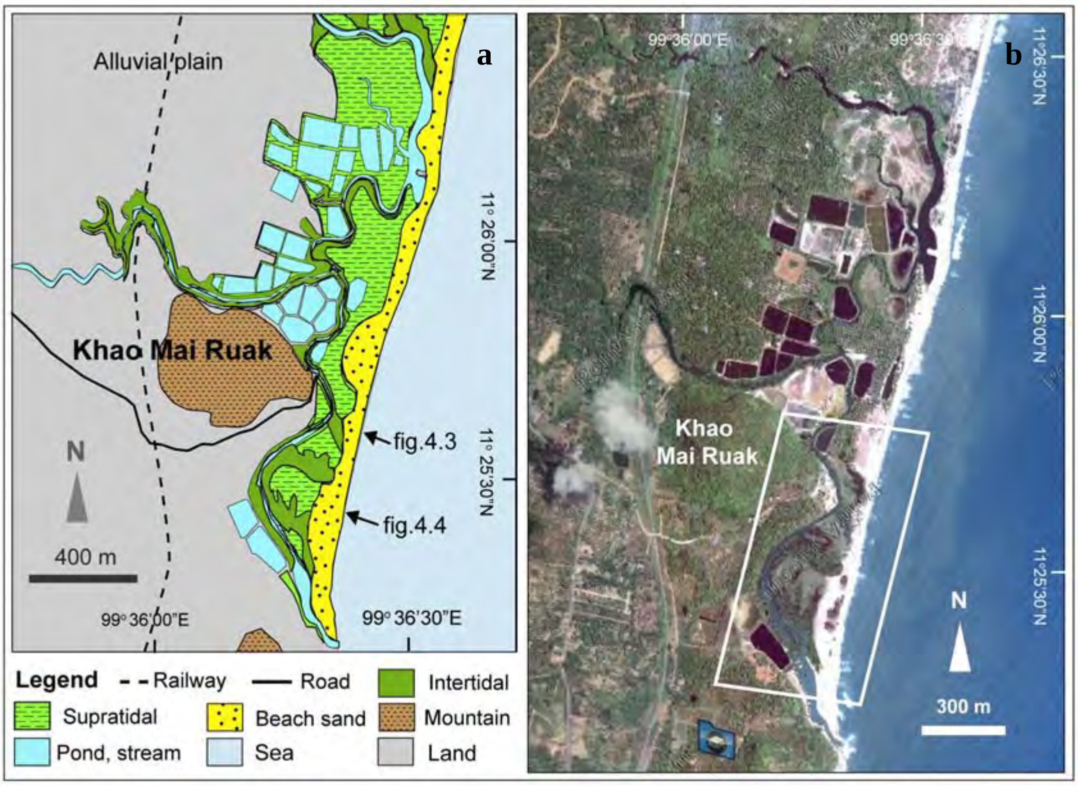


Figure 4.1 Geomorphologic map and high resolution satellite image at Khao Mai Ruak area. Satellite image from PointAsia; acquisition period: May 2003.

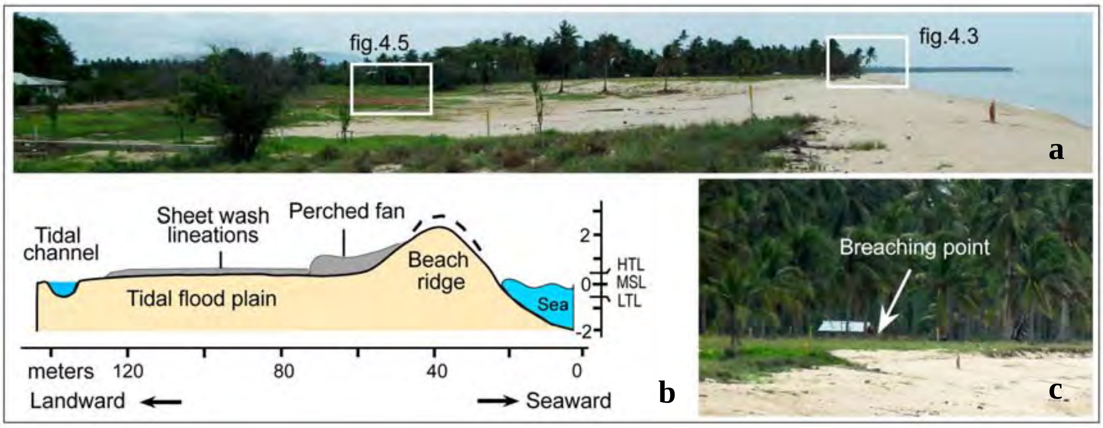


Figure 4.2 a) Cross-shore topography showing washover sediment deposit on tidal flood plain. b) Beach profile showing perched fan and sheetwash lineations on tidal flood plain. c) Breached point at beach face. Pictures taken from the white polygon area in Figure 4.1

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 (Figure 2.27).

**4.1.2 Detail sedimentary characteristic from Khao Mai Ruak (MR) area**

Site investigation at the MR area was performed on 13th June 2011. The evidence of erosion by the 2010 and 2011 storm surges were 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 (Figure 4.3). 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 (Figure 4.2a, 4.5a).


Figure 4.3 Beach scarp resulting from wave attacked.
Picture a) looking north b) looking south.

The 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, the 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 also likely to be higher.

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. This feature was classified as a perched fan type. Both of the sheetwash lineations and perched fan type 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 (Figure 4.4a). In the distal part, the lobes of old washover deposits were superimposed on the older lobe on the marsh surface (Figure 4.4b) as a boundary between two washover deposits from at least two different events.

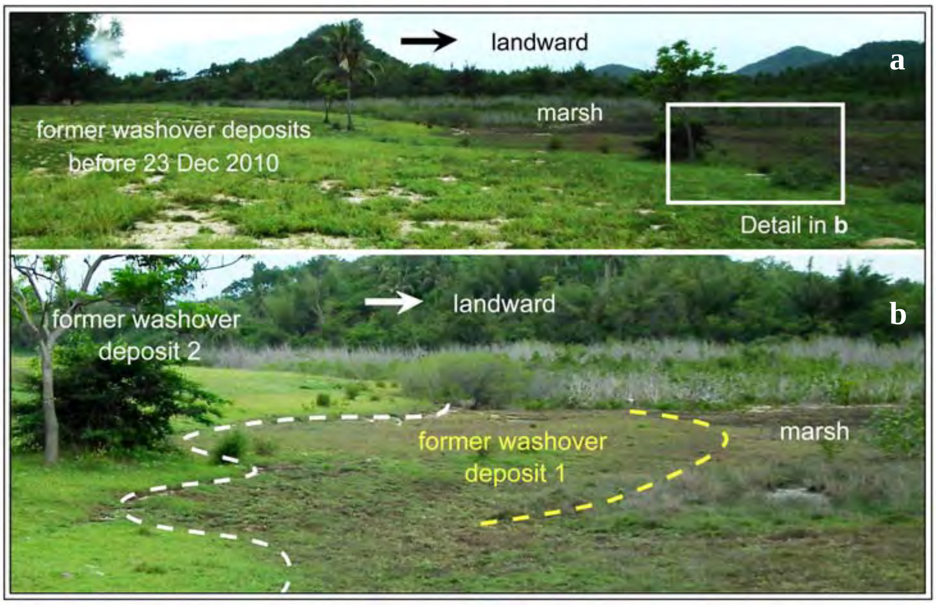


Figure 4.4 a) The former washover deposits before 23 December 2010 that terminated in the marsh. b) Margin of the former washover deposits from two different events on the marsh surface. Pictures taken location is indicated in Figure 4.1.

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.

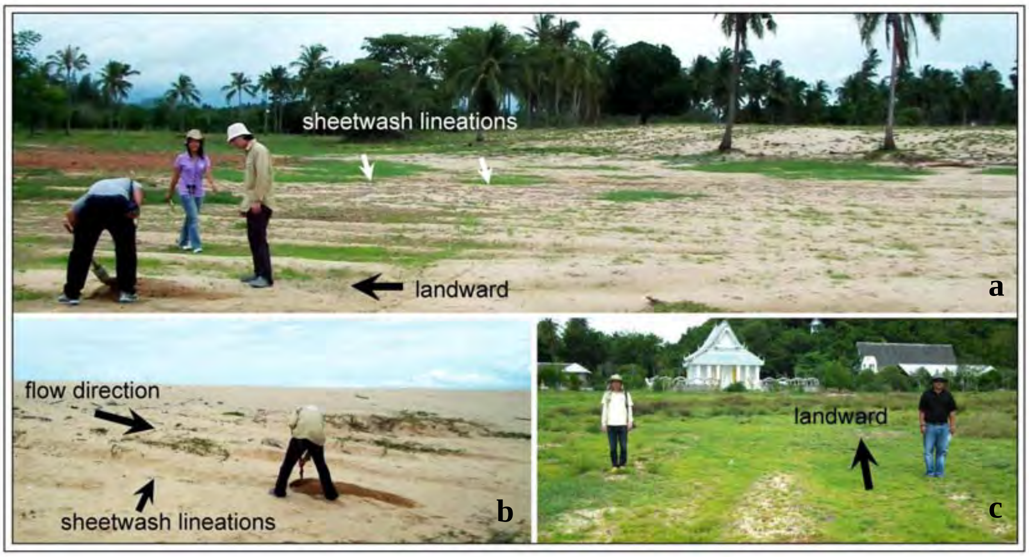


Figure 4.5 a) Elongated and narrow sheetwash lineations on the tidal flood plain at backshore as result of overwash flow by inundation regime. b) Sheetwash lineations at backshore reflecting the flow direction from the NE to SW. c) Three lineations of sheetwash deposits indicated by men standing on crest of lineations. Pictures a and b taken on June 2011, while picture c taken on August 2012. Pictures taken location is indicated in Figure 4.2.

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 (Figure 4.2a and c). A narrow and elongated zone of erosion and deposition as sand lineations was found behind the barrier on the tidal floodplain surface (Figure 4.5a). These sheetwash lineations were straight and showed a flow direction from the NE to the SW (Figure 4.5b). The crest of the sheetwash lineations was 20-30 cm in thickness and the gap between each lineation was 50-70 cm in width. (Figure 4.5c).

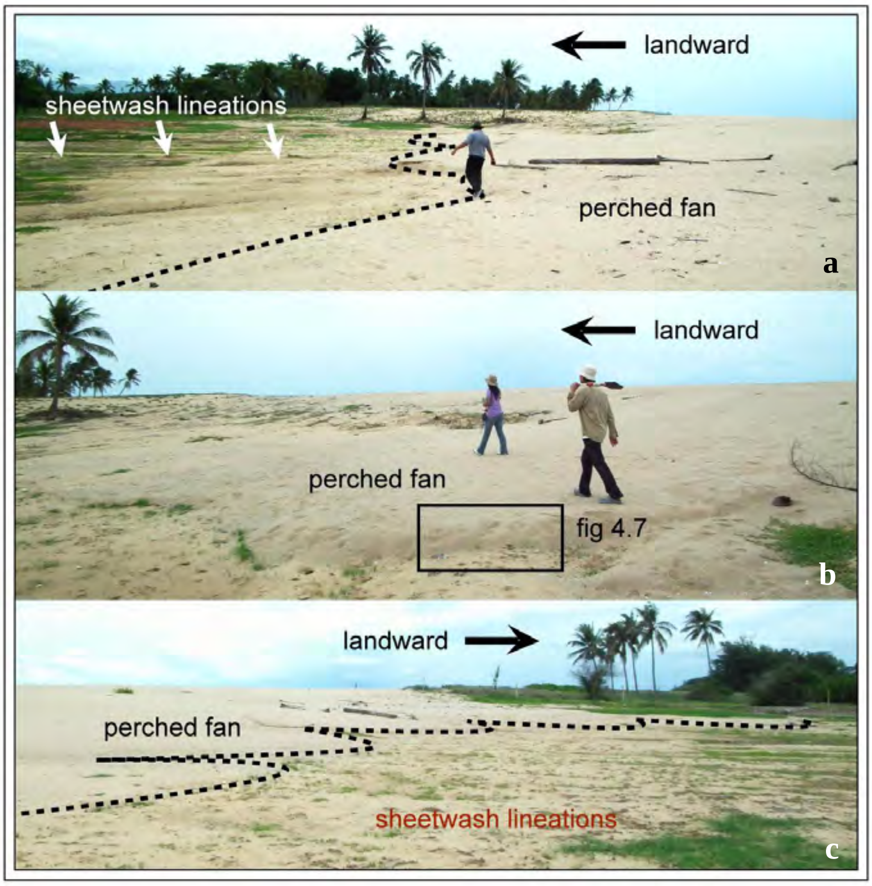


Figure 4.6 a) New perched fan deposited on top of the sheetwash lineations behind beach that was b) spilt into 4-5 lobes at the distal part (looking north). c) Tiny green grasses are starting to cover the sheetwash lineations area which contrasts to the clean sand at new perched fan deposit (looking south). Black dash line is a boundary between perched fan and sheetwash lineations area. Pictures taken location refer to Figure 4.2 and 4.5

Behind the breached barrier, another washover deposits were found preserved as a perched fan shape overlain on the sheetwash lineations (Figures 4.6). Based on the storm impact scale for barrier islands proposed by Sallenger (2000), perched fan and sheetwash features were 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.

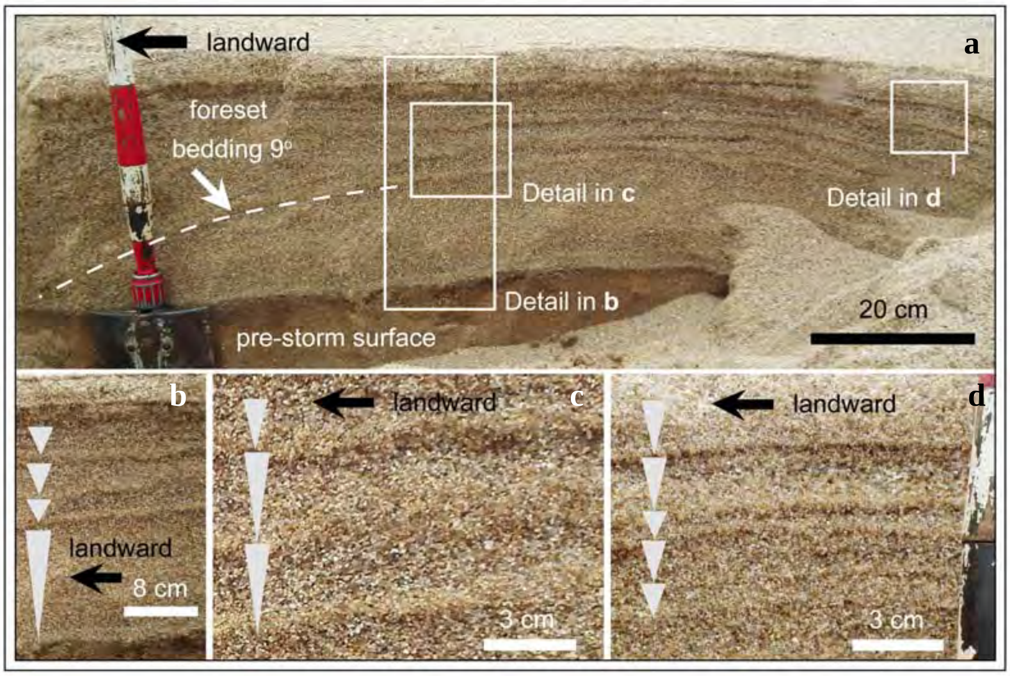


Figure 4.7 a) The multiple laminae and foreset bedding within the perched fan deposit. b) Thickness of each layers show upward thinner trend. c) Thick sand laminae at the middle part of the perched fan succession and the d) thin sand laminae at the upper part of perched fan deposit. Pictures taken location is indicated in Figure 4.6.

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 (Figure 4.7). 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 (Figures 4.6b and c). Trenching there revealed twelve sub-horizontal layers of very coarse grained sand with numerous laminae dipping landwards (Figure 4.7). 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 (Figures 4.7). 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 (Figures 4.7b, c and d). The reason that the bottom part yield the most thickest layer might resulting from the initial wave attacked that bring numerous of eroded sediments from beach to deposited behind as washover deposit. Consequently, the sediment supply that being source of washover deposit were decreased from beach (erosion zone). Then, when the next overwash come, and eroded beach again, the new washover layers were become thinner as a result of decreased sediment supply.

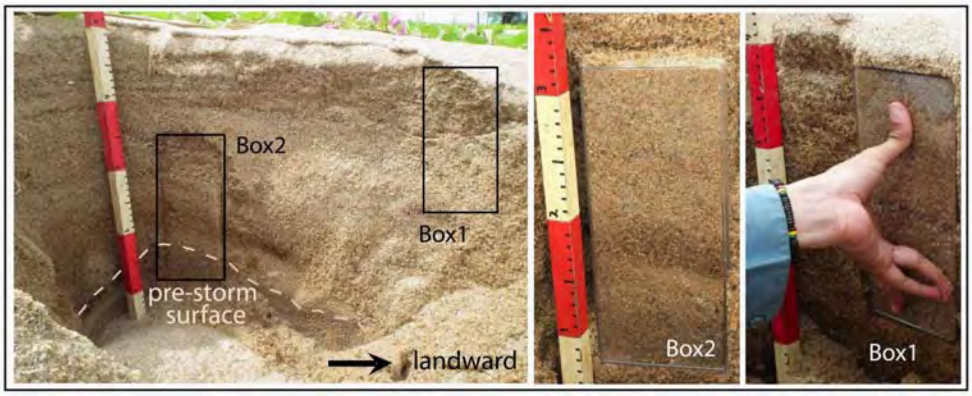


Figure 4.8 Two lunch box samples at the distal part of perched fan. Box1 was collected from surface to depth 25 cm, and box2 was collected at dept 15-40 cm. Pictures taken location refer to perched fan in Figure 4.6.

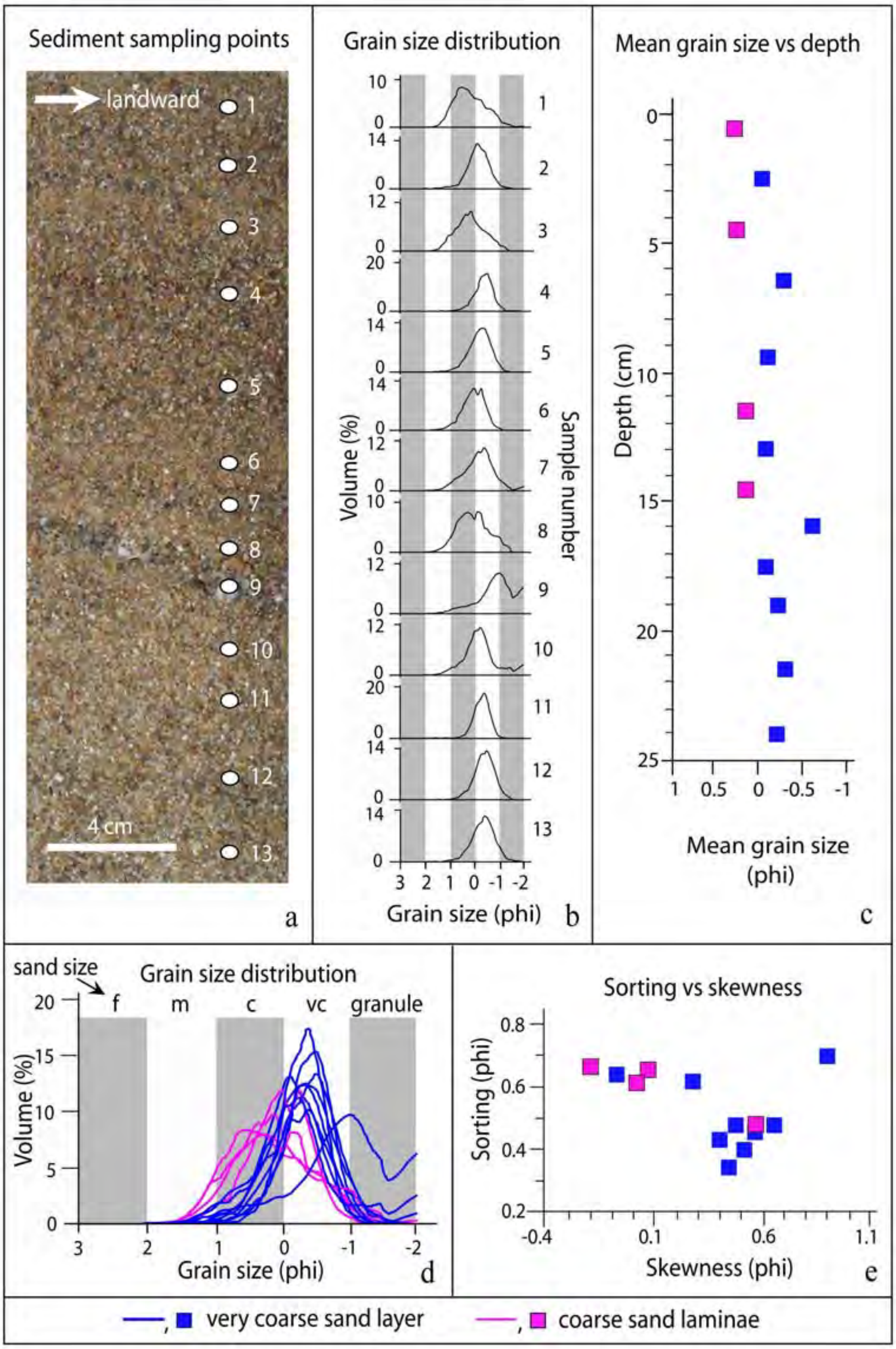


Figure 4.9 Grain size analysis data from box 1. a) Sampling locations in the washover sediment. b) Grain size distribution graph of washover sediments. c) Average grain size change from top to bottom within the washover deposit. d) Comparing grain size distribution graph of very coarse sand layer and coarse sand laminae. e) Sorting and skewness value of very coarse sand layer and coarse sand laminae.

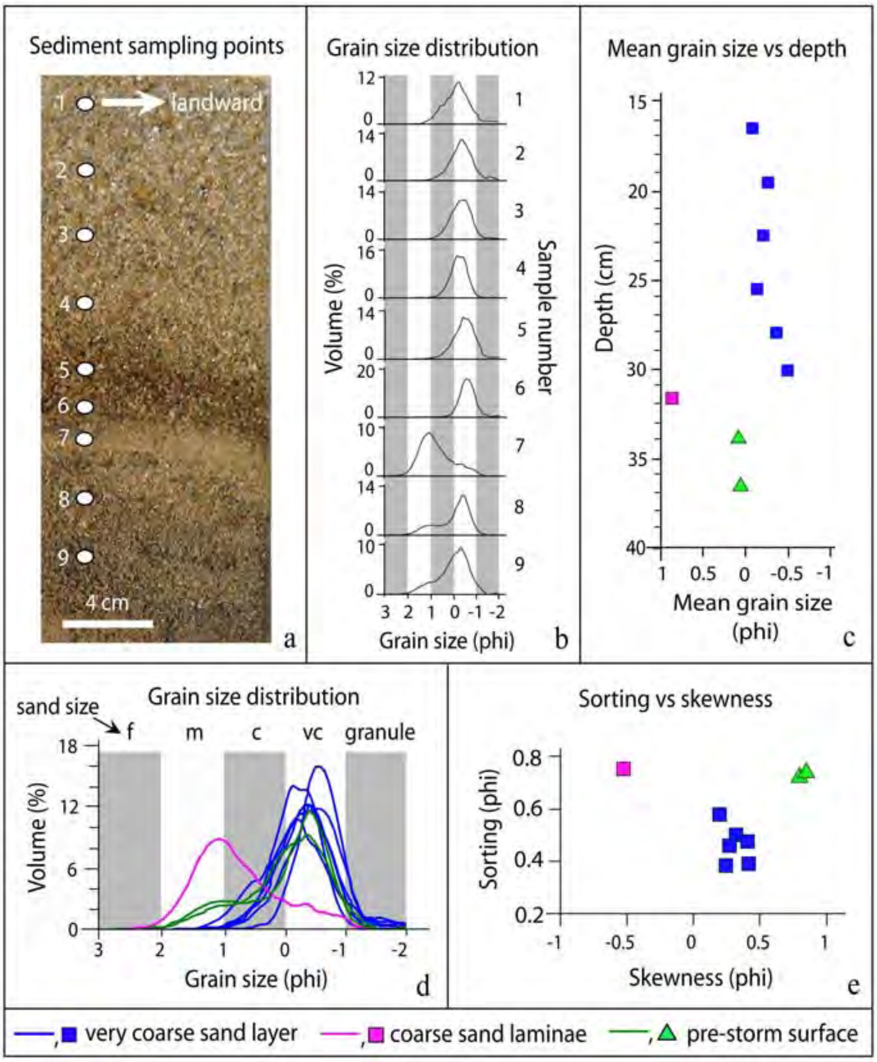


Figure 4.10 Grain size analysis data from box 2. a) Sampling locations in the washover sediment. b) Grain size distribution graph of washover sediments and pre-storm surface sediments. c) Average grain size change from top to bottom within the washover deposit. d) Comparing grain size distribution graph of very coarse sand layer and coarse sand laminae. e) Sorting and skewness value of very coarse sand layer and coarse sand laminae.

At the distal part of perched fan, the sediment samples were collected by lunch box technique and brought back to the laboratory for analyzing their physical properties (Figure 4.8). The sampling area of box1 and 2 were overlap at depth 15-25 cm. According to grain size analysis data of box1 and box2, five layers of washover sediments, separated by coarse sand laminae, can be identified (four layer in box1 and one layer in box2) (Figure 4.9, 4.10). Although twelve layers of washover sediment were recognized in the field, but sampling in the coarse sand lamiane at the upper part are very difficult due to theirs thickness that are very thin. Thus, those thin sand laminae were skipped. The size of very coarse grained-sand is in the range of -0.63 to -0.04 phi (Figure 4.9, 4.10). Whereas the coarse sand laminae is in the range of 0.12 to 0.85 phi. The finest sand-grained was at the base of washover deposit at sample 7 (Figure 4.10).

Most of very coarse sand layer showed the unimodal distribution with positive skewness (Figure 4.9, 4.10). In contrast, the coarse sand laminae showed asymmetrical distribution with a negative skewness. Average sorting value in the very coarse sand layer is better than the coarse sand laminae (Figure 4.9, 4.10). At the pre-storm surface layer, graph of grain size distribution show negative skewness with a fine grained sediment in a trail (Figure 4.10). Additionally, when analyzing percent of mud content in the sediment samples, the pre-storm surface layer showed high mud content about 10% whereas another samples from very coarse sand layer and coarse laminae are not found. This high mud content in pre-storm surface indicated the normal condition of the sediments deposit in this tidal flood-plain area which clearly different from the overlain washover deposit.

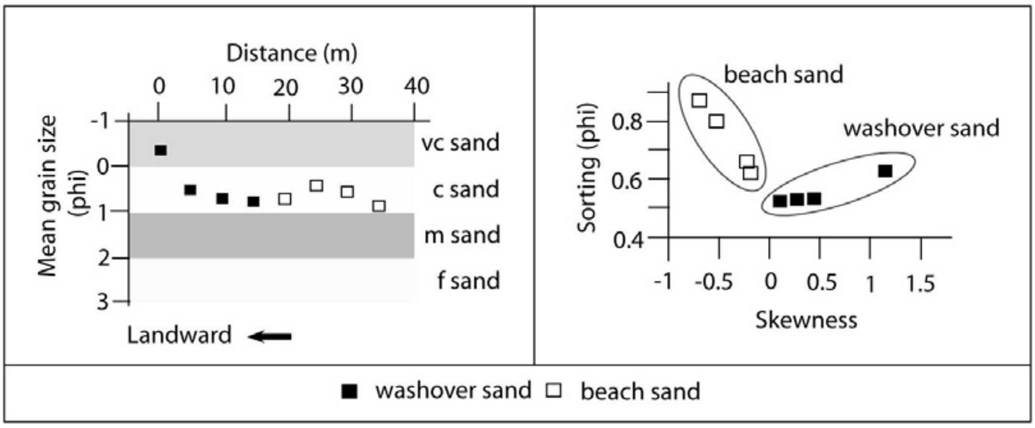


Figure 4.11 Mean grain size values of washover sediment showing grain size increasing in landward side (left). Sorting and Skewness values of washover deposits and beach deposit (right).

To observe the lateral change in grain size, the samples were collected at surface of perched fan every 5 meters from distal to proximal, and then continue to beach and foreshore zone. From grain size analysis data, the average grain size of perched fan is increasing when go further inland (Figure 4.11a). At the proximal washover deposit, the average grain size is 0.80 phi, then increasing to 0.71 phi, 0.54 phi, and finally -0.31 phi at the distal margin. This unusual landward coarsening in washover deposit may have resulted from the error of sampling. According to the date of sediment surface sampling that was carried out almost one year after the overwash event, thus the finer sediments at surface of washover deposit may were blown away by eolian process or washed out during the heavy rainfall before the sampling date, and then left behind the coarser sediments. Washover sand also yield the better sorting value when comparing to beach sand as moderately well sorted and moderately sorted, respectively. Additionally, washover sand shows the plus skewness value while beach sand yield minus skewness value (Figure 4.11b).

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 (Figure 4.7a). 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 (Figure 4.7c). At the end of perched fan margin inland, many shells and shell fragments were found deposits on the surface of perched fan (Figure 4.12). These shells commonly found at the foreshore and shoreface zone. Thus, it indicated the source of washover sediments that possibly come from shoreface zone.


Figure 4.12 Shells deposits on the surface of perched fan which concentrated at the distal margin of washover deposit. Pictures taken location refer to Figure 4.6 at the distal part of perched fan.

## 4.2 Washover deposits from Chumphon

Chumphon province has experience storm surge from typhoon Gay in 1989 which cause a seriously damage to the affected area especially in Pathio and Tha Sae district. Recently, there is no report of washover deposits from typhoon Gay. Washover deposits may be destroyed during the renovation activity by people in the affected area after the event. Apart from typhoon Gay in 1989, the temporary strong NE wind during the NE monsoon season at the end of year 2011 also generated the overwash flow to the coastline of Chumphon. Washover deposits from this storm surge in 2011 were reported in a newspaper and television. Unfortunately, a few weeks later, the washover sediments were completely removed from the affected area as a result of the cleaning activity by people. Furthermore, the preservation area such as a swale behind beach that can keep the washover sediment is very rare in Chumphon, thus, it is difficult to find the record of washover deposits here. However, when go further inland about 800 m; the large swale between relict sandy ridges was exhibited. At this swale the multiple sand layers were found deposited between muddy sediment with sharp contact. These sand layers might be the record of ancient storm surge deposit here.

### 4.2.1 Description of Phanang Tak bay (PT) area

Phanang Tak bay, Chumphon province is a coastal strand plain which relict strand lines are obviously seen from satellite image. When go further inland about 800 m, the geomorphic condition of the area shows a paleo lagoon-liked shape between the relicts sandy ridges (Figure 4.13). Its present topography becomes a large swale, 340 m wide (west-east) and 1.4 km long (north-south), between relict sandy beach ridges. The swale is wide at the south and narrows toward to the north with an elevation high above present mean sea level about 4.3 m. Phantuwongraj et al (2010) porposed that Phanang Tak bay was an estuary during the middle Holocene period. Subsequently, these relict sand ridges were generated as result of the prograded of sand barrier at estuary’s mouth during the regressive sea level after the mid-Holocene. From the evolution model of Phanang Tak bay based on sediments coring data proposed by Phantuwongraj et al (2010), it shows the episodic of regressive sea level from mid-Holocene to the present day (Figure 4.14). Firstly, at the highstand period the flat area was an estuary and flooded by sea water (Figure 4.14a). After that, sea-level began to retreated, sand bar, sand ridge, and sand spit was appeared at the estuary mouth (Figure 4.14b). Then, during 3,300 year ago, barrier island was develop and lagoon is appear. The inner part of the area began to dry and river was developed (Figure 4.14c). Finally, at the present day, beach ridge, coastal sediment, flood plain, meander scar, and point-bar were present which are result of regressive sea level change and fluvial process of modern river (Figure 4.14d).

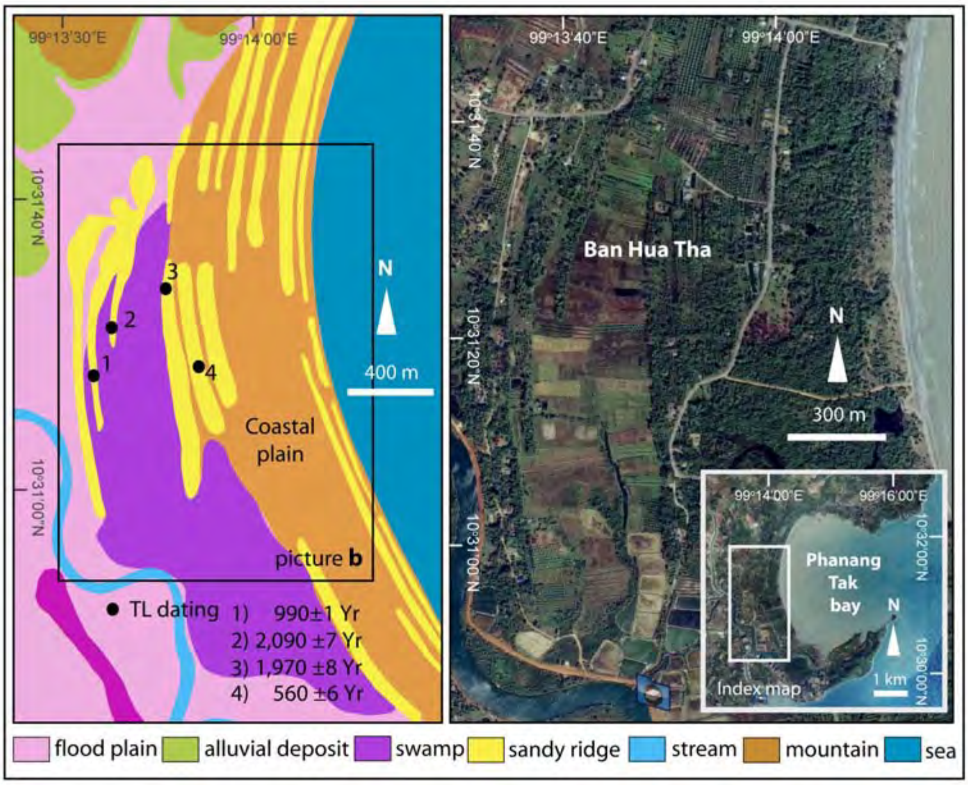

Figure 4.13 Geomorphologic map (left) and high resolution satellite image (right) showing large swale between series of relict sandy ridges and TL sampling locations. Satellite image from PointAsia; acquisition period: December 2005.

To acquire the coastal evolution data, especially the occurrence time of the lagoon, sediment samples were collected from four relict sandy ridges which located at the edge of the large swale aiming to dating the age of each ridge. At sampling sites, small pit was made for collecting the sediment samples for Thermoluminescence (TL) dating (Figure 4.15). Paleo dose and annual dose were collecting with carefully at depth 30-40 cm from ground surface. Paleo dose were collecting in opaque plastic tube for protecting from sunlight while annual dose were collecting in plastic bag.

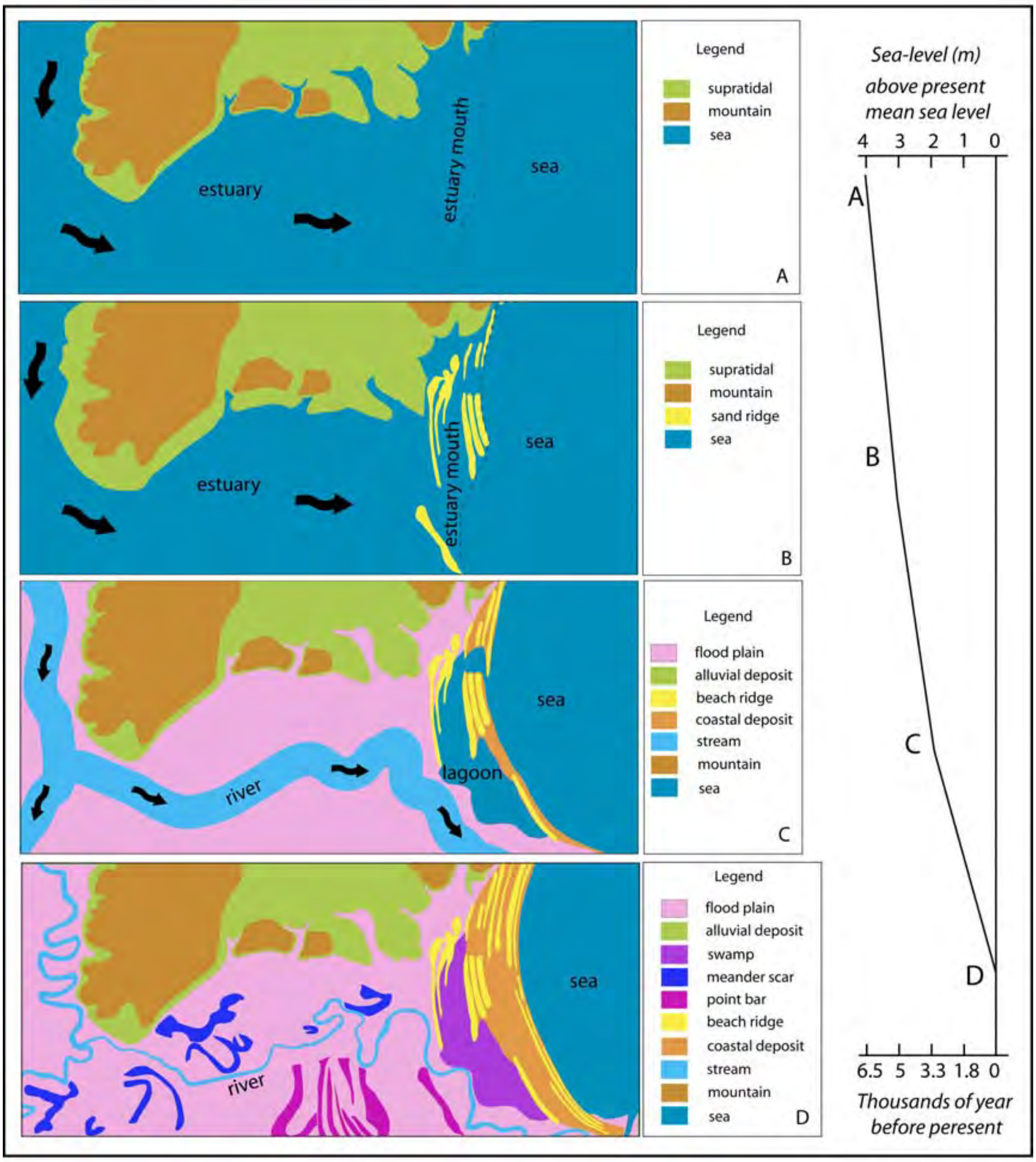


Figure 4.14 Evolution model of Phanag Tak bay after Phantuwongraj et al (2010)

a) Highstand period showing the area was exhibited as an estuary. b) Sand bar, sand ridge, and sand spit was developed at the estuary mouth during the regression. c) Barrier island was developed and lagoon was present as sea level continues falling while the inner part become to subaerial area which river also developed. d) Beach ridge, coastal sediment, flood plain, meander scar, and point-bar were present as result of the regressive of sea level and also fluvial process of recently river.


Figure 4.15 a) Pictures showing small pit for collecting sediment samples for TL dating. b) Annual dose in plastic bag and paleo dose in opaque plastic tube. c) Sediment sampling by opaque plastic tube for paleo dose. Pictures taken locations are refer to the 2nd and 3rd ridge in Figure 4.13.

According to the Thermoluminescence (TL) dating data of relict sandy ridge, the inner beach ridge (1st ridge) was aged 990±1 years, the 2nd ridge was aged 2,090 ±7 years, the 3rd ridge was aged 1,970 ±8 years, and the 4th ridge was aged 560 ±6 years (Figure 4.13a and Table 4.1). From the result of TL dating, relict sand ridges show age from young to old as go further inland, except the 1st ridge that show age younger than the 2nd and 3rd ridge. The unusual age of the 1st ridge that younger than the outer ridge may resulted from the contamination or error during the sediment sampling. In this case, the cross-check data from another samples collected from the same location is required. Unfortunately, there is only one sample collected from the 1st ridge, thus the dating data from this ridge was omitted.

Table 4.1 Results of TL dating analysis from relict sandy ridges.

| Name | U (ppm) | Th (ppm) | K (%) | W (%) | AD (Gy/ka) | ED (Gy) | Age (Yr) |
|---|---|---|---|---|---|---|---|
| **1** | 1.13±0.06 | 6.45±0.35 | 0.55±0.02 | 9.60 | 1.45±0.13 | 1.45±0.06 | 990±1 |
| **2** | 0.77±0.06 | 4.12±0.35 | 0.85±0.03 | 12.65 | 1.49±0.09 | 3.14±0.31 | 2,090±7 |
| **3** | 1.58±0.06 | 8.77±0.44 | 0.67±0.02 | 19.96 | 1.77±0.20 | 3.49±0.35 | 1,970±8 |
| **4** | 3.69±0.09 | 28.64±0.75 | 0.72±0.02 | 13.28 | 3.70±1.11 | 2.09±0.15 | 560±6 |

Therefore, based on TL dating data, the 1st ridge should deposited before 2,090 ±7 years ago, then the 2nd ridge was developed at 2,090 ±7 years ago, and then following by the 3rd ridge at 1,970 ±8 years ago, and finally, the 4th ridge was developed at 560 ±6 years ago. From the evolution of relict sand ridge, the swale should develop during the 1,970 ±8 years ago after the occurring of the 3rd ridge.

In dry season this swale is completely dry, whereas during rainy season this swale is usually flood by the pouring rain. The average water dept in the swale during rainy season is about 40 cm. Additionally, the suitable time for collecting subsurface sediment sample or making a trench/test pit in this area is should perform during the summer season. The deepest sample that can collect from this swale is at depth 4 m by using gauge core during the summer season. At the middle of swale, there is a small creek in the north-south direction which acts as an outlet channel for draining water from swale. The majority sediments deposit in this swale is mud that represents the very calm environment here. However, the unusual deposits from large particle such as sand layers were found here. In the swale, multiple layers of sand sheets were found intervening between muddy sediment with a sharp contact at each layer.

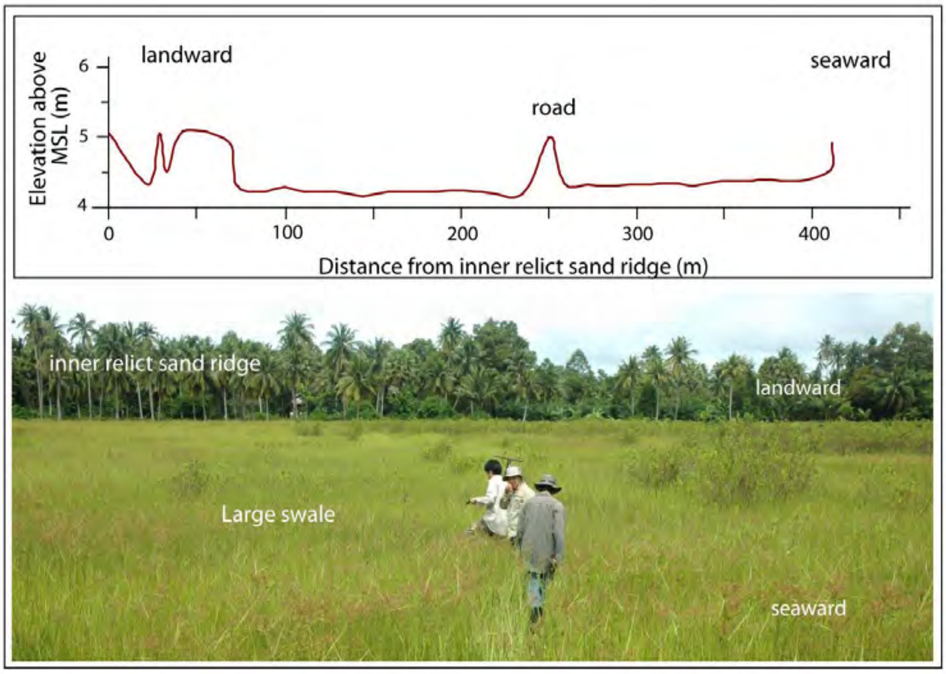


Figure 4.16 Cross-shore topographic in the muddy swale. High peaks at the distance 0 m, 50 m, and 415 m were indicated relict sandy ridges (top). Large swale between relict sandy ridges (bottom). Line of coconut trees is indicated relict sandy ridge.

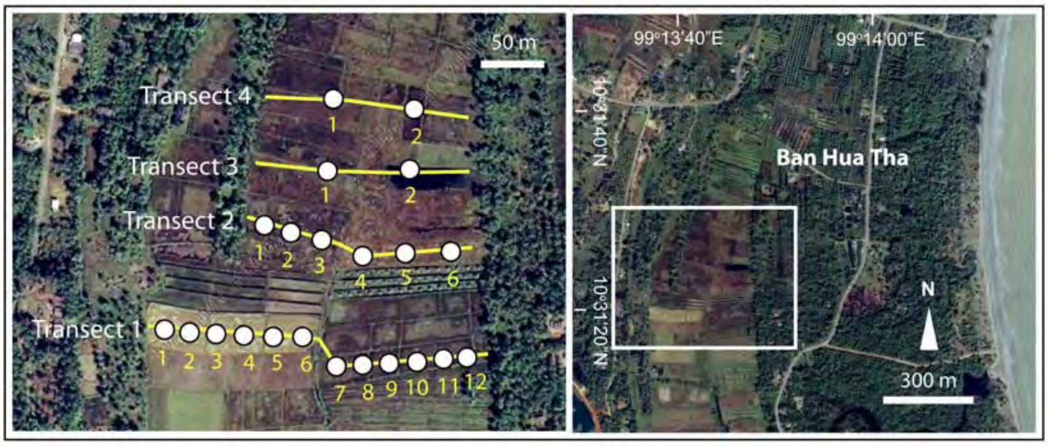


Figure 4.17 Four transects and core sampling locations in the muddy swale (left) and index map of the Ban Hua Tha at Phanag Tak area (right). Satellite image from PointAsia; acquisition period: December 2005.

**4.2.2 Detail sedimentary characteristic from Phanang Tak bay (PT) area**

At the Phanang Tak area, fourteen sand sheets of possible ancient-storm deposit, origin from 22 cores, were found with a sharp contact between muddy layers in the large swale. Topography in the swale is almost flat but at the seaward side the elevation is slightly higher than the landward side (Figure 4.16). Four transects were made at the center of the swale aiming to observe the continuity and geometry of sand sheets in swale (Figure 4.17). Hand auger was use as a tool for coring and sediment samples were collecting by gauge core. At the 1$^{st}$ transect, twelve cores were coring from the 1$^{st}$ sandy ridge to the 3$^{rd}$ sandy ridge. The age dating data from the subsurface sediment between the ancient storm sand sheets may reveal the time of storm surges event. Unfortunately, the funding for this study is not enough to acquire these dating data. Additionally, the main propose of this research is to study the sedimentary characteristics, thus the time of storm surges occurrence are not including here.

Form coring data, topsoil is thick about 6-7 cm. Then the sediments change to dark grey mud and slightly transfer to light grey mud when go down deeper until depth 60 cm (Figure 4.18). At this muddy layer, fresh water shells were found at the upper part, whereas the lower part yellow mottles were found spreading in the grayish mud. Then sand sheets were found intervening between mud deposits from depth 55-

60 cm to depth 140-150 cm (Figure 4.19). Subsequently, at depth 150-170 cm, the sediment gradual change to mud and silty clay with shell fragments.

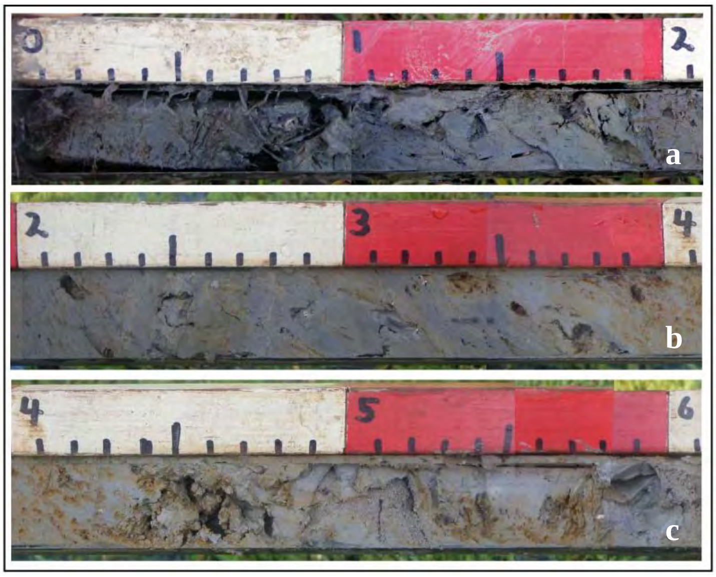


Figure 4.18 Sediment samples from coring at transect 2. a) Depth 0-20 cm, topsoil and dark grey mud. b) Depth 20-40 cm, dark grey mud gradual change to light grey mud. c) Depth 40-60 cm, yellow mottles in the light grey mud layer and sand sheet at depth 50 cm. Picture a) from core 5, picture b) and c) from core 2.

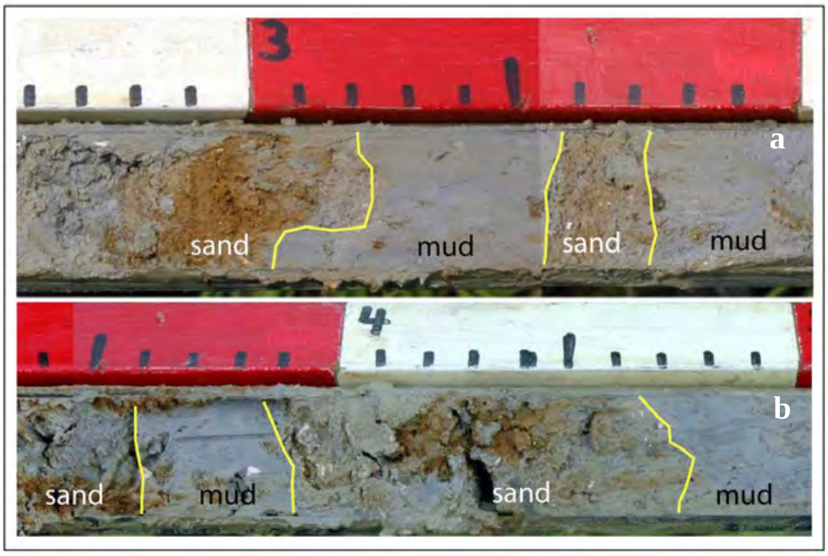


Figure 4.19 Sand sheets deposit between mud from coring at transect 1.
a) Depth 96-110 cm at core 4. b) Depth 95-110 cm at core 6.

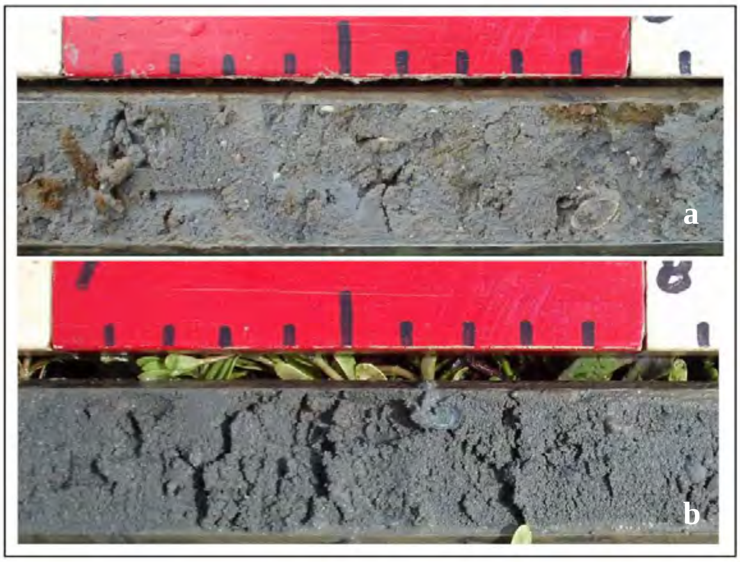


Figure 4.20 a) Silty-sandy clay with yellow mottles at depth 159-171 cm and b) sandy clay without mottles at depth 350-360 cm.

Then, at depth 170-190 cm (Figure 4.20) the sediment compositions are still similar to the depth 150-170 cm, except grain size that increasing from silt to sand. The brown to yellow mottles were presented spreading in the silty clay to sandy clay from depth 150-190 cm.  Finally, from depth 190-380 cm (Figure 4.20), the sediments are compose of sandy clay, shell fragments, shells similar to the upper layer, except the brown to yellow mottles were not present here. Additionally, at depth 190-380 cm, shells and shell fragments were decreased when go down deeper.

From the interpretation based on sedimentary data, the lower part of the swale from depth 190-380 is not exhibited the mottles, thus it indicated the reducing environment in a subaqueous zone such as tidal channel or subtidal area. Then at depth 150-190, the mottles were found which indicted the oxidizing environment such as intertidal zone or tidal flat area. At the upper part of depth 150 -190 cm which the sediment gradual changes from sandy clay to silty clay, this indicated the environment is calming as stagnant water due to the decreasing of grain size. Subsequently, from depth 55-150, the sediment is present as mud which indicated the reducing environment of a subaqueous zone such as back-barrier lagoon. Sand sheets between muddy sediment at depth 55-150 were resulting from overwash process as sand from the outside barrier transported into the back lagoon. During this sedimentation period, sea water level was falling while shoreline was prograded. The lagoon was shallower as sediment continues to deposit. Lastly, from depth 20-50 cm, the mottles were found spreading in the muddy layer again which indicated oxidizing environment as water are shallower. This indicated the recent period that water is usually flooding in this swale during rainy season.

As stated earlier in Chapter I that the possibility of sand sheet deposits generated by tsunami at the GOT side is very low, thus, the unusual sand sheet deposited onshore between layers of peaty mud at PT are resulted of other high energy processes like storm surge. According to the coring data from the 1st and the 2nd transect, fourteen sand sheets were found deposit with a sharp contact between mud from depth 55 to140 cm (Figure 4.21, 4.22, 4.23, 4.24). The sand sheet is characterized as a fine to medium sand with shell fragments. The thickness of sand sheet is ranging from 1-22 cm. Vertical grading in sand sheet is present at some layers as normal grading. Grain size was also shown the decreasing in diameter from seaward to landward. Sorting of sand layer is well sorted to moderately sorted. Shell fragments were found mixing in sand sheet layer which indicated the transportation process. Whereas in muddy layer, shells were well preserved in the living position which was indicated the *in situ* deposition.

The thickest sand sheet is present at layer K which thick 22 cm and shows a continuity of deposition along the 1st transect from core 1 to 12 and core 2 to 6 at transect 2. The thickest part of sand sheet is at the seaward side, and then become thinner in landward side. Sand sheet from layer J, K, L, M, N were found deposited continuous in the cross-swale direction whereas other layers were missed at some cores. Additionally, Roy (1990) found the modern storm deposits from typhoon Gay far away 1 km inland from the shoreline in Prachuap Khiri Khan Province. In contrast, the modern washover deposits along the southern coast of Thailand which induced by strong wind during the NE monsoon season were commonly found limited in 100 m from shoreline as reported by Phantuwongraj et al. (2013). The different in limited distance of washover storm deposit from shoreline between tropical storm or typhoon induced and strong wind during the NE monsoon induced are indicated the different magnitude of storm surge. In other word, storm surge generated by tropical storm or typhoon can penetrated and also transported the eroded sediments inland further than storm surge generated by strong wind during the NE monsoon.

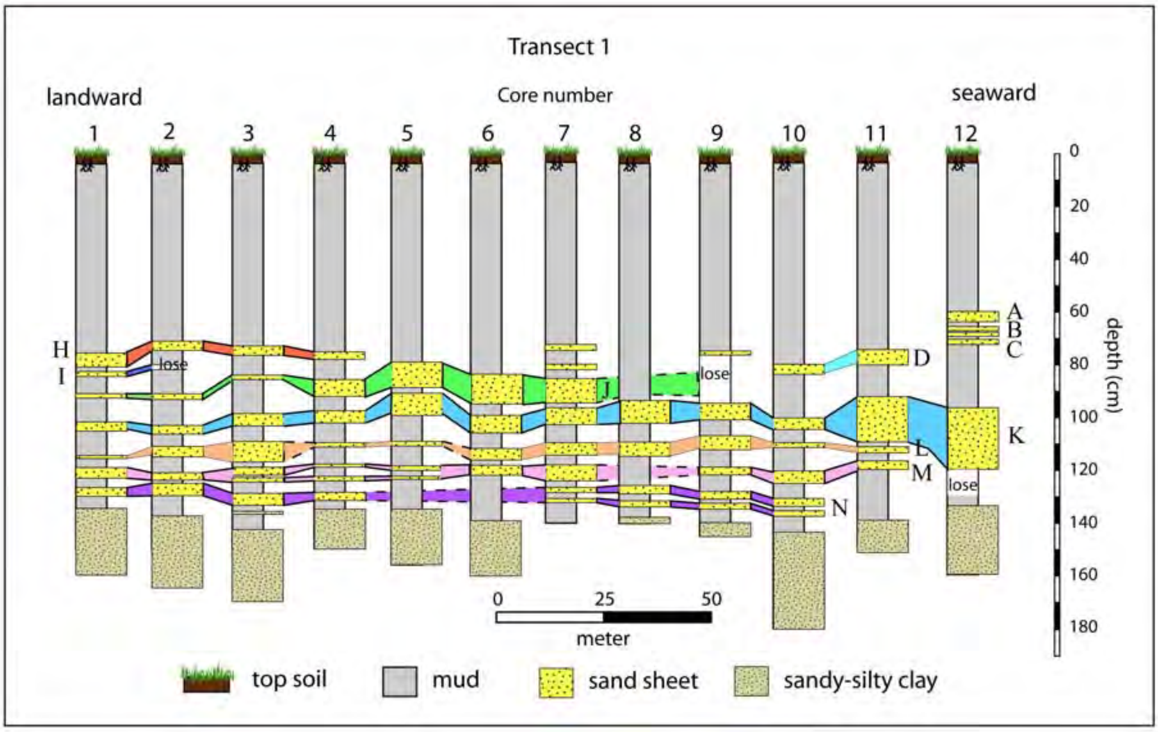


Figure 4.21 Graphic log showing sand sheets from the 1st transect. Transect location is indicated in Figure 4.17.

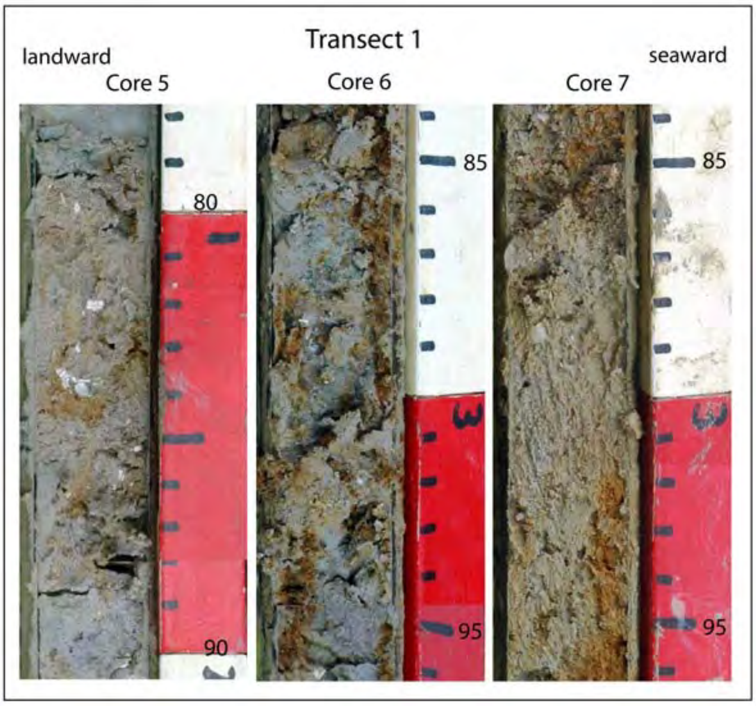


Figure 4.22 Sand sheet layer J at depth 78-95 from core 5, 6, 7 at transect 1.

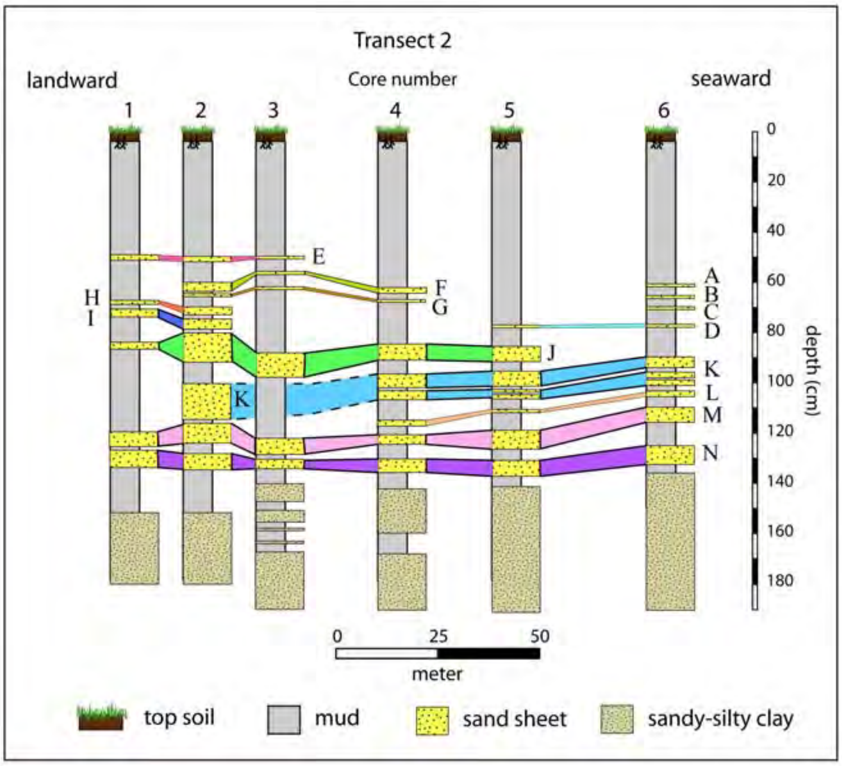


Figure 4.23 Graphic log showing sand sheets from the 2nd transect. Transect location is indicated in Figure 4.17.

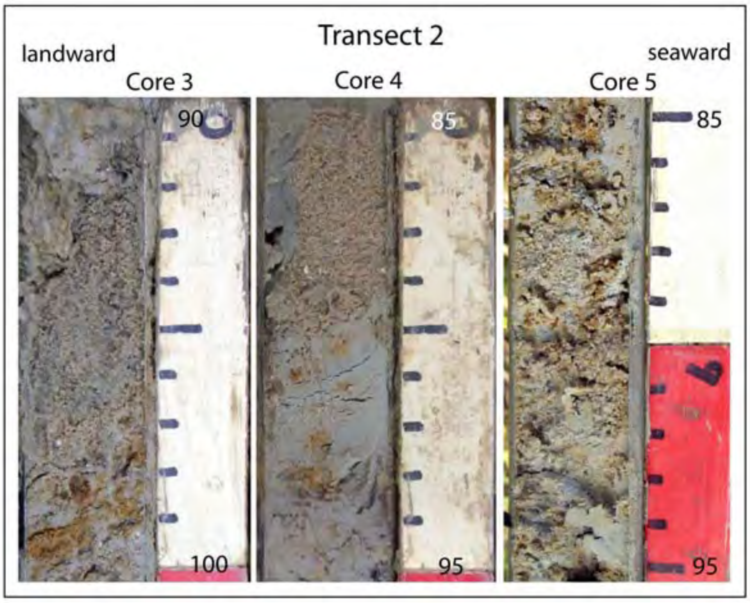


Figure 4.24 Sand sheet layer J at depth 85-100 from core 3, 4, 5 at transect 2.

These sand layers, including J, K, L, M, N, may result from the high intensity storm surge which can bring amount of sand from seaward side to deposit in this swale as a thick sand sheet far about 400 meters inland. In contrast, sand sheet from layer A, B, C, D were so thin and found limited only in the distance of 50 meter from the former beach ridge. The zone of these sand sheet deposited is similar to the modern storm surge washover deposits induced by strong wind during the NE monsoon season as stated by Phantuwongraj et al. (2013). Thus, these A, B, C, D layer could be the resulted of strong wind during the monsoon season.

Additionally, some sand layers such as layer E, F, G, H, I that show discontinuity in lateral deposition may result from the erosional process of the latter overwash events that eroded the previous washover sand.

### 4.3 Washover deposits from Surat Thani

Surat Thani is one of the affected areas from the tropical storms event, according to the report of Grossman (2009), since tropical storm Ruth strike Samui Island, and then, landfall at Surat Thani coast on 30th November in 1970. In 1989, when Typhoon Gay strike Chumphon province, the coast of Chaiya was also affected from strong wave attack at the shore. The eyewitness confirmed that sea water was flowed across the beach and flooding inland about 200-300 m. However, the report of washover deposits from “Ruth” and “Linda” in Surat Thani are never revealed. Recently, storm surge from temporary strong NE wind during the NE monsoon season is often generating the washover deposits along the shoreline especially, in Tha Chana and Chaiya district. The surge high 3-4 m was generated overwash flow that result in washover deposit particularly, in the coastal lowland. Modern washover deposits were found along the Tha Chana and Chaiya coastline at swale behind the beach in different preservation type.

#### 4.3.1 Description of Ban Pak Nam Tha Krachai (TK), Tha Chana area

The study area is situated near the tidal channel Khlong Taling Thao which part of the Khlong Tha Chana delta plain beach ridge as mentioned in Chapter II (Figure 4.25). The average tidal range here measured from the nearest tide gauge at Ko Prap station is 1.09 m and the maximum range during spring tide is 2.07 m. Behind the beach ridge, the recent washover deposits, cover by green grass, were recognized as a washover fan lobe (Figure 4.26). Subsequently, beside the recent washover, the swale wide 20 m with a surface elevation lower than beach ridge about 1 m was exhibited. The naturally sediment in the swale is mud which indicated the calm environment. Normally this swale is completely dry during the summer and winter season; however, in rainy season the swale is usually flooded (Figure 4.26). During the heavy rainfall, the water level in a nearby tidal channel is commonly rising, and then, running out of the channel as overbank flow, and flooded in this swale. In the swale, sand sheet was found deposited with sharp contact between mud. As mentioned before that mud in this swale was indicated the calm environment, thus the possible processes that can bring the sand sheet to deposit in this swale may came from the high energy flow such as storm surge.

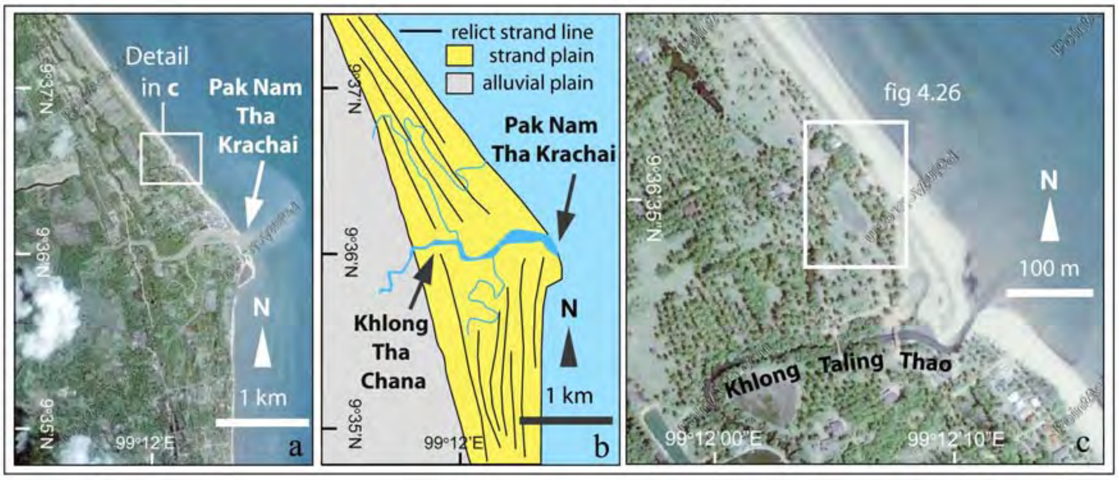


Figure 4.25 a) High resolution satellite image and b) geomorphologic map of Pak Nam Tha Krachai area showing relict strand lines along the Khlong Tha Chana delta plain. c) High resolution satellite image show swale near Khlong Taling Thao tidal channel. Satellite images from PointAsia; acquisition period is not available.

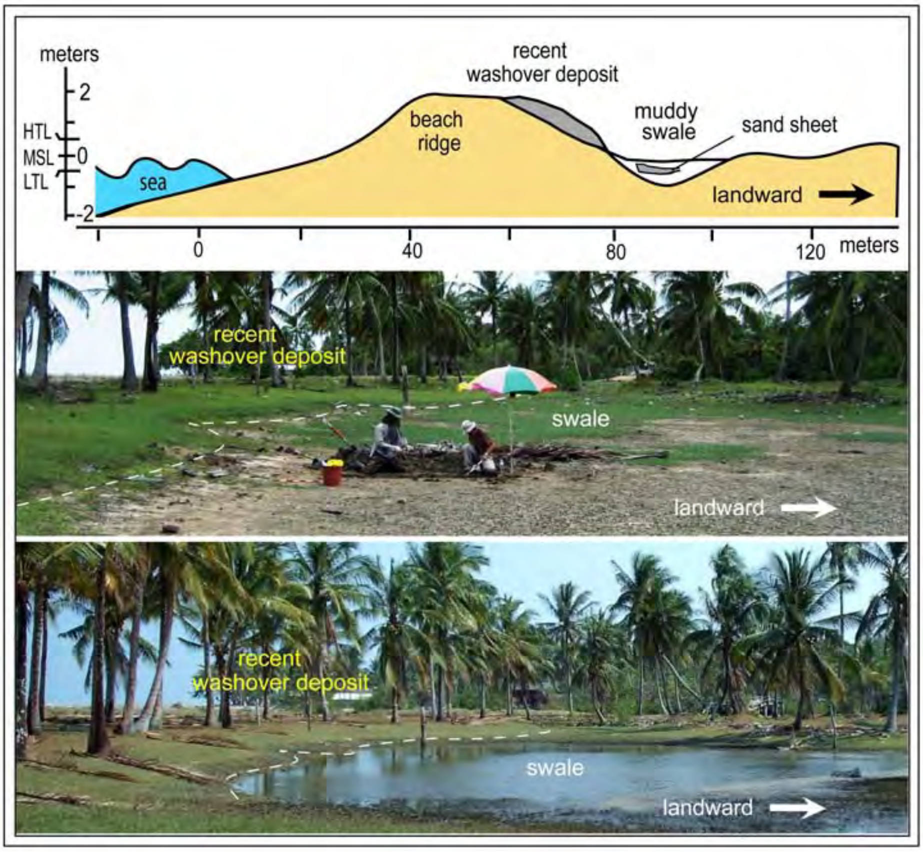


Figure 4.26 Picture showing beach profile and swale behind the recent washover deposit (top) during summer season (middle) and rainy season (bottom). Pictures taken location refer to the white polygon in Figure 4.25c.

**4.3.1.1 Detail sedimentary characteristic from Ban Pak Nam Tha Krachai (TK)**

A trench long 3 m wide 0.6 m was excavated within a swale behind the recent washover deposited which aiming to observe the horizontal continuous of sand layer (Figure 4.27). In the muddy swale, a sand sheet with sharp contact at top and bottom between muddy sediment was observed at a distance of 80 m far from the shoreline (Figure 4.28). The possible processes that can transport sand to deposit here could be occurred by high energy flow such as storm surge during storm or temporary NE strong wind. The geometry of sand sheet was thick 4 cm at the seaward side and slightly thinner to 1 cm at the landward side in the middle of swale (Figure 4.29). The landward thinning is one characteristic of washover deposits induced by storm as reported in Japan and USA (Nanayama et al., 2000 and Tuttle et al., 2004). From surface to depth 20 cm, the sediment is displayed as pure mud with bioturbation and burrows structure. Washover sand sheet was found at depth 20 cm from surface with sharp contact at top and bottom. Beneath the washover sand sheet, the sediment is showed as pure mud again until depth 30 cm, subsequently the sediment was abruptly change from mud to medium sand. Then, the sediment is gradual change from medium sand to coarse-very coarse sand with bioclasts, shell fragments, and corals mixing within the very coarse sand layer.


Figure 4.27 a) and b) Trenching in the swale exhibited sand sheet layer between mud deposited. c) Trench location behind former washover deposit. Pictures taken location refer to the swale in Figure 4.26.

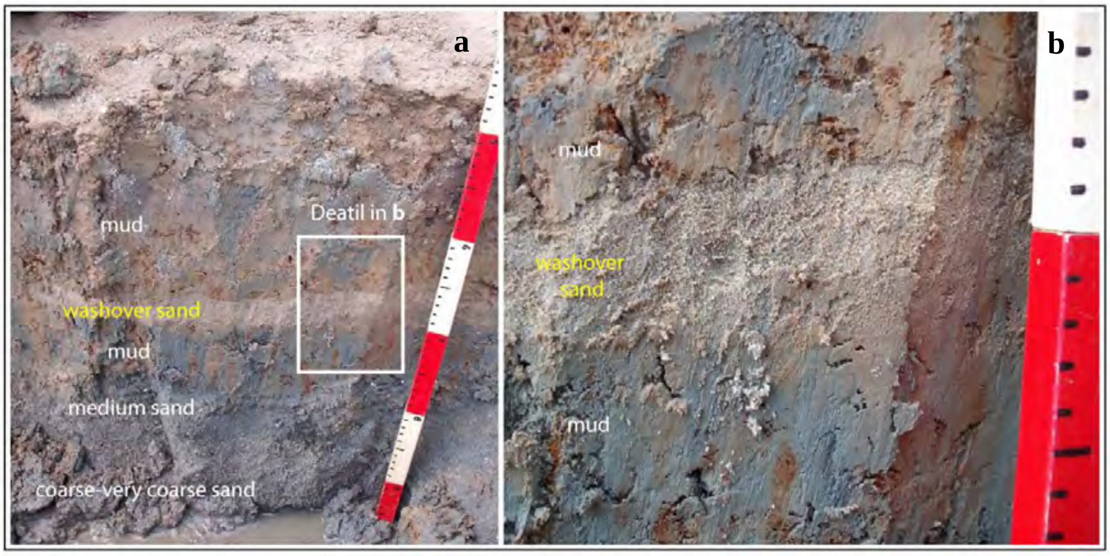


Figure 4.28 Sand sheet deposited between mud with sharp contact at bottom and top in a swale behind beach ridge. Pictures taken location refer to the trench in Figure 4.27.

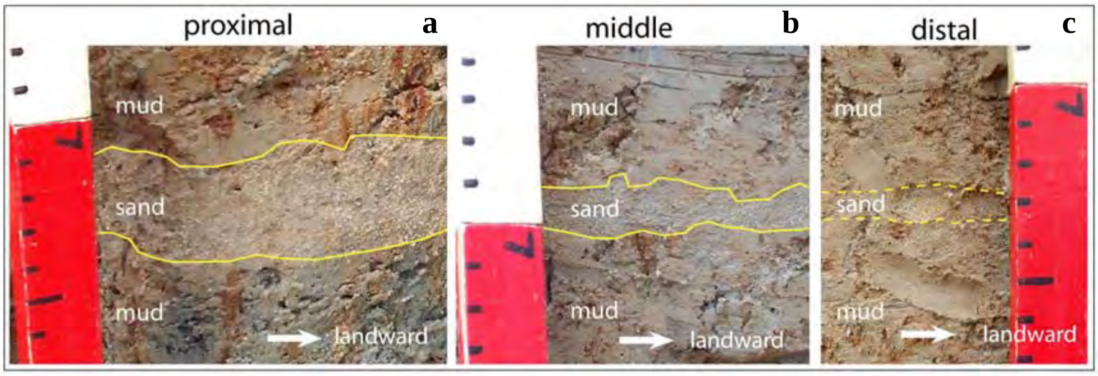


Figure 4.29 Landward thinning of sand sheet in a swale from a) proximal part, b) middle part, and c) distal part. Pictures taken location refer to the trench in Figure 4.27.

From the stratigraphic profile, the bottom part layer that is coarse-very coarse sand, is indicated the shoreface environment. The following medium sand layer indicated beach environment. Lastly, the muddy layer is indicated calm environment as a swale behind beach ridge. According to this stratigraphic data, this area was interpreted as the prograded shoreline (Figure 4.30) which corresponded to the geomorphology characteristics of the area that located within the delta plain.

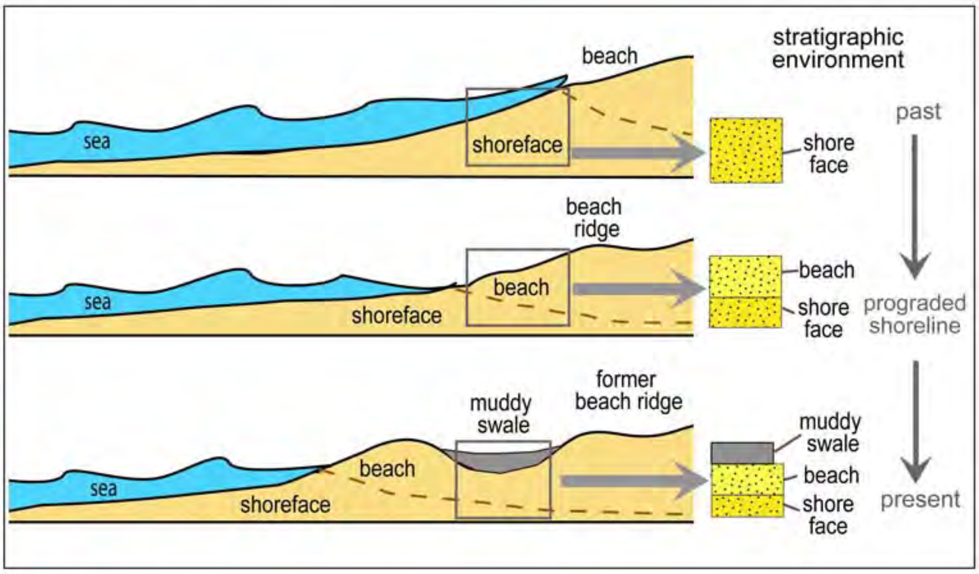


Figure 4.30 Beach evolution model based on stratigraphic data showing prograded shoreline during regressive sea level from past to present at TK area.


Figure 4.31 Sediment sampling locations of washover deposits (TK1, 3, and 4) and beach deposits (TK2). a) TK1 and TK2 were collected from trench. b), c) TK3 was collected from the margin of recent washover deposit. d), e) TK4 was collected near tidal channel behind beach. Pictures taken location a), b), and c) refer to Figure 4.27c and d), e) at the north of white polygon in Figure 4.25a.

To estimate the time of mud deposited in this swale the rate of sediment deposition in calm environment such as lake, that familiar to this site, was applied. Chittrakarn et al (1996) reported the average rate of shallow sediment deposited, 0-45 cm depth from bottom surface, in Songkhla Lake as 5±0.25 mm/year by using Caesium-137 isotope. Dumrongrittamatt (2005) also study the rate of sediment deposit in Songkhla Lake by using Caesium-137 isotope which resulted as 5±2.1 mm/year. Based on this deposition rate of 5 mm/year, the 20 cm thick of mud deposited above sand sheet might have been beginning since 40 years ago. According to the surveying date that carried out on July 2008, this sand sheet may result from storm surge possibly during the year 1968. However, based on the historical record of storm surge event, the most possible storm surge event that can generated sand layer between mud in this swale is form tropical storm Ruth in 1970 because it is the only one storm among others that came closer to Tha Chana area during that time.

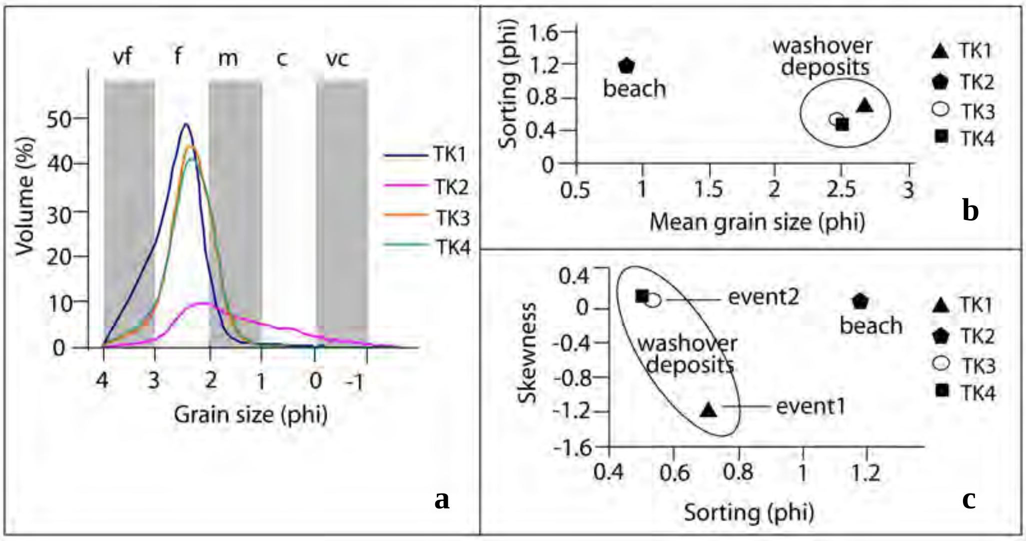


Figure 4.32 a) Graph of grain size distribution of sample TK1-TK4. b) Mean grain size vs Sorting values from sample TK1-4 which show two types of sediment deposits as beach and washover deposits, respectively. c) Sorting vs Skewness values of sample TK1-4 which separated beach deposit out of washover deposit and also differentiated two groups of washover deposits as event1 and event2, respectively.

Washover sand sheet in the swale is presented as homogeneous sand without the sedimentary structure. However, in lateral trend, average grain size was decrease from seaward to landward direction. At TK area, four samples of sediments from washover layer and beach layer were collected for grain size analysis (Figure 4.31). The average grain size of washover sand sheet is 2.66 phi with moderately well sorted (Figure 4.32). Whereas, the recent washover deposited is 2.48 phi with moderately well sorted. Contrastingly, at coarse-very coarse layer, average grain size is 0.88 and sorting is poorly sorted. Additionally, when go up further to the north of TK area, sand sheet thick 9-10 cm was found deposited between soil layers near the tidal channel behind beach ridge (Figure 4.32). The average grain size is 2.46 with moderately well sorted that is similar to the former washover deposited layer at TK. When comparing sorting and skewness data from three washover layers (TK1, TK3, and TK4) by plotting into the graph, it show two group of data including, TK1 and TK3, TK4 (Figure 4.32). Therefore, TK3 and TK4 may result from the same storm surge event due to the similar sorting and skewness values. This washover sand layer might result from the overwash event during the end of year 2005 as interpreted from the thickness of vegetation layer at the washover surface. Based on the 5 cm thickness of vegetation layer, the maximum growth year should not older than 2 years.

The composition of washover deposit (TK1) in swale is composed of pure quartz without any bioclasts. Whereas, at TK2 layer, some shell fragments were found mixing within the sand. All washover samples (TK1, 3, and 4) yield the high sphericity and subrounded for sphericity and roundness characteristics, respectively.

**4.3.2 Description of Ban Takrop (BT), Chaiya area**

At Ban Takrop (BT), Chaiya district, Suratthani province, the area displays as prograded shoreline which is composed of relict strand lines oriented in the northwest-southeast direction (Figure 4.33). 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 (Figure 4.34). The average tidal range here is 1.09 m while the maximum range during spring tide time can be up to 2.07 m.

Field work at BT was carried out 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 (Figure 2.27). 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.

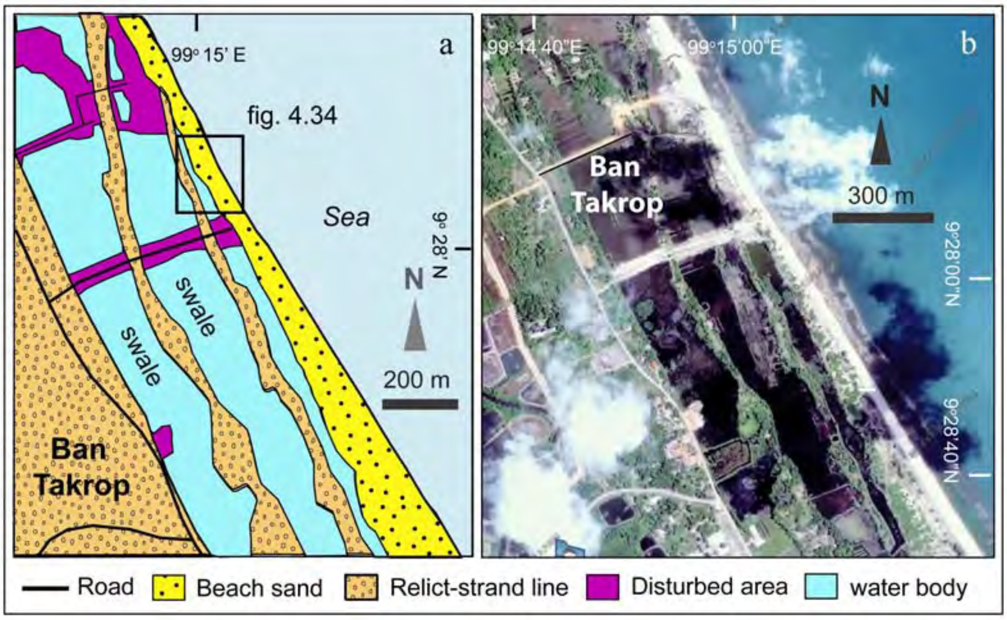


Figure 4.33 a) Geomorphologic map and b) high resolution satellite image showing prograded shoreline and swales in NW-SE trend. Satellite image from PointAsia; acquisition period is not available.

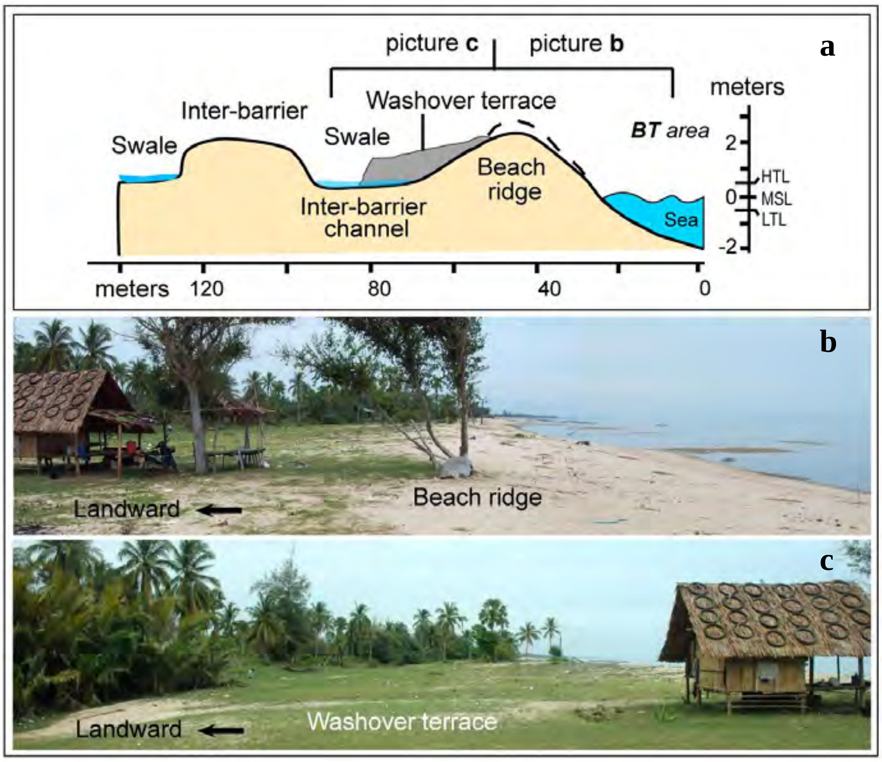


Figure 4.34 a) Cross-shore topography at BT area. b) Photo showing beach ridge and foreshore slope during low-tide time. c) Washover terrace penetrated into a swale. Small cottage at the beach was build after the storm surge event.

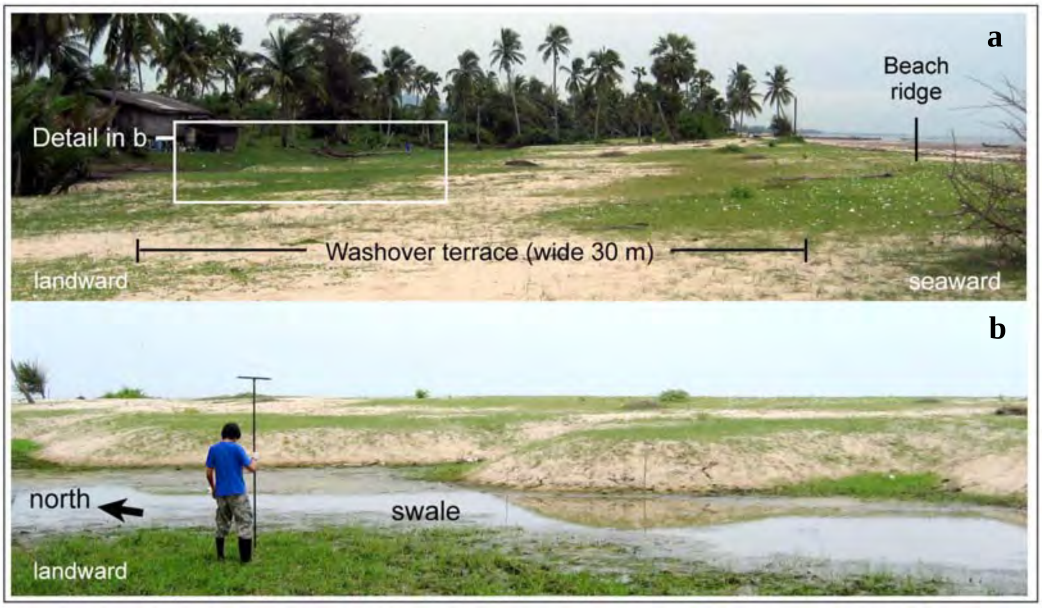


Figure 4.35 a) The washover terrace (wide 30 m cross-shore and long 600 m along-shore) at BT and b) the washover lobes showing the avalanche face at the distal part of the terrace. Pictures were taken on 2 July 2008.

**4.3.2.1 Detail sedimentary characteristic from Ban Takrop (BT)**

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 (Figure 4.35a). 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 (Figure 4.35b). The thickness of the washover sediment reaches a maximum thickest in the proximal part and terminates with a steeply avalanche face into the swale. Some parts of washover sediment also penetrate into the Nipa palm habitat zone, as observed from the sand body the buried a palm tree (Figure 4.36a). 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 (Figure 4.36b). Additionally, at the middle part of washover terrace, the sub-surfaces sediment was change from black mud to medium sand.

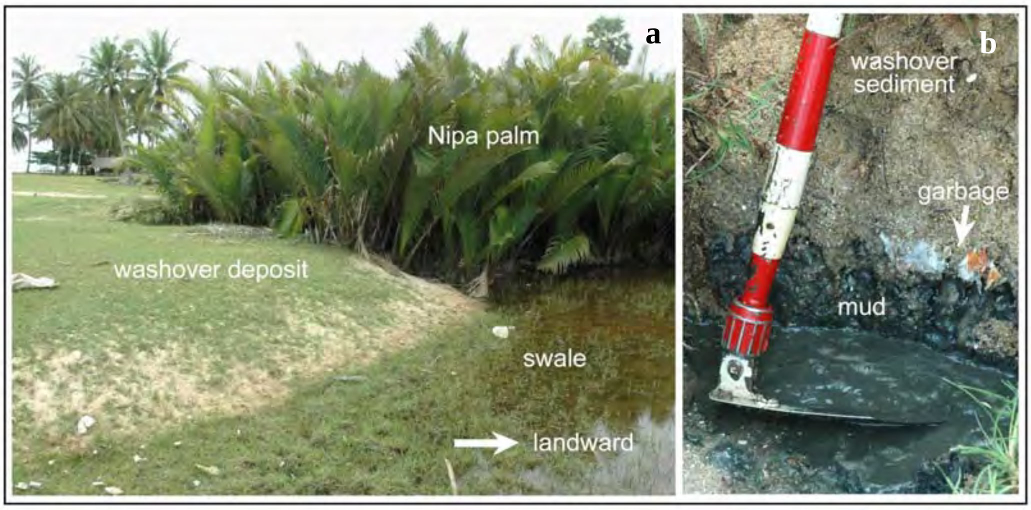


Figure 4.36 a) Washover terrace penetrated into a swale and buried some part of brackish trees. b) Bottom contact of washover terrace showing sharp contact between washover sand and mud in a swale.

To observe the sedimentary structure within the washover terrace, small trench long 4 m perpendicular to the shoreline was made at the distal part of washover deposit (Figure 4.37a and b). Additionally, the extension trench parallel to shoreline was also made to acquire 3D sedimentary structure data (Figure 4.37d). The thickness of the washover sediment was 80 cm at the proximal part and terminated with a steeply avalanche face at the margin (Figure 4.37c).


Figure 4.37 a) and b) Trenching perpendicular to the shoreline at the margin of washover terrace. c) Washover successions at the avalanche face thick 80 cm. d) Trenching in west and south direction for observing 3D sedimentary structure. Pictures taken location refer to Figure 4.35.

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. Each layer showed reverse grading 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 2-7 cm (Figures 4.38). The washover deposit here can be divided into two units based on its difference in lithology, including the thickness and inclination of layers. The thickness of washover sand layers at the lower unit ranges from 2-6 cm and displays a low dip angle being almost horizontal to sub-horizontal bedding. In contrast, the thickness of 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 (Figure 4.38). The foreset bedding was cutting into the 1st unit below which indicated the erosional of bottom unit during the deposition of the 2nd unit.

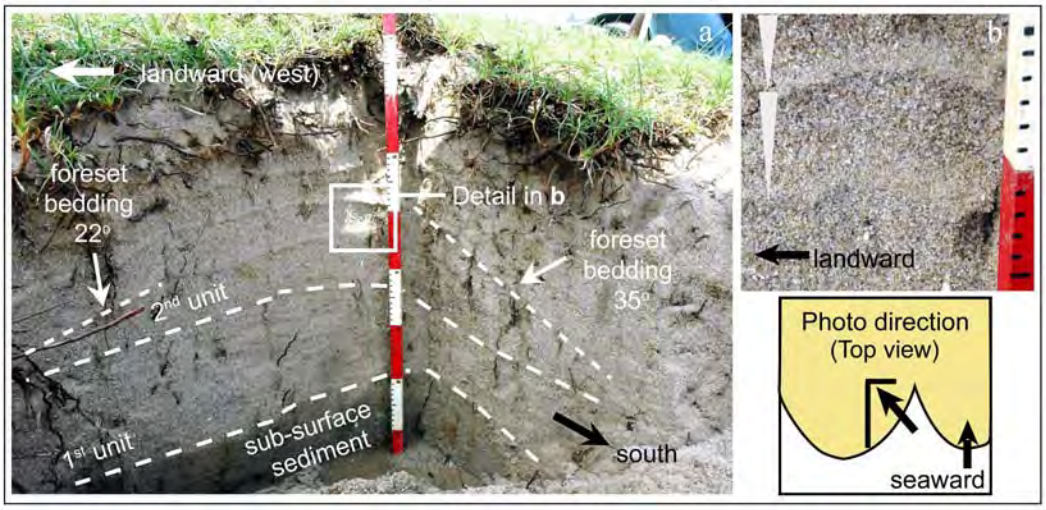


Figure 4.38 a) Two units within the washover deposit and foreset bedding at the distal end of the washover deposits. b) Reverse grading layer in the washover sediment. Pictures taken location refer to Figure 4.37d.

Sediment samples were collected layer by layer from top to bottom. Nineteen samples were collected from washover sediment (layer 10 to 1) and sub-surface sediment (Figure 4.39). 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 (Figure 4.39a). 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 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 (Figures 4.38). 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 included quartz, shell fragments, feldspar and rock fragments. Sand grains were moderately well to moderately sorted, but the sorting of the medium grain sand laminae was better than that of the coarse grain sand layer when compared between layers (Figure 4.39). All of washover deposit layers are showed the high sphericity and subangular-subrounded for sphericity and roundness of grain characteristics, respectively. Whereas, the grain characteristic of pre-surface layer are showed the high sphericity shape and subrounded shape.

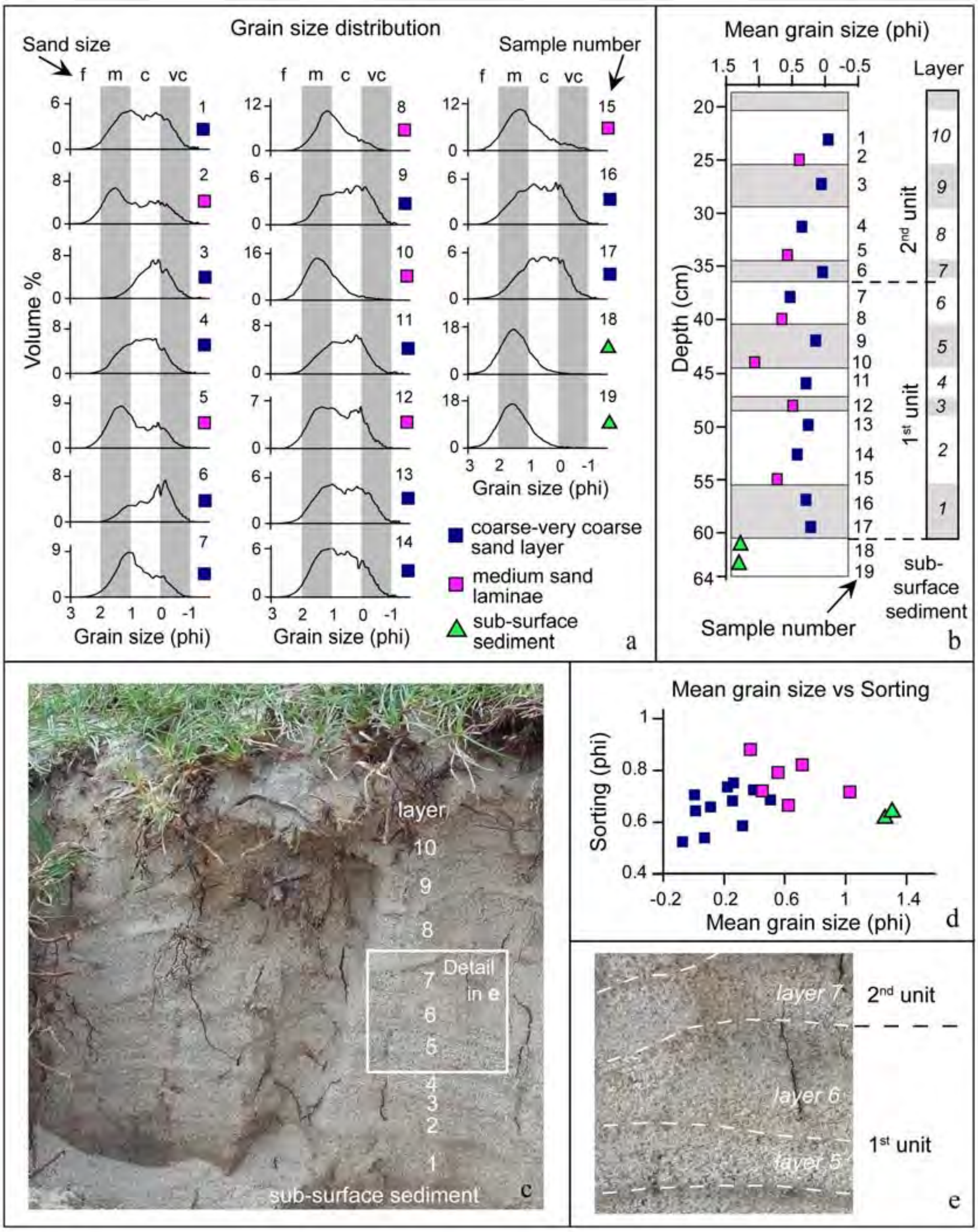


Figure 4.39 a) Grain size distribution graph of washover sediments and pre-storm surface sediments. b) Average grain size change from top to bottom within the washover deposit and pre-storm surface sediment. c) The sampling locations (at scour) in the washover deposit. d) Mean grain size and sorting characteristics of three groups of sediments (coarse-very coarse sand layer, medium sand laminae and sub-surface sediment). e) Contact boundary between the 1st unit and 2nd unit.

## 4.4 Washover deposits from Nakhon Si Thammarat

In 1962, Nakhon Si Thammarat was seriously damage from tropical storm Harriet particularly at Laem Talumphuk sand spit. The storm surge from Harriet had swept the village into the sea and killed at least 670 people who staying at the shoreline and offshore area as described by Grossman (2009). The record of storm deposits from Harriet is still undisclosed. As mentioned in Chapter II that temporary strong NE wind during the NE monsoon season is also generated the storm surge during the November – February which causing in overwash flow in the coastal low land area. Laem Talumphuk is one of the most affected areas of overwash flow from temporary strong NE wind due to the coastal low land topography and morphology of itself as sand spit which penetrate into the sea. Erosion from storm surge attack also causes the damage to the people and village near the shoreline of Laem Talumphuk every year.

Modern washover sediments were easily observed behind the beach and sometime also found penetrating into the shrimp pond too. However, washover deposits in the human activity area such as village, temple, or shrimp pond are usually destroyed after the event, due to the cleaning of the area by the land owner. When go further to the head of Laem Talumphuk sand spit, out of the village and shrimp farm area, the washover sediments from recent storm surge were found along the coastal behind beach. This study is describing the sedimentary characteristics of washover deposits found at the head of Laem Talumphuk sand spit.

### 4.4.1 Description of Laem Talumphuk (LT) area

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 (Figure 4.40). 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. At the distal of sand spit, the series of former beach ridge, high 1 m from ground surface, were exhibited in the west-east trend. Between the former beach ridges, the tidal channel wide 10-20 m was exceeding narrow toward to the south. In general, during the NE monsoon season, washover deposits were commonly found along the coastline of LT which can also observe from the high resolution satellite image (Figure 4.41). Two types of washover sediments (perched fan and washover terraces) were both scattered at the backshore throughout the coastline (Figures 4.42). The detail of sedimentary characteristics of washover deposits from storm and NE monsoon surge in this study were selected from the distal part of sand spit part, namely LT1 site and LT2 site (Figure 4.40).

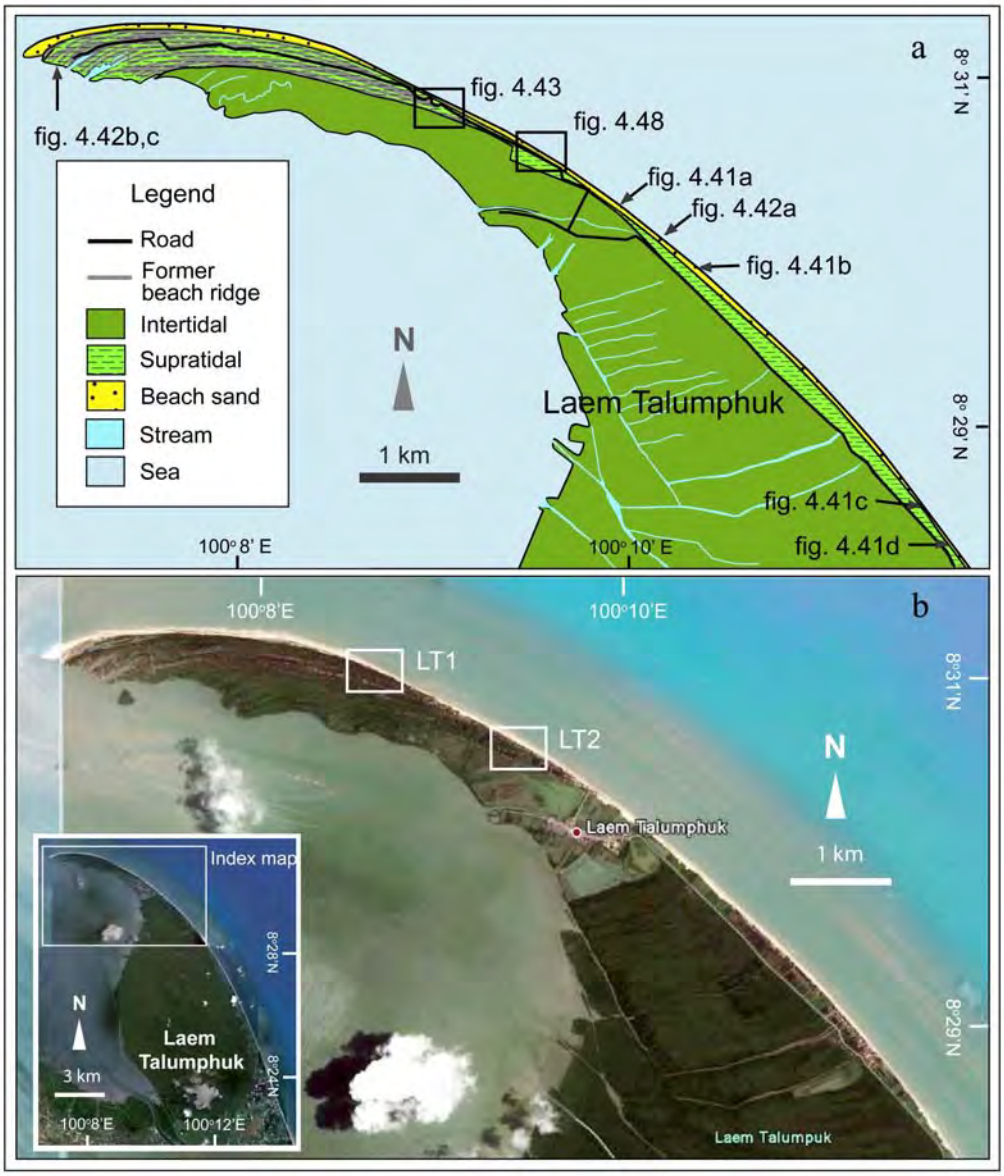


Figure 4.40 a) Geomorphologic map and b) high resolution satellite image showing Laem Talumphuk sand spit which now recurves to the eastward at the distal end. White polygons are indicating study locations. Satellite image from Google Earth; acquisition date: 4 May 2009.

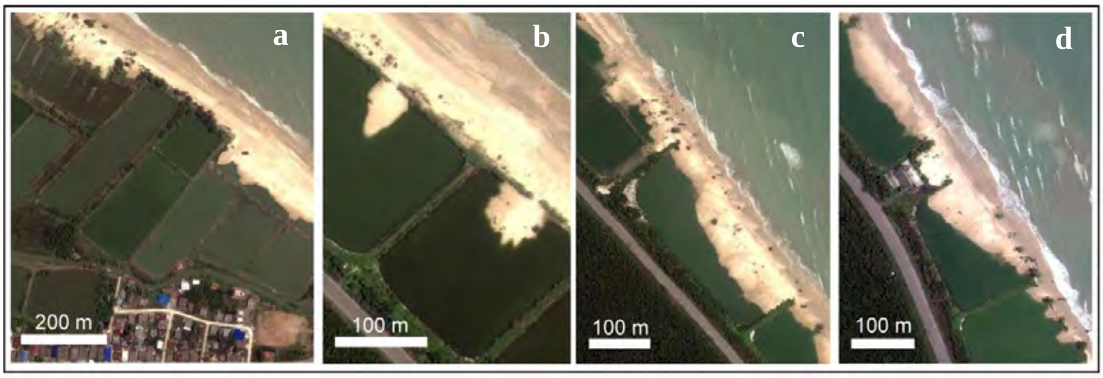


Figure 4.41 Satellite images showing washover deposits, which generated before May 2009, penetrated into the shrimp pond behind beach as washover terrace shape a), c), d) and perched fan shape b), d). Pictures taken locations are indicated in Figure 4.40. Satellite images were from Google Earth; acquisition date: 4 May 2009.

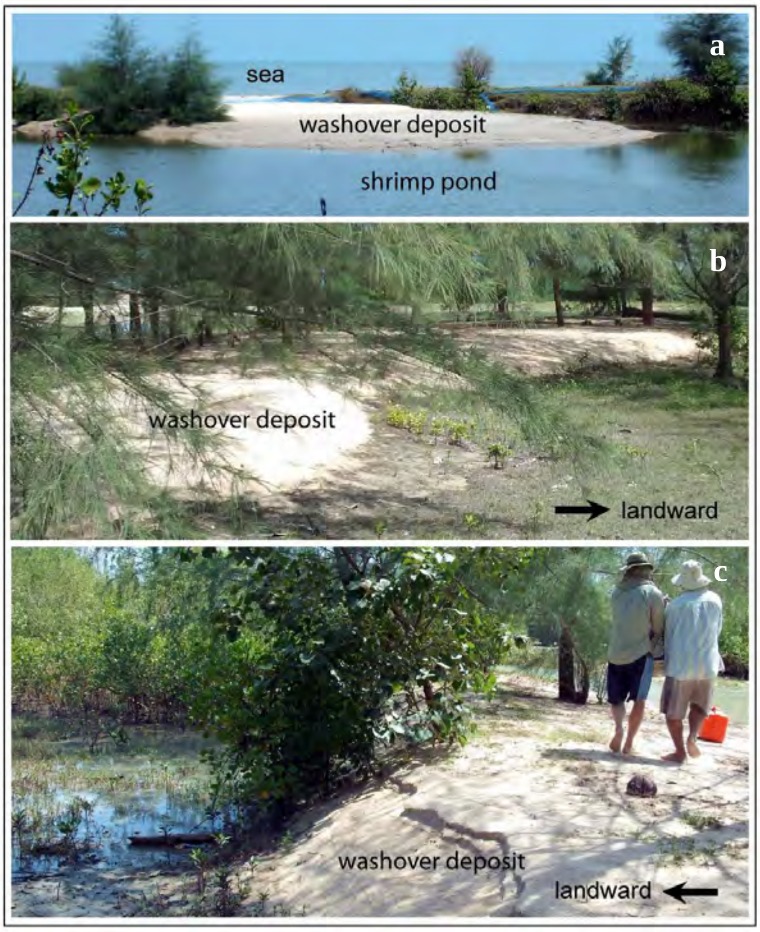


Figure 4.42 a) Washover sediments penetrated into the shrimp pond as perched fan shape. b) Washover deposit on the intertidal area behind beach. c) Washover sediment penetrated into the mangrove area at the head of LT sand spit (north of study site). Pictures taken locations are indicated in Figure 4.40.

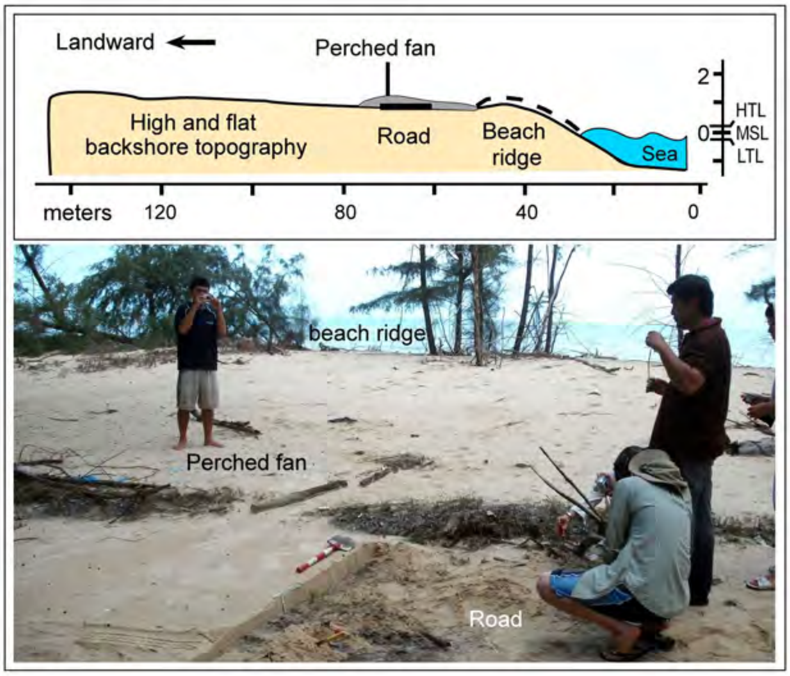


Figure 4.43 Cross-shore topography model show a flat topography behind the backshore (top). Washover deposit behind beach as a perched fan shape (bottom). Picture taken location is indicated in Figure 4.40.

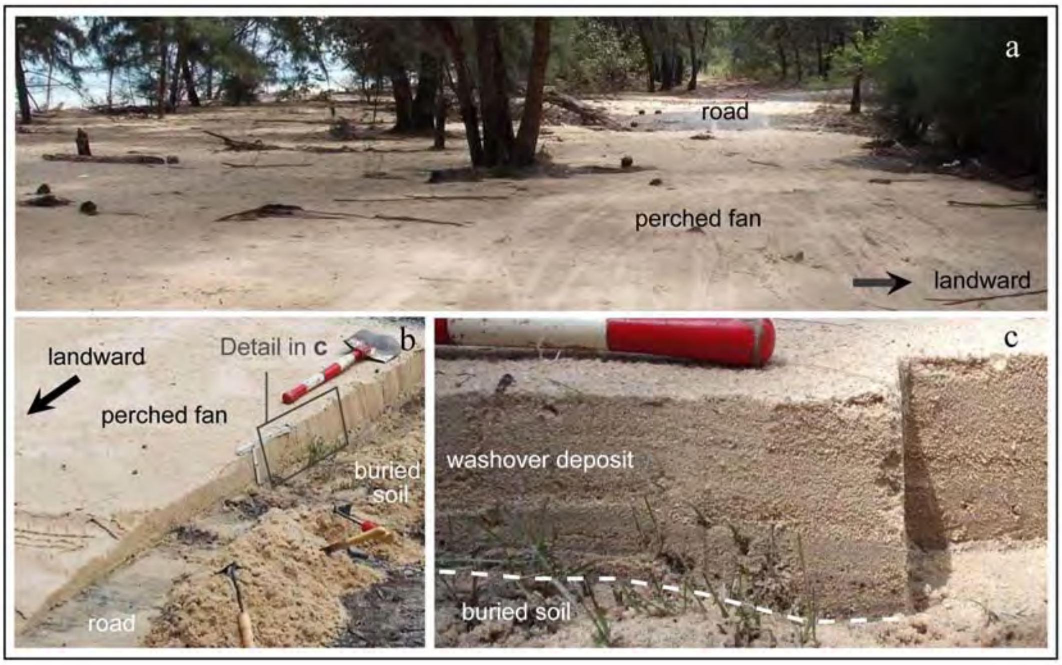


Figure 4.44 a) Washover deposit on the road as a perched fan shape. b) Washover deposit showing landward thinning at the distal part (trenching perpendicular to the shoreline). c) Three layers of washover deposit with a normal grading in the vertical direction. Pictures taken location is refer to Figure 4.43.

**4.4.2 Detail sedimentary characteristic from Laem Talumphuk (LT1)**

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. Site investigation was performed 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 (Figure 4.42, 4.43, 4.44). In mangrove area, the washover sediment 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).

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 (Figure 4.43). Small trench was made where the washover deposit was found on the road behind the beach in order to describe the physical characteristics and sedimentary structures (Figure 4.44). 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 (Figure 4.44c). 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 (Figure 4.44b, 4.45).

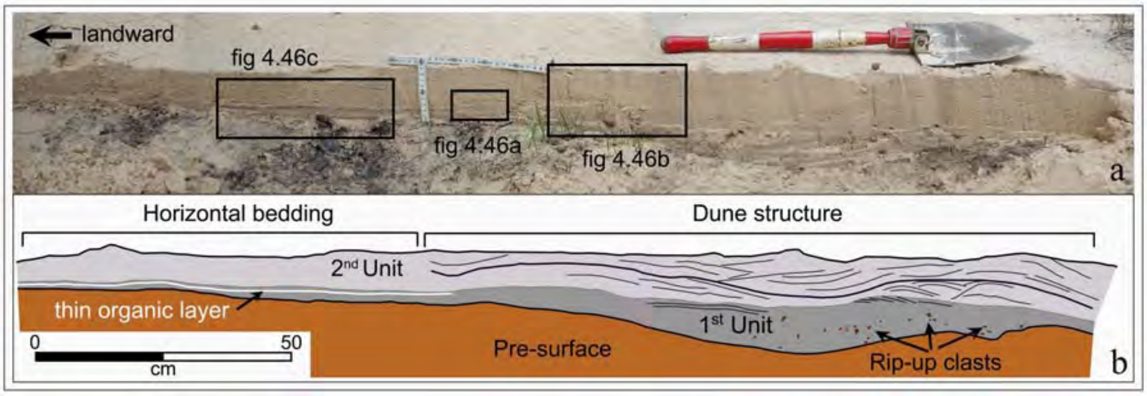


Figure 4.45 a) The internal sedimentary structure of the washover deposit at LT1. b) A detail sedimentary structure in the washover deposits revealing two sediment units and a dune structure. Pictures taken location is refer to Figure 4.44b.

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 (Figure 4.44b, 4.45). 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 (Phatuwongraj et al., 2013). 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 (Figure 4.46c). 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 (Figure 4.45). 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.

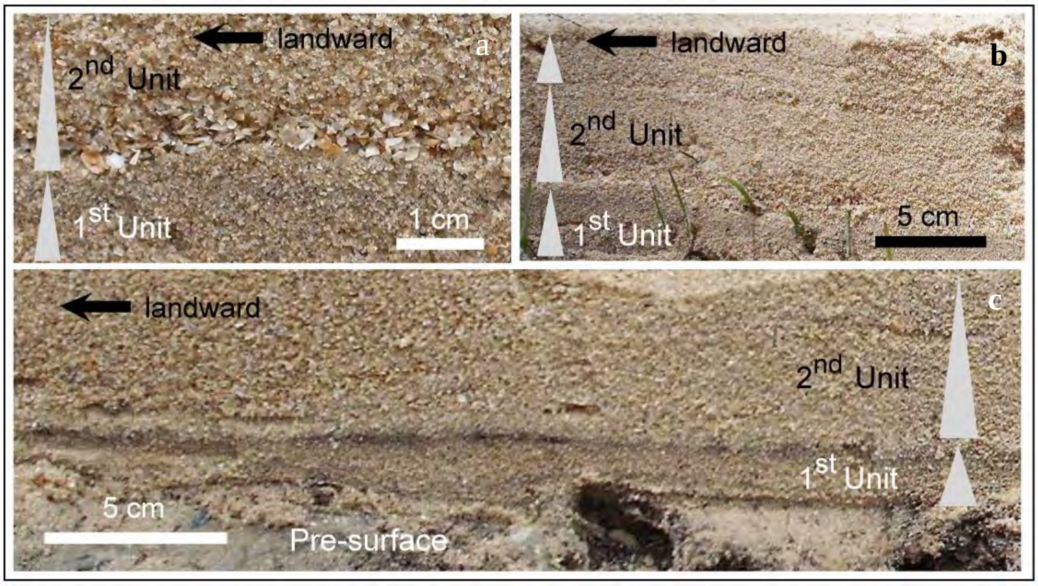


Figure 4.46 a) Shells laminae at the base of the 2nd unit. b) Normal grading in the washover sediment within the 1st and 2nd units. c) The thin organic layer found at the distal part of the washover sediment in the 1st unit. Pictures taken location is indicated in Figure 4.45.

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 (Figures 4.46a and b). Normal grading, from very coarse to coarse-grained sand at the bottom to medium grained sand at the top, was revealed in both layers (Figure 4.44c, 4.46b). 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 (Figure 4.45). 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 (Figure 4.46b). Sorting of sediment in the first unit was also better than the second unit. The 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.

### 4.4.3 Detail sedimentary characteristic from Laem Talumphuk (LT2)

Here, washover sediment was found deposit at the backshore on the road and continue to the swale (Figure 4.47a). The washover deposit is far 41 m from the present shoreline. However, some part of washover sediment that deposit on the road was already removed. Fortunately, sedimentary structure within the washover deposit can be observed at the backshore side, on a road-cut profile (Figure 4.48).

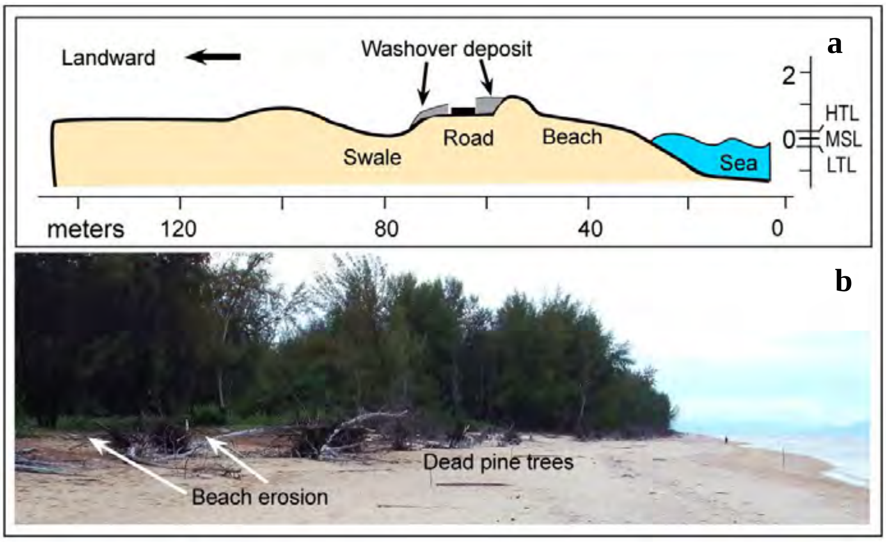


Figure 4.47 a) Cross-shore profile at TL2 showing the remaining of washover deposit at the rim of the road. b) Photo show beach erosion and dead pine tree from strong wave attack. Picture taken location is indicated in Figure 4.40.


Figure 4.48 a) and c) Road cut profile of washover deposit along the road behind beach. b) The remaining washover sediment penetrated into a swale. Picture taken location is indicated in Figure 4.40.

The washover sediment is long about 15 m perpendicular to the shoreline and wide 20 m parallel to the shore. Additionally, at the seaward side of washover deposit, a feature of beach erosion was found continuous along the shoreline (Figure 4.47b). At the swale behind the road, the bottom contact of washover sand and muddy sediment in swale is very sharp.

To observe the inner sedimentary structure of washover deposit, the wall surface of washover profile was cleaning. From top surface to depth 20cm, the 1$^{st}$ sand layer is characterized as fine sand with shell fragments (Figure 4.49). Subsequently, the sediment change abruptly to organic soil layer and gradual transform to fine sand again that is the 2$^{nd}$ sand layer. Beneath the fine sand layer, the organic soil layer was present again then gradual change to fine sand. This sand layer (the 3$^{rd}$) is thick 60 cm and composes of several medium sand laminaes (Figure 4.49).

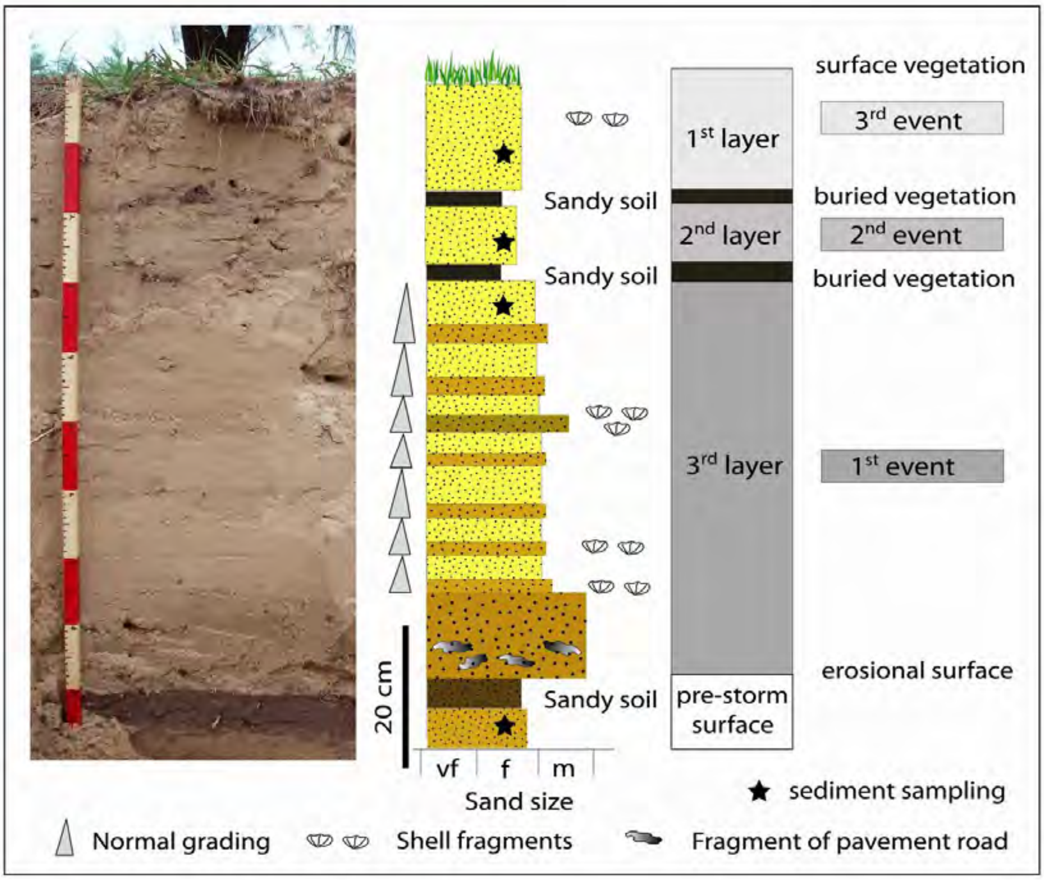


Figure 4.49 Washover deposit profile (left), stratigraphic column (center), and the interpretation of its deposition timeline (right). Picture taken location is referring to washover deposit in Figure 4.48a.

Shell fragments were found concentrated within these medium sand laminae. The 3rd sand layer show dipping in landward direction with an angle of 9 degree as recognized from the inclination of sand laminae (Figure 4.50). At least 7 fining upward sequences of medium to fine sand were observed clearly. At the bottom part of the 3rd sand layer, fragments of pavement road from pre-storm surface layer were found mixing as rip-up clasts within the medium to coarse sand. Bottom contact of the 3rd sand layer is very sharp and show erosional surface of the burial pre-storm surface sand. Two organic layers at top and bottom of the 2nd washover sand layer is a good key indicator that can use to separate the boundary of different overwash events (Figure 4.50). In other word, this site is located at the far-backshore zone that did not affected from a normal high tide, thus in normal condition these organic soil layers were generally develop at the surface as seen from its recent surface (Figure 4.49).

Therefore, when the next overwash occurs, this vegetation layer so then is buried by washover sand deposit. Subsequently, after the overwash event, the vegetation will normally develop again at the surface of washover deposits.


Figure 4.50 Organic sandy soil layer within the washover sediments along the road-cut profile (top). Inclination of washover layer show dipping in landward direction (botoom). Picture taken location is referring to washover deposit in Figure 4.48a.

According to the thickness of each washover layers, the 3rd washover layer was yield the thickest sediment about 60 cm. The bottom part of the 3rd layer also displayed the sharp contact and erosion surface to the pre-storm surface. These two evidences were indicated the high intensity of overwash that possible resulted from the high magnitude of storm surge. Additionally, from the historical record of storm surge events nearby to this site, the storm surge from the tropical storm Harriet in 1962 is the most powerful storm event that generates the high magnitude storm surge which destroyed the village and road at LT. Therefore, the 60 cm thick of washover sediment at layer 3 may possible resulted of storm surge from Harriet 1962.

In contrast, the thickness of the 1st and 2nd layer was thick at 20 and 10 cm, respectively. This sedimentary characteristic as a thin layer is indicated the lower magnitude of storm surge which commonly generated by strong wind during NE monsoon season as stated by Phantuwongraj et al. (2013). Based on the thickness of vegetation layer at the upper surface of washover deposit, the age of vegetation may not older than one year. Thus, the 1st layer may possible resulted from the overwash event during the end of year 2007 which occurred before the survey date about one year. Subsequently, the 2nd layer also displayed the thin layer of buried vegetation at the upper part similar to the 1st layer. According to the thickness of buried vegetation that is similar to the recent washover surface, the age of vegetation is so implied as one year. Therefore, the overwash event that generated the 2nd washover layer may possible occurs during the end of year 2006.

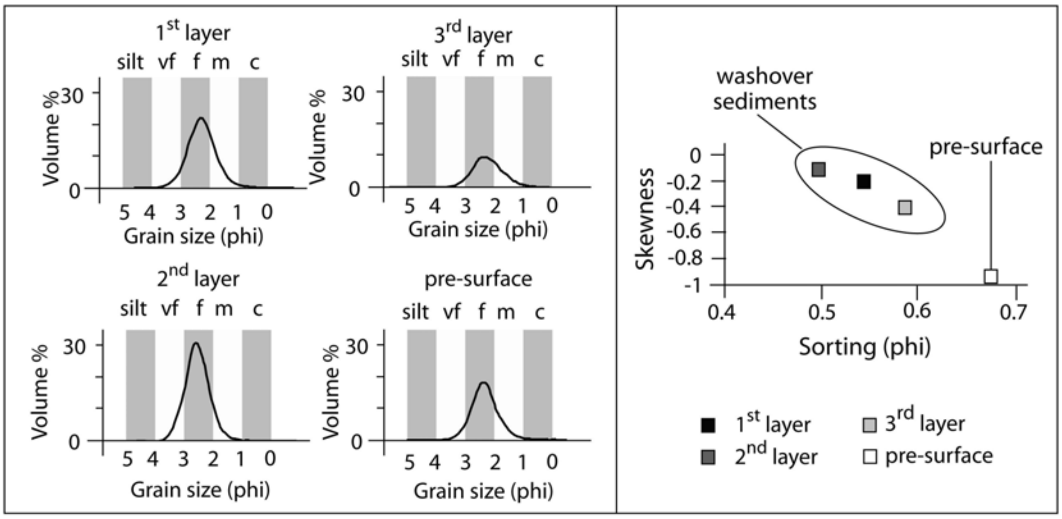


Figure 4.51 Graph of grain size distribution from four sediment samples (left). Sorting and Skewness values of washover sediments and pre-surface sand (right).

At this site, sediment samples were collected from the three washover sediment layers and pre-surface sand layer (Figure 4.49). From the grain size analysis data, all of samples are show the fine grain sand size. Mean grain size value of the 1st sand layer is 2.13 phi, the 2nd sand layer is 2.43 phi, the 3rd sand layer is 2.03 phi, and the pre-surface layer is 2.15 phi. Grain size distribution of washover sediments are show unimodal distribution as well as pre-surface sand layer (Figure 4.51). Sorting of washover sediments are show well sorted to moderately well sorted value, whereas the pre-surface layer show moderately well sorted value. Skewness values of washover sand layer are ranging from -0.12 to -0.40, whereas at pre-surface layer skewness value is -0.94 (Figure 4.51).

**4.5 Mollusca and foraminifera in washover sediments**

In the washover deposits, shell fragments were common found mixing within the washover sediments which usually exhibited as a lamination or shell lag as found at LT area or mixing within the layer as found at MR, PT, and BT area. These shell fragments can use for indicating the source zone of washover sediments and the depth of storm wave base. Shells and foraminifera are a good key indicator to identified sand sheet of storm deposit in a geological record (Hippensteel and Martin, 1999). If shells that living in the shoreface zone were found deposit within the sand sheet between mud in the lagoon or swamp, it can indicated the unusual processes such as storm surge that can bring the shells to “deposit out of its place”. Unfortunately, from these shell fragments, we can indicates just only the type of them such as freshwater shell, brackish shell, and sea shell because it hardly to classify the genus or species as it bodies are already broken. However, at BT area, small shells that are not broken were found mixing within the washover sediments. These shells can use to indicating the source zone of washover sediments and the depth of storm wave base as stated by Sedgwick and Davis (2003).

At BT area in Surat Thani, mollusca and benthic foraminifera were found mixing within the coarse-very coarse sand layer. Mollusca which found in the washover sediments are including bivalve, gastropod, and scaphopods (Figure 4.52). Only one type of foraminifera which found in the washover sediment is *Elphidium crispum* (Linnaeus, 1767) (Figure 4.52). Mollusca and foraminifera which found in the washover sediments are living at the shallow water zone in transition environment from mangrove to shoreface zone. Mollusca and foraminifera which found more frequently in this study are including, gastropod; *Cerithidea cingulata* (Gmelin, 1791), bivalve; *Vepricardium* - Iredale, 1929 and *Nuculana (Thestyleda) soyoae*, and foraminifera; *Elphidium crispum* (Linnaeus, 1767).

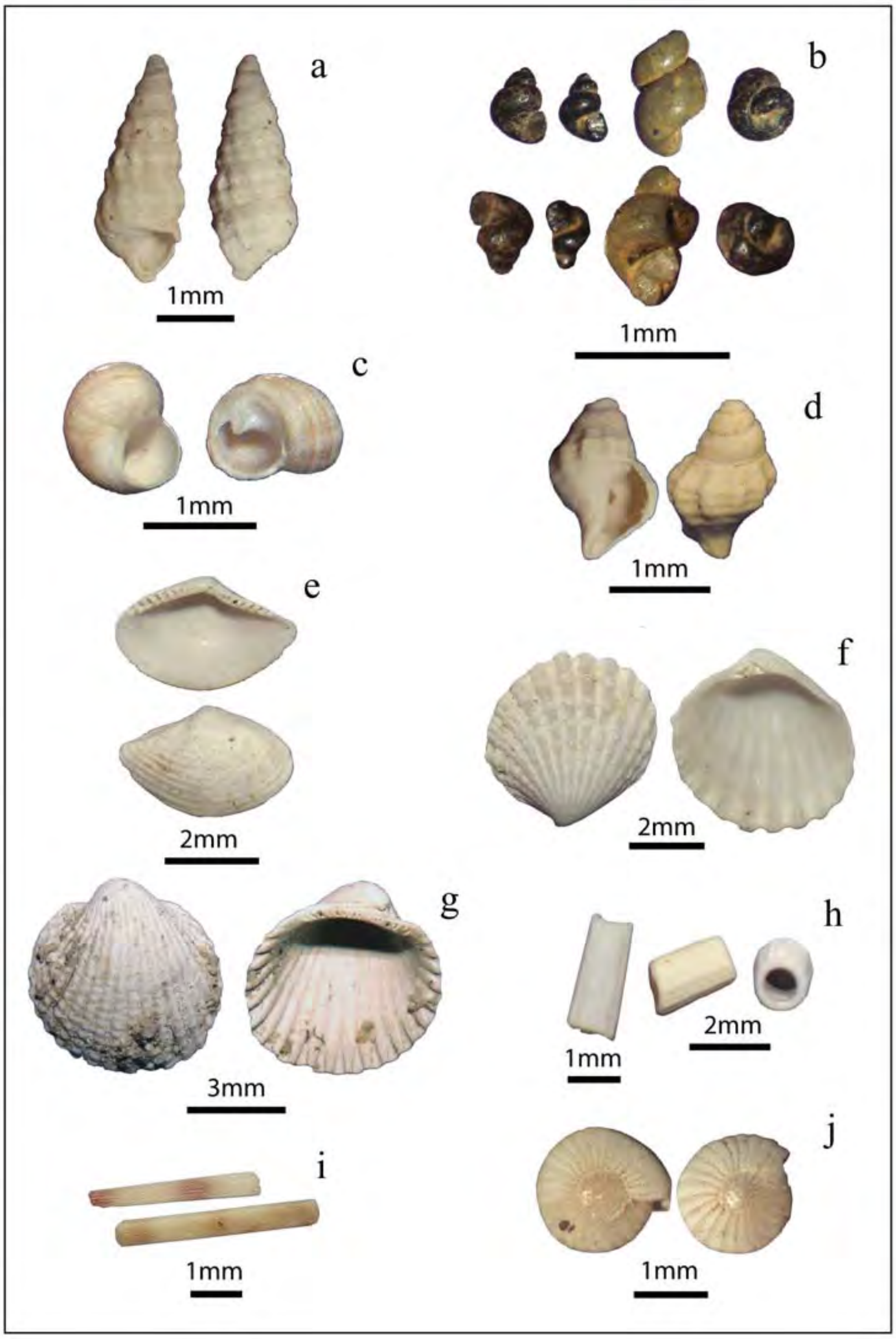


Figure 4.52 The majority mollusca and foraminifera founded in washover sediments from Ban Takrop (BT), Surat Thani. a) *Cerithidea cingulata* (Gmelin, 1791). b) *Siliquaria* (J.G. Bruguière, 1789). c) *Natica* (Scopoli, 1777). d) *Pseudoneptunea varicosa* (Gmelin, 1791). e) *Nuculana (Thestyleda) soyoae*. f) *Vepricardium* (Iredale, 1929). g) *Anadara* (Gray, 1847). h) *Antalis dentalis* (Linnaeus, 1758). i) *Antalis vulgaris* (da Costa, 1778). j) *Elphidium crispum* (Linnaeus, 1767).

# CHAPTER V

# DISCUSSIONS

In this study, three types of washover deposits (washover terrace, perched fan and sheetwash lineations) from different geomorphic settings area in four provinces were found deposited at a maximum distance of 100 m and 400 m from the shoreline, in case of modern washover sediments and ancient washover sediments, respectively. A washover terrace with thick bedded sand, thickness ranging from 60-80 cm, was found at Ban Takrop (BT), and Laem Talumphuk2 (LT2) whereas perched fans with a thickness ranging 15-50 cm were found at Khao Mai Ruak (MR), Ban Pak Nam Tha Krachai (TK), and Laem Talumphuk1 (LT1). Lastly, sheetwash and sheetwash lineations were found at Phanang Tak bay (PT) and Khao Mai Ruak (MR), respectively.

For the recent washover deposits, the sedimentary characteristics were recognized as the distinctive successions that corresponded to the topography and were classified into two types as (i) a thick-bedded sand, thickness ranging from 50-80 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 chapter, the controlling factors of washover preservation type, flow condition and sedimentary characteristics were discussed from each location. Washover deposits from BT, LT1, and MR sites were selected for the discussion as a representative of washover deposits in this study, due to their well preserved morphology and sedimentary characteristics.

## 5.1 Preservation type and flow condition of washover deposits

In this study, 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 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 (Figure 5.1a). 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 LT1 and MR, the beach morphology and backshore topography are different. The beach configuration at LT1 is moderately uniform and the backshore topography is densely covered by pine trees (Figures 5.1b and 4.44a). 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 LT1.

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 (Figures 5.1c and 4.2). 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 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).

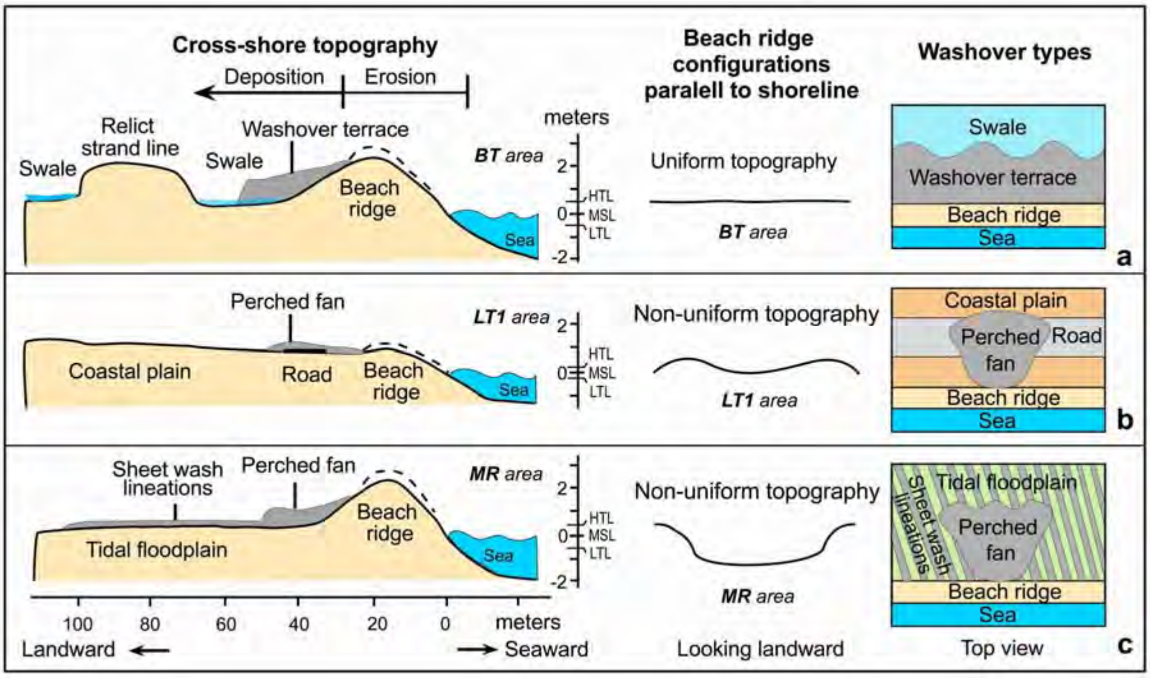


Figure 5.1 Cross-shore topography and beach ridge configuration from three areas that control the preservation type and sedimentary characteristics of washover deposits. a) A large swale behind the beach and uniform beach ridge configuration result in a washover terrace deposit at BT. b) A flat and high coastal plain topography behind beach with a non-uniform beach ridge configuration results in perched fan deposits at LT1. 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

To confirm the relationship between topographic factors and the pattern of washover deposits, the site investigation at BT and MR areas was performed 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 (Figure 5.2a and b). At MR, the new washover deposit, resulting from December 2011 storm, also observed as a perched fan shape which was similar to the March 2011 washover deposit (Figure 5.2c and 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 the new sediment was deposited as a perched fan on top of the sheetwash lineations. This observation suggested that the magnitude of storm surge is also important. The sheetwash lineations from the December 2010 storm surge indicated the high magnitude of 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.

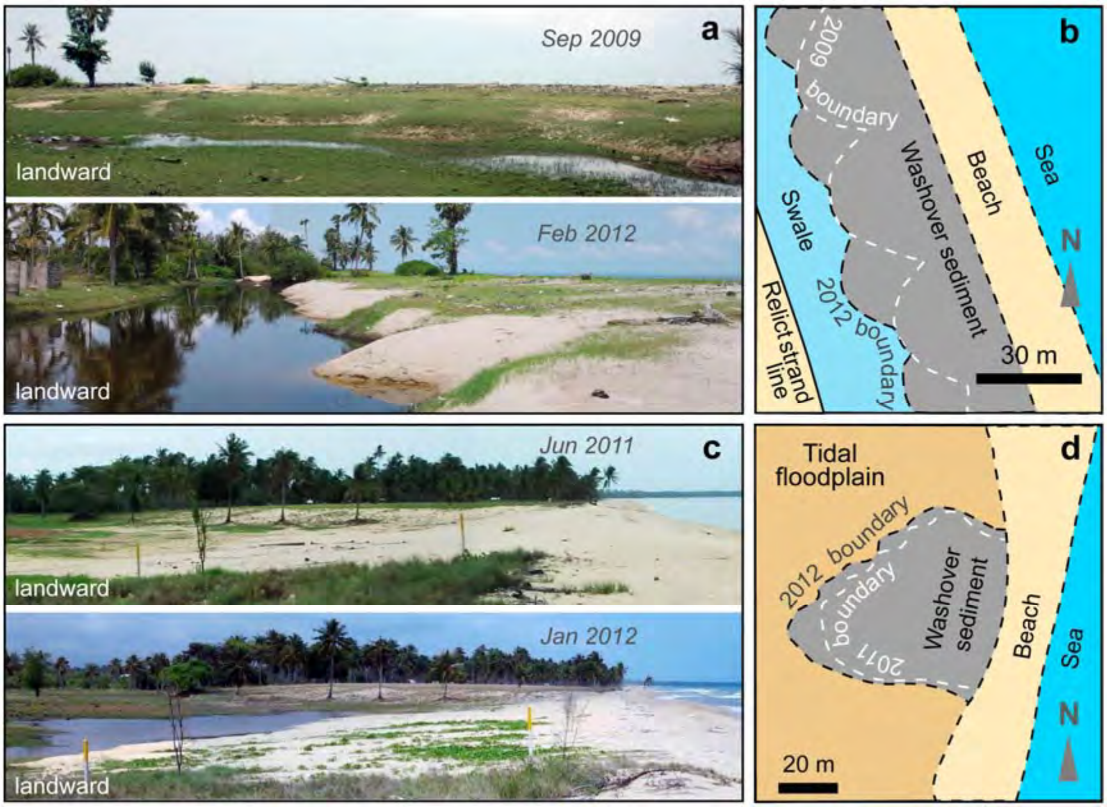


Figure 5.2 Series of photographs taken from 2009 to 2012 and sketch maps showing similar pattern and shape of washover deposits in the same topographic area resulting from two different NE monsoon surge events. a) Washover deposit as a terrace at BT resulting from the 2007, 2008 and 2011 NE monsoon surge. 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.

### 5.2 Sedimentary characteristics of washover deposits

The lateral discontinuity in the deposition of sheetwash lineation is one significant characteristic making it difficult for these features to be preserved. Thus, in this section, the discussion 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 washover sediment layers was described in Figure 5.3.

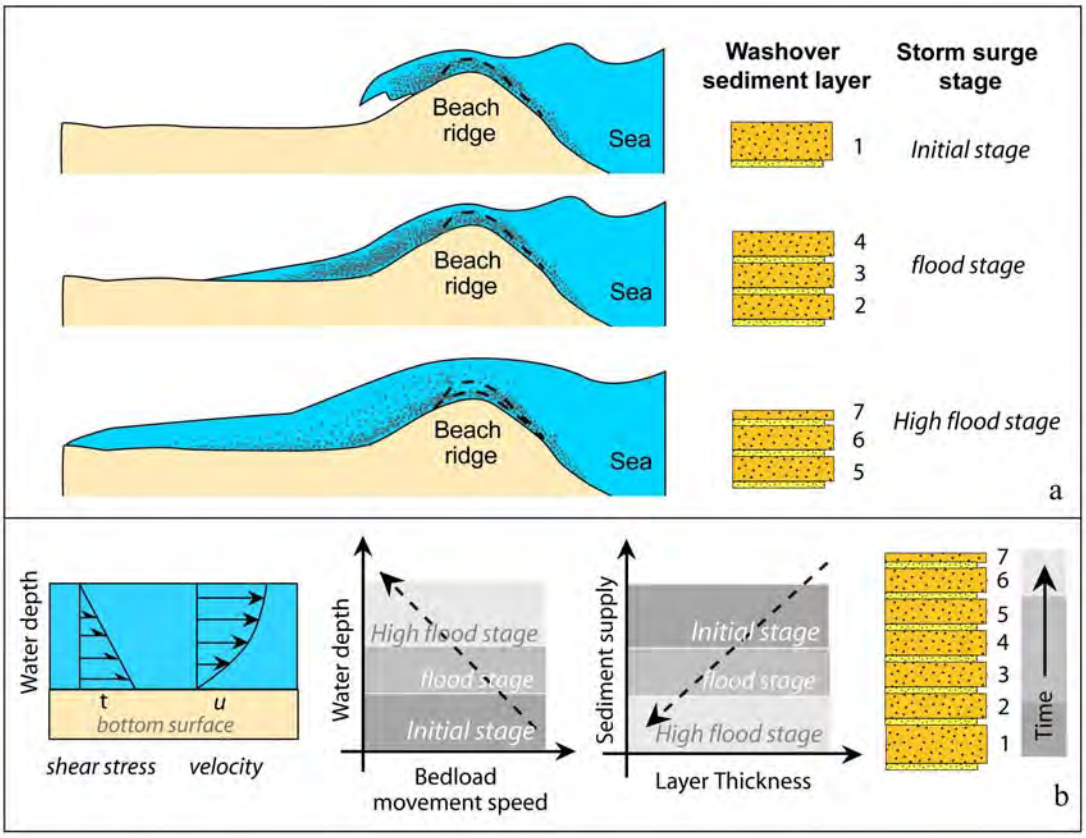


Figure 5.3 Schematic diagrams showing the formation of washover sediment layer. a) Three stage of storm surge on cross-shore topography in relationship with the washover sediment layers. b) The relationship of the formation of washover layer with water depth, shear stress, bottom velocity, and sediment supply.

The multiple layers of normal or reverse grading in washover sediments were the result of the pulsation from overwash flow as stated by Phantuwongraj et al. (2013). Here in this study, the three stage of storm surge, including (i) initial stage, (ii) flood stage, and (iii) high flood stage, is proposed as the important factor that controls the sedimentary characteristic of washover layer. The first stage is occurred when the first overwash was generated, with amount of eroded sediment from shoreface and beach in the flow, during the shallow flow depth. The washover sediment at this stage is exhibited as the thickest layer due to the high sediment supply and shallow water depth condition (Figure 5.3a). Then the flood stage occurred when the water depth is increasing. In this stage, the erosion continues focusing at the shoreface and beach zone whereas the backshore zone begins to flood as the storm surges level is increasing (Figure 5.3a). The multiple layers are formed as a result of pulsation wave. However the thickness is decreased due to the decreasing of sediment supply from erosional zone (shoreface to beach). Then, the high flood stage occur when the storm surge reach to the highest level. At this last stage, the washover sediment is exhibited as thin layer due to the low sediment supply and high water depth condition (Figure 5.3b).

According to the sedimentary transport mechanism of storm deposition that is dominantly moved by traction process (Morton et al, 2007), the sediments are thus concentrated at the base of flow. When the water depth increased, the shear stress at the bottom surface is also increased. Consequently, as the shear stress increased, the velocity at the bottom surface is so then decreased (Figure 5.3b). Therefore, based on the relationship of shear stress and bottom velocity, when the water depth is increased to the high flood stage level the bedload sediment is difficult to transport and then the deposition by traction process is end (Figure 5.3b). These will result in the thinner layer exhibited at the top of washover deposit. However, this hypothesis is based on the condition that the velocity of overwash is not increasing from the first stage to the final stage.

The formation of the thick-bedded sand with several sand laminae at BT and MR (see pictures in Figures 4.7 and 4.34) 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 the 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 (Figures 5.1a and c). Additionally, the existence of a large swale behind the beach is also a good preservation zone for sediment arising from such a high energy process as storm and tsunami to be deposited and last longer in the geological record (Phantuwongraj and Choowong, 2012).

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 at 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 dominantly moved by traction process (Morton et al, 2007), thus the reverse grading in washover sediment at BT and MR may result from dynamic sorting during bedload transport under the condition of high grain concentration in the overwash flow (Phantuwongraj et al., 2013). As the sediments are transported as traction load, the coarser grains preferentially roll over finer grains, thus resulting in reverse grading (Figure 5.4). 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.

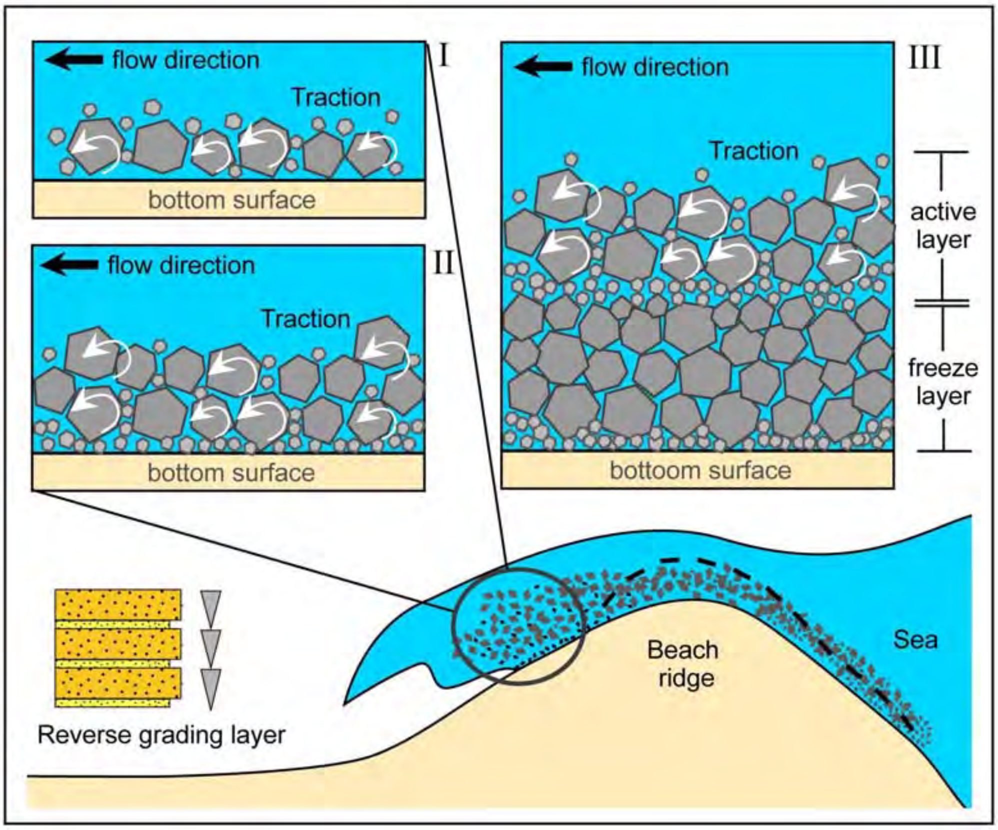


Figure 5.4 Schematic diagram explained the occurrence of reverse grading by dynamic sorting during bedload transport. (i) Coarse and fine particles are dominantly transported at the base of flow by rolling on the bottom surface as traction process. (ii) Collision among grain occurred during traction due to the high grain concentration. Then, fine particles are fall into the space between coarse particles as dynamic sorting. Consequently, fine particles are concentrated at the base of layer and generating the reverse grading. (iii) The bottom layer is freeze by the compaction during dynamic sorting. Subsequently, the new layers are formed by the following waves and generate the reverse grading again.

In contrast, the beach ridge at LT1 is relatively small compared with BT and MR. The backshore topography also exhibited as flat coastal plain without swale (Figure 5.1b). Small and narrow beach ridge implies that the volume of sediment supply to form the beach at LT1 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 (Figure 5.1b).

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 LT1 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 LT1 area (Figure 5.1b). 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 includes sub-horizontal bedding, reverse grading, lamination, foreset bedding and wavy bedding. At LT1, 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 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 skewness value of washover storm deposits are ranging from -1.19 to 1.14 phi, whereas beach/pre-storm surface sediments are ranging from -0.94 to 0.79 phi. However, most of washover storm sediments are showed the skewness value more than 0 phi, whereas skewness value of beach/pre-storm surface sediments are less than 0 phi (Figure 5.5). The different of value in skewness between washover storm sediments and beach/pre-storm surface sediments indicated the different processes of sedimentation. When comparing the grain size and sorting value of washover storm deposits to beach/pre-storm surface sediments from all study sites, the washover storm sediments showed the better sorting value (Figure 5.5). The better sorting value in washover storm deposits may resulting from the dynamic sorting during overwash flow as stated before.

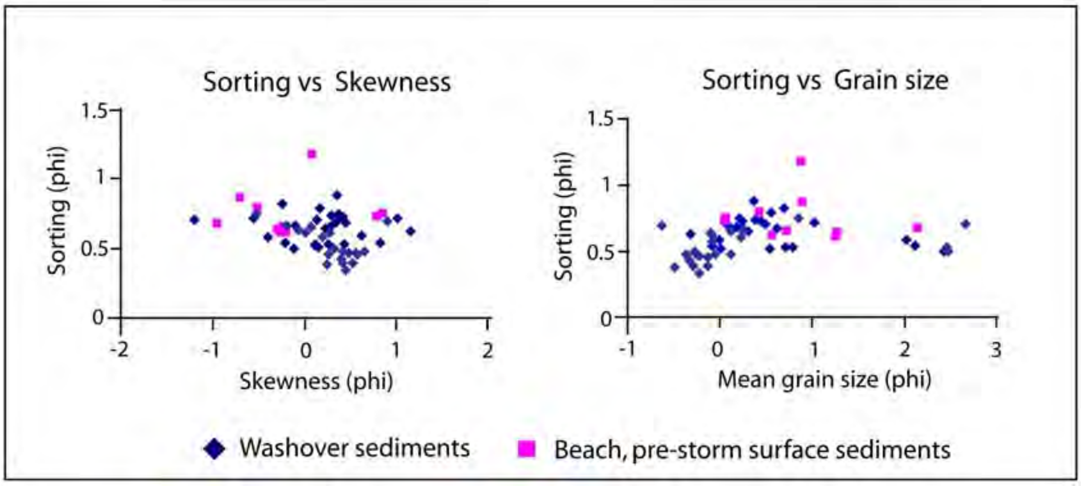


Figure 5.5 Sorting versus skewness values and sorting versus grain size values of washover sediments and beach, pre-storm surface sediments in this study.

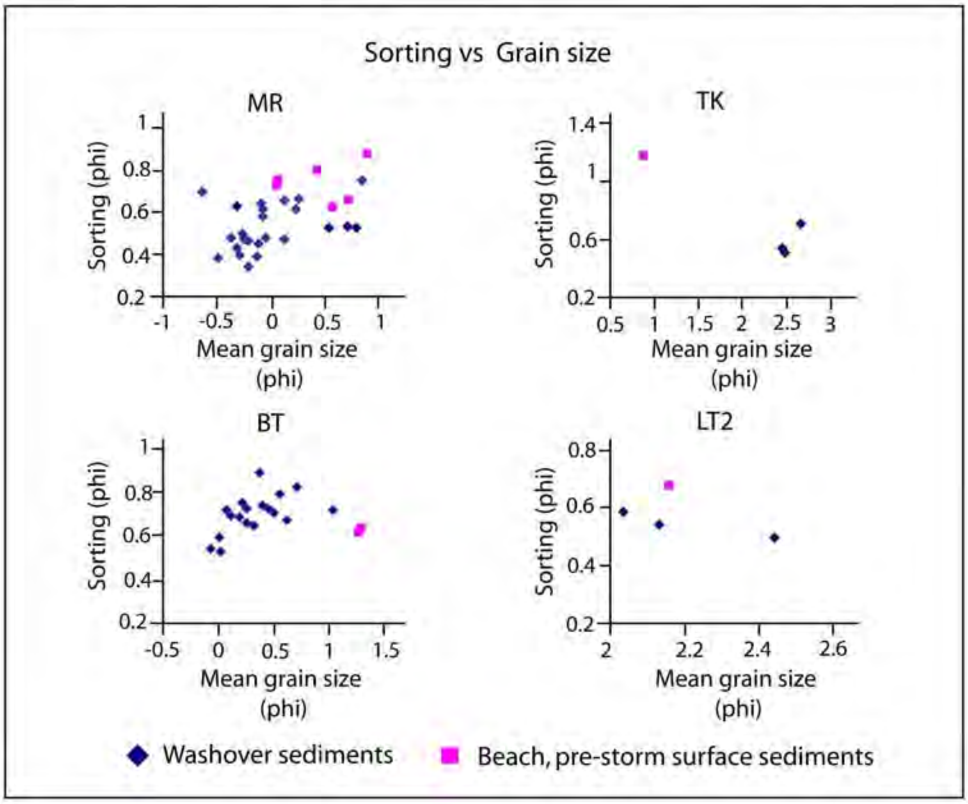


Figure 5.6 Sorting versus grain size values of washover sediments and beach, pre-storm surface sediments in this study, separated by study sites.

However, at BT, the sorting value of pre-storm surface sediments is better than washover storm deposit (Figure 5.6). The pre-storm surface samples at BT are characterized as medium sand with moderately well sorted. These samples may result from aeolian process which commonly generated the well sorted sediment deposition. Therefore, sorting value of the pre-storm surface sediments at BT is better than washover storm sediments. However when comparing sorting and grain size values at each sites, two group of sediment can be recognized (Figure 5.6). The different in sorting and grain size value between washover storm sediments and beach/pre-storm surface sediments is also indicated the different processes of sedimentation. Based on this study, the sorting versus skewness value and sorting versus grain size value can be used to distinguished storm deposits from other sediment deposits.

## 5.3 Storm deposits versus tsunami deposits

The occurrence of similar sedimentary characteristics of storm washover deposits from Thailand in this study 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; Phantuwongraj and Choowong, 2012).

However, in this study there are some features that can be used to differentiate storm deposit from tsunami deposit, including the number of layer, the multiple reverse grading layer, and foreset bedding structure. The number of layer in storm deposit is tended to be much more than the tsunami deposits, which confirmed by eleven to twelve layers of storm deposits found in BT and MR that 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 commonly in storm deposit than those we found in tsunami deposit in agreement with those reported by Morton et al. (2007).

Phantuwongraj and Choowong (2012) stated that the tsunami and storm flows mostly limit their depositional characteristics from place to place. 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.

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). In contrast, in the case of a storm flow, it seems likely that the storm process contains only the transformation and deposition stages.

Based on the study of Phantuwongraj and Choowong (2012), the transformation stage and the depositional stage 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).

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. 5.7a), 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. 5.7a). 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.

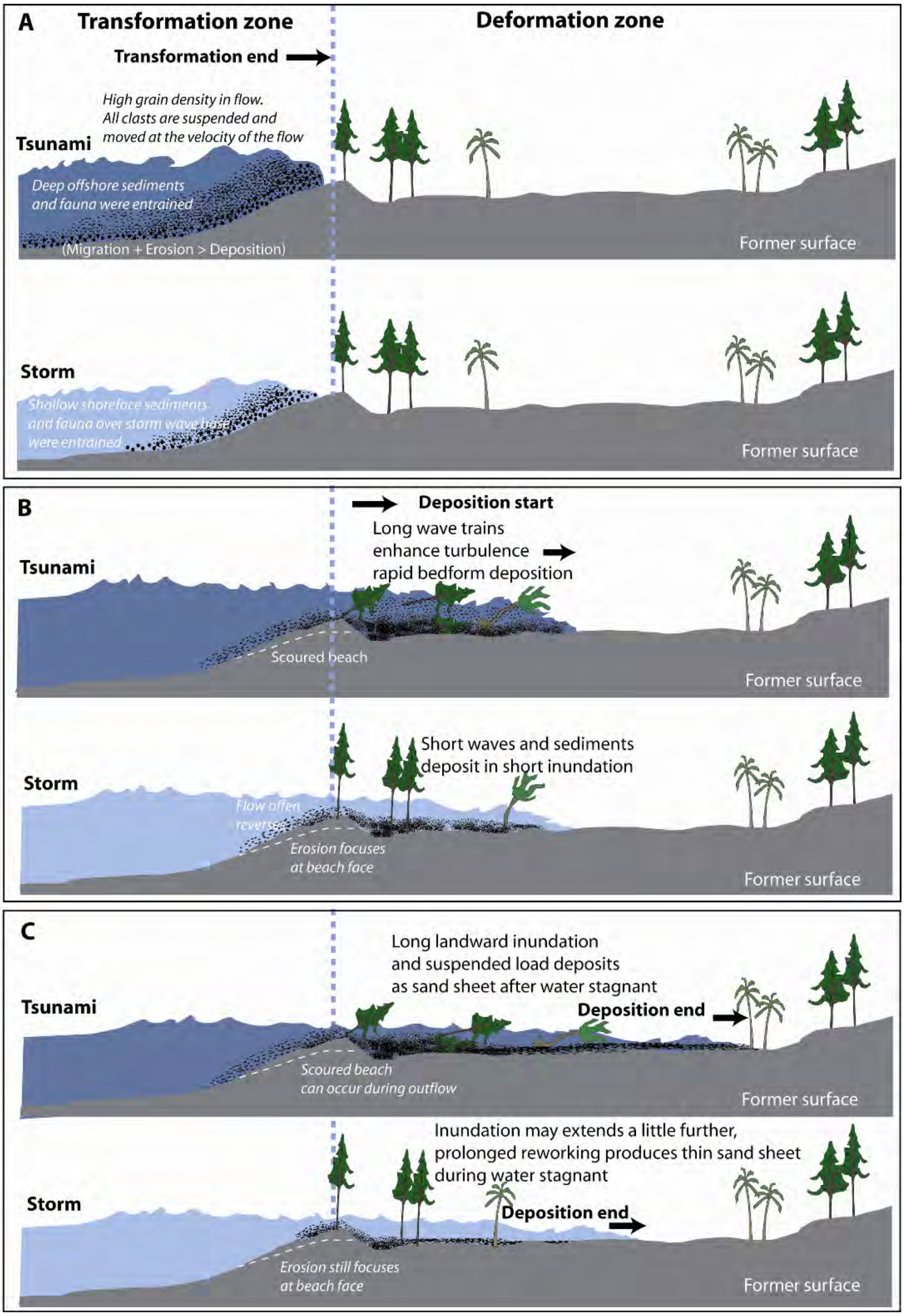


Figure 5.7 Schematic model of the flow conditions for a tsunami versus that for a storm from Phantuwongraj and Choowong, (2012). a) transformation stage. b) early depositional stage. c) the end of depositional stage (detail in text).

Depositional stage; tsunami and storm depositional stages occur after their turbulent head hits the beach zone, causing a decreased flow speed (Fig. 5.7b). 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 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. 2008b). 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.

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. 5.7c). 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.

Phantuwongraj and Choowong (2012) mentioned that 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 grading layers within storm deposits may be used to infer a longer period of flooding on the land than that for tsunamis.

# CHAPTER VI

# CONCLUSION

Modern and ancient storm surge washover deposits resulting from (i) temporary strong NE wind during the NE monsoon season and (ii) tropical storm were studied from the southern part of Thailand at (1) Khao Mai Ruak (MR), Prachuap Khiri Khan, (2) Phanang Tak bay (PT), Chumphon, (3) Ban Pak Nam Tha Krachai (TK) and Ban Takrop (BT), Surat Thani, and (4) Laem Talumphuk1 (LT1) and Laem Talumphuk2 (LT2), Nakhon Sri Thammarat on the eastern (GOT) side of southern peninsular Thailand (Figure 6.1). The explanations of possible storm surge events timeline that generated washover storm deposits in this study were mentioned in Chapter 4 separating by each study sites. The geomorphic setting of these study sites included beach barrier at MR, swale between relict sand ridge at PT, swale behind beach on strand plain at TK, prograded shoreline at BT, and sand spit at LT1 and LT2. Washover deposits were found 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 of storm surge induced by temporary strong NE wind during the NE monsoon are limited to 300 m from the shoreline. Three types of modern washover deposits, being perched fan at MR, TK and LT1, washover terrace at BT and LT2 and sheetwash at MR and PT, were found behind beach/former beach ridge up to a 100 m in landward direction. However, the ancient washover deposits at PT showed the continuity of sand sheet further inland up to 400 m from the paleo-shoreline. The differences in the geomorphic settings, washover type, flow conditions and sedimentary characteristics are summarized in Table 6.1

The modern washover deposits displayed two types of sedimentary characteristics, namely (i) a thick bedded sand, thickness ranging from 50-80 cm having multiple reverse grading layers and laminae at the bottom of each layer, as seen at MR, BT, and LT2 and (ii) a medium-bedded sand, thickness ranging from 15 to 20 cm, which shows multiple normal grading layer, as seen at LT1. In case of washover deposits at PT and TK, the separating layers in washover sediments were

Table 6.1 Summary of geomorphic setting, washover type, flow condition, and sedimentary characteristic in washover deposits from each area.

| **Features** | **MR 1st event** | **MR 2nd event** | **PT** | **TK** | **BT** | **LT1** | **LT2** |
|---|---|---|---|---|---|---|---|
| Topographic setting | Beach barrier | Beach barrier | Swale behind relict sandy ridges | Swale behind beach on strand plain | Prograded shoreline | Sand spit | Sand spit |
| Backshore topography | Tidal flood plain lower from beach ridge 2.5 m | Tidal flood plain lower from beach ridge 2.5 m | Swale | Swale | Swale lower from beach ridge 2 m | Flat coastal plan higher than beach ridge | Flat coastal plan higher than beach ridge |
| Erosional features | Beach scarp, Breached barrier | Beach scarp | - | - | Beach erosion | Beach erosion, scour | Beach erosion, scour |
| Storm impact regime | Inundation regime** | Overwash regime* | Inundation regime** | Overwash regime* | Overwash regime* | Overwash regime* | Overwash regime* |
| Flow confinement | Unconfined flow | Confined flow | Unconfined flow | Confined flow | Unconfined flow | Confined flow | Unconfined flow |
| Washover type | Sheetwash | Perched fan | Sheetwash | Perched fan | Washover terrace | Perched fan | Washover terrace |
| Deposition distance from beach ridge | 80 | 30 | 400 | 3 | 30 | 25 | 15 |
| Deposit thickness | 30 cm at crest of sand lineations | 50-30 cm | 1-22 cm | 1-4 cm | 60-80 cm | 15-20 cm | 8-60 cm |
| Number of layers | - | 12 | - | 1 | 11 | 3 | 9 |
| Number of overwash events | 1 | 1 | 14 | 1 | 2 | 1 | 3 |
| Vertical grading in layer | - | Reverse grading | Normal grading | - | Reverse grading | Normal grading | Normal grading |

Table 6.1 (continue). Summary of geomorphic setting, washover type, flow condition, and sedimentary characteristic in washover deposits from each area.

| Features | MR 1st event | MR 2nd event | PT | TK | BT | LT1 | LT2 |
|---|---|---|---|---|---|---|---|
| Sedimentary structure | - | Lamination, foreset bedding, subhorizontal bedding | - | - | Lamination, foreset bedding, subhorizontal bedding, wavy bedding | Horizontal bedding, dune structure | Lamination, foreset bedding, subhorizontal bedding |
| Rip-up clasts | None | None | Rare | None | None | Present at bottom unit | Present at bottom unit |
| Basal contact | Sharp contact | Sharp contact | Sharp contact, erosional contact | Sharp contact | Sharp contact | Sharp contact, erosional contact | Sharp contact, erosional contact |
| Shell laminae | None | None | Rare | None | None | Common | Common |
| Geometry | Elongate narrow parallel to flow direction | Lobate sand, thickness increasing in the depression area | Sand sheet, Landward thinning | Landward thinning | Sand sheet, lobate sand, thickness increasing in the depression area | Lobate sand, Landward thinning | Sand sheet, Landward thinning |
| Bedding inclination | - | Landward | - | - | Landward | Landward | Landward |
| Lateral deposition parallel to shoreline | Discontinuous | Patchy | Extensive | Patchy | Extensive | Patchy | Extensive |

*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.

**MR**= Khao Mai Ruak, Prachuap Khiri Khan, **PT**= Phanang Tak bay, Chumphon, **TK**= Ban Pak Nam Tha Krachai, Surat Thani, **BT**= Ban Takrop, Surat Thani, **LT1** and **LT2**= Laem Talumphuk, Nakhon Sri Thammarat not recognized, but the lateral change in grain size as landward decreasing and landward thinning in geometry can be observed.

The sedimentary structures, which presented in the thick bedded washover deposits at MR and BT, were including subhorizontal bedding, reverse grading, lamination, foreset bedding and wavy bedding. Additionally, at LT2 the sedimentary characteristic also similar to the MR and BT area, except the vertical grading in layer that show a normal graded. Whereas, the sedimentary structure of medium bedded washover sediments at LT1 show the normal grading, horizontal bedding and dune structures. At TK, the thickness of washover sediment is so thin and homogeneous, thus the sedimentary structure was difficult to observe. For ancient washover deposits at PT, the sedimentary structure was observed only normal grading. Rip-up clasts were also found in the bottom part of washover deposits where the mud supply was available as seen at LT1 and LT2. Washover successions were exhibited the inclined bedding in landward direction with basal sharp contact.

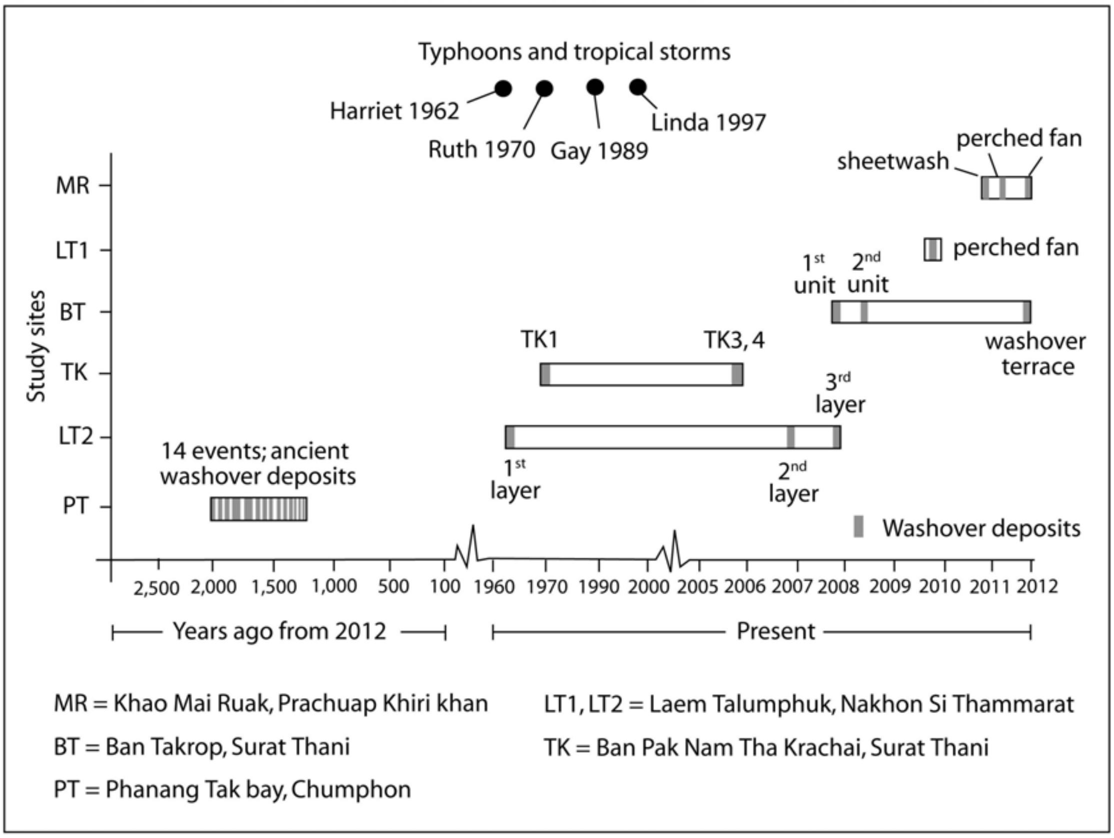


Figure 6.1 Possible timeline of washover storm deposits proposed in this study. See the explanation in Chapter 4 separating by each study sites.

Physical properties of washover sediments such as mean grain size, sorting, and skewness can use for distinguish the washover sediment from the other sediments by using the plotting chart comparing sorting versus skewness value and sorting versus mean grain size value. Grain size of washover sediments commonly shows the lateral change from seaward to landward side as finer inland. Sorting of washover deposits is commonly better than beach deposit when comparing within the same location. Sphericity and roundness of washover sediments are show as a high sphericity and sub-rounded which similar to the beach sand that is the sediments source location.

The compositions of washover sediments are compose of quartz, feldspar, heavy minerals, shells, shells fragments, and fauna which is generally depend on local sources sediments that can differ from place to place. Most of mollusca and benthic foraminifera which found in the washover sediments are living at the shallow water zone in transition environment from mangrove to shoreface zone. Additionally, the majority of mollusca and foraminifera which found frequently are including, gastropod; *Cerithidea cingulata* (Gmelin, 1791), bivalve; *Vepricardium* - Iredale, 1929 and *Nuculana (Thestyleda) soyoae*, and foraminifera; *Elphidium crispum* (Linnaeus, 1767).

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 and LT2. 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 MR, TK, and LT2. 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 modern washover sediments at BT and MR. The swale behind beach ridge is a well preservation area of washover sediments to stay in a geological record as proved by the discovery of ancient washover deposits in a large swale at PT. 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 LT1. 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. Three stages of storm surge, including (i) initial stage, (ii) flood stage, and (iii) high flood stage, are proposed as the important factor that controls the sedimentary characteristic of washover deposits which relevant to water depth, shear stress, bottom velocity, and sediment supply.

Based on the data from this study, the typical sedimentary characteristics of storm surge washover deposits can be listed as the following.

1. Commonly show multiple layers that result from pulsation of overwash wave.
2. Laminations of fine particles were usually observed.
3. Bedding shows dipping in landward direction.
4. Foreset bedding shows dip angle in landward direction.
5. Thickness of layer commonly decreases upward.
6. The bottom part normally shows the sharp contact that indicates a sudden depositional process.
7. Dark organic layer or fine particle such as aeolian sand inside the washover deposits is a good indicator of storm surge events boundary.
8. It is commonly composed of quart sand with low mud content.

The analysis of the geomorphic setting, washover type, flow condition and sedimentary characteristics from modern and ancient washover deposits in this study may improve our knowledge to better understand the behavior of storm surge washover deposits. These may reveal some hints to geoscientists for use in identifying storm deposits in the geological records.

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