



รายงานวิจัยฉบับสมบูรณ์

โครงการ การสำรวจร่องรอยสึนามิและพายุตามแนวชายฝั่งทะเลไทย

โดย

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จุฬาลงกรณ์มหาวิทยาลัย

สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัย และ
สำนักงานคณะกรรมการการอุดมศึกษา
(ความเห็นในรายงานนี้เป็นของผู้วิจัย สกว. ไม่จำเป็นต้องเห็นด้วยเสมอไป)

สารบัญ

หน้า

กิตติกรรมประกาศ	1
Abstract	2
บทคัดย่อ	3
บทที่ 1 บทนำ (Introduction)	4
1.1 ความสำคัญและที่มาของโครงการ	4
1.2 วัตถุประสงค์	4
1.3 ขอบเขตการวิจัย	5
1.4 ผลที่คาดว่าจะได้รับ	5
1.5 ผลงานวิจัยที่เกี่ยวข้อง	5
บทที่ 2 วิธีการศึกษา (Methodology)	7
2.1 ระเบียบวิธีวิจัย	7
2.2 อุปกรณ์ที่ใช้ในการวิจัย	7
2.3 รายละเอียดแผนการดำเนินโครงการ	7
2.4 การเชื่อมโยงกับนักวิจัยที่เป็นผู้เชี่ยวชาญในสาขาวิชาที่ทำการวิจัย ทั้งในและต่างประเทศ	8
บทที่ 3 ผลการดำเนินโครงการ (Results)	10
3.1 การวิจัย สํารวจข้อมูลพื้นฐานทางธรณีสัณฐานวิทยาชายฝั่ง	10
3.2 งานวิจัยพื้นฐานด้านตะกอนวิทยาของคลื่นสึนามิและคลื่นพายุซัดฝั่ง	11
บทที่ 4 บทสรุป (Conclusion)	12
ภาคผนวก	14

กิตติกรรมประกาศ

ขอขอบคุณคณะกรรมการการอุดมศึกษา (สกอ.) และสำนักงานกองทุนสนับสนุนงานวิจัย (สกว.) ที่ได้อนุมัติเงินทุนวิจัยสำหรับอาจารย์รุ่นกลางในสถาบันอุดมศึกษาในครั้งนี้ ตั้งแต่ปี พ.ศ. 2553 จนถึงสิ้นสุดโครงการ พ.ศ. 2556 เป็นเวลารวม 3 ปีเต็ม ซึ่งหัวหน้าโครงการได้ระบุนโยบายโครงการ (RMU5380020) ไว้ในกิตติกรรมประกาศของทุกบทความวิจัย บทความวิชาการ รวมถึงการเผยแพร่ในรูปแบบอื่นๆ ที่เกิดขึ้นในระหว่างการรับทุนนี้แล้วตามเงื่อนไขทุกประการ รวมถึงขอขอบคุณบุคลากร สกว. ทุกท่านที่ดูแล แนะนำ และอำนวยความสะดวกในการดำเนินโครงการนี้ด้วยดีจนโครงการบรรลุเป้าหมาย และได้ผลลัพธ์ออกมาเกินกว่าความคาดหมายที่ได้รับไว้ในข้อเสนอโครงการ

ขอขอบคุณต้นสังกัด คือ คณะวิทยาศาสตร์ และจุฬาลงกรณ์มหาวิทยาลัย ที่อนุมัติเงินทุนสมทบในการทำวิจัยครั้งนี้เป็นอย่างดี ขอขอบคุณภาควิชาธรณีวิทยา คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ที่เอื้อเฟื้อสถานที่พาหนะเดินทาง และห้องปฏิบัติการสำหรับวิเคราะห์ตัวอย่างตะกอนที่ได้จากภาคสนาม

หัวหน้าโครงการขอขอบคุณนักวิจัย อาจารย์ จากหน่วยงานในต่างประเทศที่ได้ให้ความอนุเคราะห์ในการวิเคราะห์ขนาดตะกอน และดูแลนิสิตที่ทำงานวิจัยในโครงการ ได้แก่ Dr. Futoshi Nanayama แห่ง Geological Survey of Japan, Professor Dr. Ken-ichiro Hisada, University of Tsukuba, Ibaraki, Japan, Professor Dr. Brady Rhodes, Associate Professor Dr. Matt Kirby, University of California (Fullerton) ที่ให้คำแนะนำบทความวิชาการที่เกิดขึ้นจากโครงการ

ขอขอบคุณ รองศาสตราจารย์ ดร. ปัญญา จารุศิริ ภาควิชาธรณีวิทยา คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย สำหรับคำแนะนำและเป็นนักวิจัยพี่เลี้ยง (Mentor) เสมอมา ตั้งแต่หัวหน้าโครงการรับทุนพัฒนาศักยภาพอาจารย์รุ่นใหม่จนถึงปัจจุบัน ขอขอบคุณอาจารย์และนิสิตจากภาควิชาธรณีวิทยา ที่ได้ร่วมเก็บข้อมูลในโครงการจนประสบความสำเร็จเป็นอย่างดี ได้แก่ อาจารย์ ดร. ฐานบ จิตติมากร อาจารย์ ดร. วิชัย จูฑะโกสิทธิ์กานนท์ อาจารย์ อัคนิรุช ชะบางบอน อาจารย์ ดร. สันติ ภัยหลบลี้ ดร.สุเมธ พันธวงศ์ราช (นิสิตทุน คปก.) นายพีรสิทธิ์ สุรเกียรติชัย (นิสิตปริญญาเอก) นางสาวปาริสา นิมนตร (นิสิตปริญญาเอก) นายชนกฤต ทองขาว (นิสิตปริญญาโท) และนิสิตปริญญาตรีอีกหลายคนจัดทำโครงงานวิทยาศาสตร์ที่เป็นส่วนหนึ่งในการดำเนินงานโครงการวิจัยนี้

Abstract

Project Code : RMU5380020

Project Title : Investigation on trace of tsunami and storm along Thailand's coast

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Project Period : 15 June 2010 to 14 June 2013

The 2004 Indian Ocean tsunami event has increased the importance of geo-sciences research worldwide. A few years after 2004 tsunami disaster, the impact of tropical cyclone “Nargis” hit the west coast of Myanmar in 2007 also made up much awareness to local geo-scientists and raised one important question on where and when the coast of Thailand may face similar this disastrous storm event. After both events, several equivocal ideas from scientists and researchers were come out with the confusion to Thai community on whether or not tsunami and storm events will possibly be occurred again along Thailand coast.

The Nargis storm surge event led to the more panic, although the 2004 geological event has still existed in Thai memory. Clearly, the 2004 tsunami event was unpredictable and beyond the expectation of all scientists. Similarly, the occurrence of Nargis has raised the most interested geological question that whether or not the storm events have been occurred in Thailand and how to determine the recurrence interval of the cyclone. Likewise, the scientific way to answer those questions is to search for the trace of storm in the past. Once those riddles were answered, it will be high possibility to predict the recurrence of storm in the future. To date, very few local geo-science researchers have published all relevant geo-science research result from Thailand. Some of them concerned with the modern tsunami investigation under TRF sponsorship (e.g. Choowong et al., 2007; Choowong et al., 2008). Some published the recovery nature of damaged areas at the Andaman coast (e.g. Choowong et al., 2009; Di Geronimo et al., 2009). It is no doubt that more concrete research on both tsunami and storm is compulsory.

This project is drawn upon the successful investigation on paleo-tsunami from Thai's geoscientists, which has already published in 2008 (Jankaew et al., 2008). Also, the continue research on storm deposit was carried out after the successful discovery of candidate storm deposits at the Gulf of Thailand's coast by Phantu Wongraj et al. (2008). The hypothesis is set up on that the more frequency of paleo-tsunami or paleo-storm events we discovered, the more precise prediction can be done in the future. At the end of this project, 3 international papers, 2 national papers, 1 international book chapter and several social and media magazines were published. This confirms well that the research on geological disasters is still challenging and interesting among geo-science and social community both national and international levels.

Keywords : Tsunami, Storm surge, Paleotsunami, Ancient storm, Gulf of Thailand

บทคัดย่อ

รหัสโครงการ : RMU5380020

ชื่อโครงการ : การสำรวจร่องรอยสึนามิและพายุตามแนวชายฝั่งทะเลไทย

ชื่อนักวิจัย : รองศาสตราจารย์ ดร. มนตรี ชูวงศ์ จุฬาลงกรณ์มหาวิทยาลัย

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เหตุการณ์แผ่นดินไหวและสึนามิเมื่อปี 2547 ได้แสดงให้เห็นความสำคัญของงานวิจัยทางธรณีศาสตร์ทั่วโลก เพียงไม่กี่ปีหลังเหตุการณ์นี้ พายุเฮอร์ริเคนพัดเข้าถล่มชายฝั่งประเทศพม่าในปี 2550 ธรณีพิบัติภัยที่เกิดขึ้นในระยะ 5 ปีที่ผ่านมาได้สร้างความตื่นตัวต่อสังคมไทยเป็นอย่างมากในการติดตามผลกระทบ หรือคาดการณ์ว่าธรณีพิบัติภัยต่างๆ จะเกิดขึ้นอีกหรือไม่ เมื่อใด และสืบเนื่องจากธรณีพิบัติภัยแผ่นดินไหวและสึนามิ เมื่อ 26 ธันวาคม 2547 ที่เกิดขึ้นได้ส่งผลกระทบในเขต 6 จังหวัดทางฝั่งทะเลอันดามันของประเทศไทย ก่อให้เกิดความสูญเสียอย่างใหญ่หลวงต่อประเทศชาติ บุคคลสำคัญ ประชาชนทั้งคนไทยและนักท่องเที่ยวจากต่างประเทศ และความวิตกกังวลต่อพิบัติภัยดังกล่าวยังไม่ทันเลือนหายก็ได้เกิดกรณีพายุพัดเข้าถล่มชายฝั่งประเทศพม่าเพื่อนบ้านของไทยทำให้เกิดความสูญเสียใหญ่หลวงและได้เพิ่มความวิตกกังวลต่อประเทศไทยเป็นอย่างมาก

ธรณีพิบัติภัยอันได้แก่ สึนามิและพายุดังกล่าวอยู่เหนือความคาดหมายของนักวิชาการทั่วโลก สาเหตุของการเกิดพิบัติภัย และผลกระทบทางกายภาพและชีวภาพได้มีการประเมินกันเป็นที่เรียบร้อยแล้ว แต่ก็ยังปรากฏคำถามทางวิชาการธรณีวิทยาและทางกายภาพอื่น ตามมาอีกมากมาย คำถามสำคัญหลักที่เวลานั้น คือทำอะไรที่จะทราบและกำหนดคาบการเกิดวิบัติซ้ำของ สึนามิและพายุที่อาจจะก่อให้เกิดความเสียหายต่อประเทศไทยได้ การได้มาซึ่งคำตอบที่มีการวิเคราะห์ข้อมูลทางกายภาพและทางธรณีวิทยาที่ชัดเจน ปัจจุบันงานวิจัยที่กระทำโดยนักวิจัยไทยและต่างประเทศที่ผู้วิจัยโครงการนี้เกี่ยวข้องด้วยโดยการสนับสนุนจาก สกว. โดยได้เผยแพร่ผลงานออกมาเน้นในเรื่องการทำความเข้าใจในลักษณะตะกอนสึนามิที่พบในปี 2547 (ดังเช่นงานวิจัยของ Choowong และคณะ ค.ศ. 2007; Choowong และคณะ ค.ศ. 2008) และผลงานติดตามการฟื้นฟูสภาพหาดทรายหลังจากเหตุการณ์ (Choowong และคณะ ค.ศ. 2009; Di Geronimo และคณะ ค.ศ. 2009) ซึ่งเป็นผลงานในระดับเริ่มต้นและเป็นโจทย์วิจัยที่สามารถต่อยอดต่อไปได้อีกในอนาคต

โครงการนี้ได้ทำการต่อยอดหลังจากได้มีการค้นพบประวัติว่าสึนามิเคยเกิดขึ้นแล้วในอดีตในแถบทะเลอันดามันของไทย ที่เผยแพร่แล้วในปี ค.ศ. 2008 (Jankaew และคณะ ค.ศ. 2008) ซึ่งเป็นข้อมูลทางธรณีวิทยาที่สำคัญยิ่งในการที่จะนำมาประกอบการคาดการณ์ว่าสึนามิจะเกิดขึ้นอีกหรือไม่ในอนาคต และหากเกิดจะเกิดที่ไหน เมื่อใด ส่วนร่องรอยของพายุในอดีตนั้น คณะวิจัยจากภาควิชาธรณีวิทยา (นำทีมโดยหัวหน้าโครงการนี้) ได้เคยรายงานการค้นพบจากบริเวณชายฝั่งอ่าวไทย (Phantu Wongraj และคณะ ค.ศ. 2008) ซึ่งการค้นพบดังกล่าวนับได้ว่าเป็นการเริ่มตามร่องรอยสึนามิและพายุในประเทศไทยที่สำคัญยิ่ง ฉะนั้นงานวิจัยนี้เป็นการต่อยอดโจทย์วิจัยจากความสำเร็จเริ่มต้นของการค้นคว้า สืบหาประวัติการเกิดสึนามิและพายุในอดีตของประเทศไทย โครงการนี้สิ้นสุดแล้ว ได้ผลิตบทความวิชาการระดับนานาชาติ 3 บทความ ระดับชาติ 2 บทความ บทในหนังสือต่างประเทศ 1 บท และผลงานที่นำผลที่ได้จากโครงการไปเผยแพร่อื่นๆ เช่น หนังสือ บทในหนังสือ ตำรา บทสัมภาษณ์ และบทความสารคดีซึ่งพิสูจน์ให้เห็นแล้วว่า งานวิจัยด้านธรณีพิบัติภัยยังเป็นความท้าทายทางวิชาการและอยู่ในความสนใจของนักวิจัยทางธรณีวิทยาและบุคคลทั่วไปทั้งในและต่างประเทศในปัจจุบัน

คำสำคัญ : Tsunami, Storm surge, Paleotsunami, Ancient storm, Gulf of Thailand

บทที่ 1

บทนำ (Introduction)

1.1 ความสำคัญและที่มาของโครงการ

ปัจจุบันธรณีพิบัติภัยที่เกิดขึ้นในระยะ 5 ปีที่ผ่านมาได้สร้างความตื่นตัวต่อสังคมไทยเป็นอย่างมากในการติดตามผลกระทบ หรือคาดการณ์ว่าธรณีพิบัติภัยต่างๆ จะเกิดขึ้นอีกหรือไม่ เมื่อใด และสืบเนื่องจากธรณีพิบัติภัยแผ่นดินไหวและสึนามิ เมื่อ 26 ธันวาคม 2547 ที่เกิดขึ้นได้ส่งผลกระทบในเขต 6 จังหวัดทางฝั่งทะเลอันดามันของประเทศไทย ก่อให้เกิดความสูญเสียอย่างใหญ่หลวงต่อประเทศชาติ บุคคลสำคัญ ประชาชนทั้งคนไทยและนักท่องเที่ยวจากต่างประเทศ และความวิตกกังวลต่อพิบัติภัยดังกล่าวยังไม่ทันเลือนหายก็ได้เกิดกรณีพายุพัดเข้าถล่มชายฝั่งประเทศพม่าเพื่อนบ้านของไทยทำให้เกิดความสูญเสียใหญ่หลวงและได้เพิ่มความวิตกกังวลต่อประเทศไทยเป็นอย่างมาก

ธรณีพิบัติภัยอันได้แก่สึนามิและพายุดังกล่าวอยู่เหนือความคาดหมายของนักวิชาการทั่วโลก สาเหตุของการเกิดพิบัติภัย และผลกระทบทางกายภาพและชีวภาพได้มีการประเมินกันเป็นที่เรียบร้อยแล้ว แต่ก็ยังปรากฏคำถามทางวิชาการธรณีวิทยาและทางกายภาพอื่นๆ ตามมาอีกมากมาย คำถามสำคัญหลักๆ ที่ว่านั่น คือทำอย่างไรที่จะทราบและกำหนดคาบการเกิดวิบัติซ้ำของ สึนามิและพายุที่อาจจะก่อให้เกิดความเสียหายต่อประเทศไทยได้ การได้มาซึ่งคำตอบที่มีการวิเคราะห์ข้อมูลทางกายภาพและทางธรณีวิทยาที่ชัดเจน จะทำให้อย่างน้อยที่สุดการทราบช่วงของระยะเวลาที่เคยเกิดสึนามิและพายุในอดีตน่าจะเป็นแนวทางหนึ่งในการที่จะสามารถประเมินคาบการเกิดวิบัติซ้ำดังกล่าวในอนาคตได้ ซึ่งหลังจากเกิดพิบัติภัยดังกล่าว ยังไม่มีความชัดเจนโดยเฉพาะการคาดการณ์ช่วงเวลาและความเป็นไปได้ในเชิงพื้นที่ของการเกิดสึนามิและการเข้าปะทะของพายุไซโคลน จากประเด็นดังกล่าวในทางวิชาการธรณีวิทยานับว่าเป็นคำถามที่ค้นหาคำตอบได้ยากที่สุด และยังไม่มีใครกำหนดพื้นที่เสี่ยงและระยะเวลาของการเกิดแผ่นดินไหวในทะเลที่จะก่อให้เกิดสึนามิและพายุได้อย่างชัดเจนและแม่นยำ

จวบจนถึงปัจจุบัน ได้มีการค้นพบประวัติน้ำสึนามิเคยเกิดขึ้นแล้วในอดีต (Jankaew และคณะ ค.ศ. 2008) ในแถบทะเลอันดามันของไทย ซึ่งเป็นข้อมูลทางธรณีวิทยาที่สำคัญยิ่งในการที่จะนำมาประกอบการคาดการณ์ว่าสึนามิจะเกิดขึ้นอีกหรือไม่ในอนาคต และหากเกิดจะเกิดที่ไหน เมื่อใด ส่วนร่อยรอยของพายุในอดีตนั้น คณะวิจัยจากภาควิชาธรณีวิทยา (นำทีมโดยหัวหน้าโครงการนี้) ได้รายงานการค้นพบแล้วเช่นกันจากบริเวณชายฝั่งอ่าวไทย (Phantu Wongraj และคณะ ค.ศ. 2008) ซึ่งการค้นพบดังกล่าวนับได้ว่าเป็นการเริ่มตามรอยสึนามิและพายุในประเทศไทยที่สำคัญยิ่ง ฉะนั้นงานวิจัยนี้จะเป็นการต่อยอดงานวิจัยจากความสำเร็จเริ่มต้นของการค้นคว้า สืบหาประวัติการเกิดสึนามิและพายุในอดีตของประเทศไทย ผลการสำรวจและวิจัยจากโครงการนี้ นอกจากจะเป็นแนวทางในการพัฒนาการเรียนการสอนทางธรณีวิทยาที่สำคัญแล้ว ยังอาจจะสามารถให้คำตอบกับสังคมได้ว่าสึนามิและพายุจะมีโอกาสเกิดขึ้นอีกหรือไม่ในประเทศไทยและหากเกิดจะเกิดที่ไหน เมื่อใด

1.2 วัตถุประสงค์

1. สำรวจ เก็บข้อมูล และวิเคราะห์หลักฐานทางตะกอนวิทยาของสึนามิและพายุทั้งปัจจุบันและในอดีต รวมถึงธรณีแปรสัณฐานยุคใหม่ และแผ่นดินไหวที่เคยเกิดขึ้นในอดีต
2. ประเมินคาบวิบัติซ้ำของสึนามิและพายุในอดีต และในอนาคต
3. ประเมินความเสี่ยงเชิงพื้นที่และระยะเวลาของโอกาสเกิดสึนามิและพายุในประเทศไทย

1.3 ขอบเขตของการวิจัย

ขอบเขตเชิงพื้นที่ครอบคลุมพื้นที่ตามแนวชายฝั่งทะเลอันดามันและทะเลอ่าวไทย ในด้านการวิเคราะห์จะเน้นการวิเคราะห์เชิงธรณีสัณฐานวิทยา ตะกอนวิทยา และบรรพชีวินวิทยา เป็นหลัก

1.4 ผลที่คาดว่าจะได้รับ

อ้างอิงข้อเสนอโครงการวิจัยของโครงการนี้ ผู้วิจัยได้เสนอไปว่าจะทำการเผยแพร่บทความวิชาการเผยแพร่ในวารสารวิชาการระดับนานาชาติจำนวน 2 บทความ

1.5 ผลงานวิจัยที่เกี่ยวข้อง

โครงการนี้เป็นการทำงานต่อยอดจากงานวิจัยที่ผู้วิจัยได้รับทุนพัฒนาศักยภาพอาจารย์รุ่นใหม่ จาก สกว และ สกอ ตั้งแต่ปี 2546 ถึง 2551 โดยได้เผยแพร่บทความวิชาการที่สามารถนำมาเป็นข้อมูลฐานสำหรับการทำโครงการนี้ ดังต่อไปนี้

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บทที่ 2

วิธีการศึกษา (Methodology)

2.1 ระเบียบวิธีวิจัย

1. สร้างระบบฐานข้อมูลสึนามิและพายุ โดยการสืบค้นงานวิจัยทั่วโลก
2. สำนวณภาคสนามในเบื้องต้นเพื่อประเมินโอกาสพบหลักฐานทางธรณีวิทยาของสึนามิและพายุ
3. สำนวณทางกายภาพในพื้นที่ที่เคยสูญเสียไปจากสึนามิและพายุ
4. สำนวณลักษณะตะกอนสึนามิและพายุทั้งปัจจุบันและในอดีตเพื่อใช้เป็นข้อมูลพื้นฐานในการเทียบเคียง
5. ศึกษาสมบัติตะกอน และศึกษาหลักฐานทางธรณีวิทยาต่างๆ ในห้องปฏิบัติการ
6. วิเคราะห์และประเมินผลการสำนวนทั้งหมด เพื่อสรุปผลการวิจัย
7. สรุปผลและนำเสนอข้อมูลในรูปแบบบทความทั้งการประชุมวิชาการและวารสารวิชาการ

2.2 อุปกรณ์ที่ใช้ในการวิจัย

อุปกรณ์ที่ใช้ในการวิจัยเป็นอุปกรณ์ที่มีอยู่แล้ว ได้แก่

อุปกรณ์สนาม ได้แก่ เครื่องมือเจาะสำนวน เครื่องมือวัดระดับ (กล้องวัดระดับ)

เครื่องมือธรณีสนาม ได้แก่ เข็มทิศ ที่ปาดตะกอน สายวัด อื่นๆ

คอมพิวเตอร์เพื่อประมวลผล

อุปกรณ์กำหนดตำแหน่งภูมิศาสตร์ (GPS) ความละเอียดสูง

เครื่องวิเคราะห์ขนาดตะกอน (Settling tube)

อุปกรณ์จำเป็นที่ต้องการเพิ่มเติม ได้แก่

เครื่องคอมพิวเตอร์พกพา (Notebook) เพื่อใช้ในการเก็บข้อมูลภาคสนาม 2 เครื่อง

หลอดพลาสติกเก็บตัวอย่างตะกอนความยาว 1 เมตร จำนวน 200 หลอด

นอกจากนี้ ตัวอย่างซากบรรพชีวิน เพื่อใช้ในการกำหนดอายุจะต้องทำการส่งวิเคราะห์ในห้องปฏิบัติการต่างประเทศ ซึ่งต้องใช้งบประมาณค่อนข้างสูง ซึ่งผู้วิจัยจะได้ใช้เงินทุนที่ได้จากโครงการวิจัยที่เสนอขอจากแหล่งทุนอื่นๆ ต่อไป

2.3 รายละเอียดแผนการดำเนินโครงการ

ตารางที่ 2.1 แผนการดำเนินงานของโครงการตลอดระยะเวลา 3 ปี

แผนงานวิจัย	ปีที่ 1	ปีที่ 2	ปีที่ 3	ผลที่คาดว่าจะได้รับ (output)
1. สืบค้นงานวิจัยที่เกี่ยวข้องพร้อมจัดระบบข้อมูลอย่างเป็นระบบ				ฐานข้อมูลงานวิจัยที่เกี่ยวข้องทั้งหมดทั้งในและต่างประเทศ
2. สำนวณติดตามการเปลี่ยนแปลงชายฝั่งหลังเกิดพิบัติภัยสึนามิและพายุในบริเวณกว้าง				รายงานและแผนที่แสดงผลประเมินเชิงพื้นที่ในรูปแผนที่และข้อมูลการเปลี่ยนแปลง เช่น พื้นที่และทิศทางการสะสมตัวของตะกอนในรายพื้นที่ย่อย
3. สำนวณตะกอนสึนามิที่พัดพามาเมื่อ 26 ธันวาคม 2547 ในพื้นที่ที่ได้รับผลกระทบจากพิบัติภัยสึนามิ				ข้อมูลและแผนที่ระดับรายละเอียดแสดงการกระจายตัวของตะกอนและผลการวิเคราะห์ทางตะกอนวิทยาในระดับรายละเอียด

4. รั้งวัดพื้นที่หน้าหาดที่ถูกกัดเซาะจากสึนามิ ทุกปีและในพื้นที่พบหลักฐานตะกอนวิทยาของ พายุ				รายงานและภาพถ่ายช่วงบริเวณหน้าหาดที่แสดง รายละเอียดการพังตัวของพื้นที่ในแต่ละปีหรือแต่ละ ฤดูกาล
5. สืบหาตะกอนสึนามิและพายุในอดีตอย่าง ต่อเนื่องในพื้นที่ตลอดแนวชายฝั่งทะเลอันดามัน และชายฝั่งทะเลอ่าวไทย				ข้อมูลรายงานและแผนที่แสดงหลักฐานทาง ธรณีวิทยาและตะกอนวิทยาของสึนามิและพายุใน อดีตเพื่อประเมินกับผลวิเคราะห์แผ่นดินไหว เพื่อประเมินคาบวิบัติซ้ำและประวัติของ การเกิดพายุ
6. สืบหาสิ่งมีชีวิตขนาดเล็กที่ถูกพัดพามา กับสึนามิและพายุพร้อมกับเก็บตัวอย่างวิเคราะห์ ในห้องปฏิบัติการ				ข้อมูลการกระจายตัว ชนิดของสิ่งมีชีวิตในทะเล ที่ถูกพัดพาขึ้นมาสะสมตัวบนบกจากสึนามิและ พายุ เพื่อกำหนดระดับความลึกที่ได้รับอิทธิพล จากสึนามิและพายุ
7. สืบหาและเก็บตัวอย่างธรณีวิทยาเพิ่มเติม เพื่อจัดทำแผนที่ธรณีสัณฐานวิทยารายละเอียด				รายงานและแผนที่แสดงการเปลี่ยนแปลง ทางกายภาพและธรณีสัณฐานวิทยา
8. สรุปผลวิจัย พร้อมเผยแพร่ข้อมูลสู่สาธารณะ				รายงานฉบับสมบูรณ์ของโครงการ พร้อมแผนที่ประกอบ และสื่อสิ่งพิมพ์ที่เป็น ผลผลิตของโครงการ เช่น หนังสือ โปสเตอร์ วีซีดีสรุปการดำเนินงาน เป็นต้น

2.4 การเชื่อมโยงกับนักวิจัยที่เป็นผู้เชี่ยวชาญในสาขาวิชาที่ทำการวิจัยทั้งในและต่างประเทศ

ผู้วิจัยได้รับข้อเสนอแนะจากคณะผู้เชี่ยวชาญและผู้เคยร่วมวิจัยจากต่างประเทศด้วยดีตลอดมาและได้ติดต่อให้มีการทำวิจัยร่วมกันกับโครงการนี้

ประเทศญี่ปุ่น ได้แก่

Prof. Dr Ken-ichiro Hisada, University of Tsukuba, Japan เชี่ยวชาญด้านตะกอนวิทยา และธรณีแปร
สัณฐานของภูมิภาคเอเชียตะวันออกเฉียงใต้

Assoc. Prof. Dr Naomi Murakoshi, Shinshu University, Japan เชี่ยวชาญด้านตะกอนวิทยาสมัยไพลส
โตซีน และกลศาสตร์การเคลื่อนตัวของตะกอน

Dr Yuki Sawai, Geological Survey of Japan เชี่ยวชาญด้านบรรพชีวินชนิดไดอะตอม และธรณีวิทยาควอ
เทอร์นารี

Dr Futoshi Nanayama, Geological Survey of Japan เชี่ยวชาญด้านตะกอนวิทยาของสึนามิและพายุ

ประเทศสหรัฐอเมริกา ได้แก่

Prof. Dr Brady Rhodes, California State University, USA เชี่ยวชาญด้านธรณีโครงสร้าง และเคยร่วม
สำรวจหาตะกอนสึนามิในอดีตกับผู้วิจัยในปี 2548 และ 2549

Prof. Dr Brian F Atwater, US Geological Survey, University of Washington, USA เชี่ยวชาญด้าน
ตะกอนวิทยาควอเทอร์นารี ตะกอนวิทยาของสึนามิปัจจุบันและในอดีต เป็นบุคคลที่มีชื่อเสียงมากที่สุดในโลกคน
หนึ่งด้านการสำรวจตะกอนสึนามิในอดีต และได้ร่วมสำรวจกับผู้วิจัยและคณะจากภาควิชาธรณีวิทยา จุฬาลงกรณ์
มหาวิทยาลัย ปี 2549 และ 2550

Dr. Martitia Tuttle, Earthquake and tsunami expert เชี่ยวชาญด้านธรณีฟิสิกส์และกลศาสตร์ของ
แผ่นดินไหว เคยร่วมสำรวจสึนามิในพื้นที่ประเทศไทยกับผู้วิจัย ปี 2549

Prof. Dr. Williams Harry, University of North Texas เชี่ยวชาญเรื่องตะกอนพายุ และการศึกษาตะกอนพายุในอดีต (Paleotempestology)

ประเทศอิตาลี ได้แก่

Prof. Dr. Italo Di Geronimo, University of Catania, Italy เชี่ยวชาญด้านบรรพชีวินวิทยา และเคยร่วมสำรวจตะกอนวิทยา ชีววิทยาของสิ่งมีชีวิตในทะเลอันดามัน กับผู้วิจัย ตั้งแต่ปี 2549 รวมถึงทีมคณะสำรวจจากมหาวิทยาลัยโรมา มหาวิทยาลัยมิลาน

ประเทศฮังการี ได้แก่

Prof. Dr. Miklos Kazmer, Etvos University, Budapest เชี่ยวชาญด้านบรรพชีวิน

บทที่ 3

ผลการดำเนินโครงการ (Results)

ข้อมูลด้านตะกอนวิทยาจากโครงการนี้ได้มาจากการสำรวจและเก็บตัวอย่างในภาคสนามทั้งหมดซึ่งจัดเป็นข้อมูลปฐมภูมิ (Primary data) การเก็บข้อมูลเน้นเพื่อศึกษาวิวัฒนาการของธรณีสัณฐานชายฝั่งและค้นหาชั้นตะกอนที่สะสมตัวแบบผิดปกติตามแนวชายฝั่งที่น่าจะเป็นตะกอนที่เกิดจากการพัดพามาสะสมตัวโดยคลื่นพายุซัดฝั่ง (storm surge) พื้นที่วิจัยจะเน้นชายฝั่งด้านตะวันตกของอ่าวไทย คือ จังหวัดชุมพร สุราษฎร์ธานี นครศรีธรรมราช แลคมตะลุมพุก และชายฝั่งตะวันออกด้านจังหวัดจันทบุรี โดยมีรายละเอียดการดำเนินการแยกพื้นที่โดยสรุป ดังนี้

3.1 การวิจัย สํารวจข้อมูลพื้นฐานทางธรณีสัณฐานวิทยาชายฝั่ง

ธรณีสัณฐานชายฝั่งทะเลด้านตะวันออกที่ผู้วิจัยให้เป็นหนึ่งในพื้นที่สำรวจคือ แนวสันดอนจะงอยในอดีต ซึ่งอยู่ในบริเวณบ้านซึ้งล่าง ถึง บ้านบ่อล่าง อำเภอลำลูกเกด จังหวัดจันทบุรี ที่แสดงหลักฐานทางธรณีสัณฐานธรณีวิทยาว่าเกิดขึ้นมาแล้วในอดีตและสามารถเก็บตัวอย่างตะกอนมาเพื่อกำหนดอายุทางธรณีวิทยาได้ชัดเจน ผู้วิจัยใช้การดำเนินงานในขั้นแรกด้วยการศึกษาข้อมูลระยะไกล คือ ทำการศึกษา และแปลความหมายภาพถ่ายทางอากาศและภาพถ่ายดาวเทียม เพื่อจำแนกจำนวน และศึกษาถึงลักษณะของรูปร่างของสันดอนจะงอยในพื้นที่ศึกษา และได้ทำการเก็บตัวอย่างตะกอนของแต่ละสันดอนจะงอยมาเพื่อกำหนดอายุของสันดอนจะงอย ด้วยวิธีการกำหนดอายุด้วยแสง หรือ Optically Stimulated Luminescence (OSL) Dating

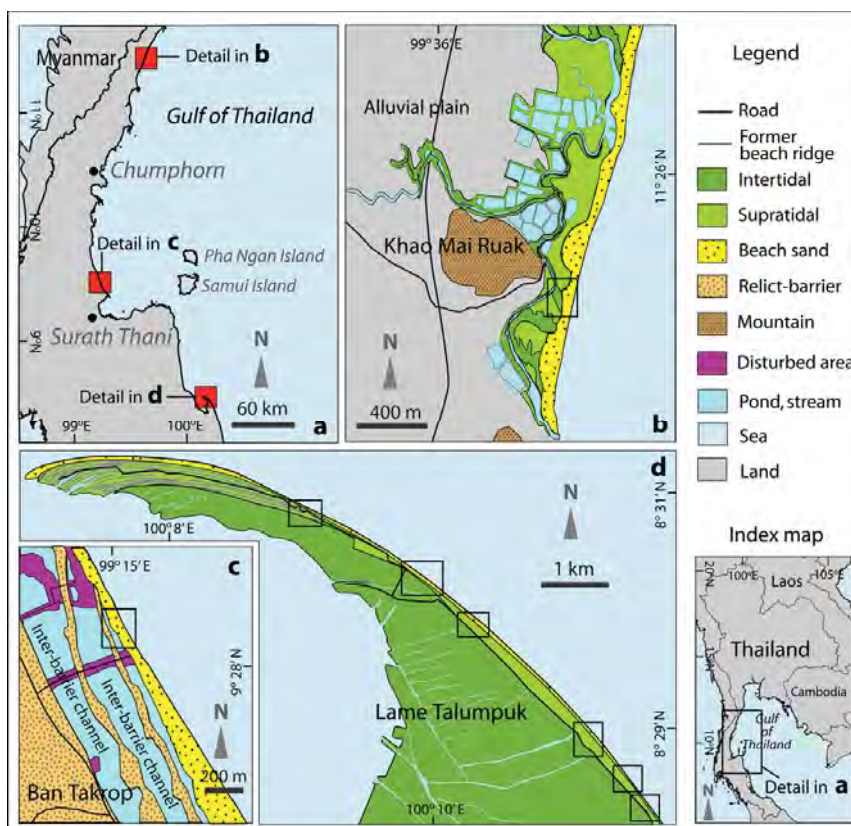
จากการแปลผลข้อมูลภาพถ่ายทางอากาศ และภาพถ่ายดาวเทียม สามารถแบ่งแนวของสันดอนจะงอยได้ทั้งหมด 10 แนว ซึ่งมีการวิวัฒนาการอย่างต่อเนื่องจากทิศตะวันตกเฉียงเหนือ มายังตะวันออกเฉียงใต้ โดยข้อมูลการวิเคราะห์อายุด้วยวิธีการกำหนดอายุด้วยแสง พบว่า อายุการวิวัฒนาการของสันดอนจะงอย อยู่ในช่วงระหว่าง $1,190 \pm 70$ ถึง $17,950 \pm 1,710$ ปีที่ผ่านมา จากผลการวิเคราะห์พบว่าสัมพันธ์กับเหตุการณ์การเปลี่ยนแปลงระดับน้ำทะเลจากรายงานเก่าที่ได้ศึกษามา โดยสรุปได้ว่า แนวชายฝั่งของบ้านซึ่งล่าง ถึง บ้านบ่อล่าง จังหวัดจันทบุรี มีวิวัฒนาการอยู่ในช่วงประมาณ 1,710 ถึง 17,950 ปีที่ผ่านมา ซึ่งพบว่าอยู่ในช่วง สมัยไพลสโตซีน ถึง โฮโลซีน



รูป 3.1 แผนที่ธรณีสัณฐานชายฝั่งแสดงบริเวณพื้นที่วิจัย (ดัดแปลงจาก กรมทรัพยากรธรณี ปี 2546) พื้นที่สำรวจ คือ บริเวณบ้านซึ่งล่าง ถึง บ้านบ่อล่าง อำเภอลง จังหวัดจันทบุรี (บริเวณสีส้มในกรอบวงกลม)

3.2 งานวิจัยพื้นฐานด้านตะกอนวิทยาของคลื่นสึนามิและคลื่นพายุซัดฝั่ง

ผู้วิจัยและนิสิตปริญญาเอกที่รับทุนจากโครงการ คปก (นาย สุเมธ พันธวงศ์รัช) ได้ดำเนินการสำรวจภาคสนามตามแนวชายฝั่งทะเลไทยในพื้นที่ที่พบตะกอนที่นำพามาสะสมตัวโดยคลื่นพายุซัดฝั่งโดยนำพามาสะสมตัวในรูปแบบของ Washover fans ในพื้นที่อำเภอทับสะแก จังหวัดประจวบคีรีขันธ์ พื้นที่อำเภอท่าชนะ และอำเภอไชยา จังหวัดสุราษฎร์ธานี และแหลมตะลุมพุก จังหวัดนครศรีธรรมราช (รูป 3.2) โดยมีหัวหน้าโครงการเป็นผู้ดูแลโครงการย่อยนี้ ผลการดำเนินงานจนถึงปัจจุบันเป็นที่น่าพอใจยิ่ง พบหลักฐานทางตะกอนวิทยาที่เป็นชั้นพายุโบราณ (paleo-storm deposit) โดยได้ผลิตบทความวิจัยและได้เผยแพร่ในวารสาร Natural Hazards และได้ศึกษาตะกอนพายุปัจจุบันเพื่อเป็นต้นแบบทางตะกอนวิทยา (Sedimentological analog) สำหรับใช้ในการสำรวจตะกอนคลื่นพายุซัดฝั่งในบริเวณอื่นๆ โดยได้เผยแพร่อีกบทความเผยแพร่แล้วในวารสาร Geomorphology (ดูรายละเอียดในภาคผนวก)



รูป 3.2 พื้นที่สำรวจพายุซัดฝั่ง (รูปจาก Phantuwongraj et al., 2013)

บทที่ 4

บทสรุป (Conclusion)

Output จากโครงการวิจัยนี้ที่ได้รับทุนจาก สกว. (*Choowong, M = Corresponding author)

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

- 1.1 Choowong, M*, 2010. Forewarning of M 7.6 earthquake at Andaman Islands: where next? *Current Science*, Vol. 98, No. 8, 1013-1014. ISI Impact Factor (2012) = 0.905
- 1.2 Phantuwongraj, S., and Choowong, M*, 2012. Tsunami versus storm deposits from Thailand. *Natural Hazards*, 63 (1), 30-50. ISI Impact Factor (2012) = 1.639
- 1.3 Phantuwongraj, S., Choowong, M*, Nanayama, F., Hisada, K., Charusiri, P., Chutakositkanon, V., Pailoplee, S., Chabangbon, A. 2012. Coastal Geomorphic Conditions and Styles of Washover Deposits by NE Monsoon from Southern Thailand. *Geomorphology*, 192, 43-58. ISI Impact Factor (2012) = 2.552

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

- 2.1 Lertnork, W., Choowong, M*, Thitimakorn, T., 2010. "Geomorphology and Ground Penetrating Radar Profiles of Holocene Coastal Dune, Western Coastal Plain of the Gulf of Thailand". *Bulletin of Earth Sciences of Thailand*, Vol. 3, No. 1, 17-27.
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3. การนำเสนอผลงานวิชาการระดับนานาชาติ จำนวน 2 เรื่องดังนี้ (ระบุคำขอบคุณ สกว. และรหัสโครงการ)

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- 3.2 Phantuwongraj, S. Choowong, M., Nanayama, F., Hisada, K., 2013. Modern sedimentological analog of storm surge deposits for future paleotempestology study from Thailand. *AOGS 2103*, 23-28 June 2013, Brisbane, Australia (Abstract and oral presentation by first author)

4. การนำเสนอผลงานวิชาการระดับชาติ จำนวน 2 เรื่องดังนี้ (ร่วมกับนิสิตทุน คปก)

- 4.1 Phantuwongraj, S., Choowong, M. Washover deposits by Northeast monsoon along the coastal area in the Southern part of Thailand. *RGJ-Ph.D. Congress XIII*, April 6-8, 2012, Pattaya, Chonburi, Thailand. (Abstract and poster)

4.2 Choowong, M. and Phantuwongraj, S., 2012. Geological evidences of tsunami and storm in Thailand: A sedimentological perspective. การประชุม นักวิจัยรุ่นใหม่พบนักวิจัยอาวุโส สกว. โรงแรมรีเจนท์บีช ชะอำ จังหวัดเพชรบุรี วันที่ 10-12 ตุลาคม 2555 (Abstract and oral presentation)

5. กิจกรรมที่เกี่ยวข้องกับการนำผลจากโครงการไปใช้ประโยชน์

5.1 บทในหนังสือที่เผยแพร่ระดับนานาชาติ (ระบุคำขอบคุณ สกว. และรหัสโครงการ)

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

5.2 หนังสือ "สึนามิในประเทศไทย" เผยแพร่แล้วตามร้านหนังสือทั่วไป (ระบุคำขอบคุณ สกว. และรหัสโครงการ)

- Montri Choowong, 2010. สึนามิในประเทศไทย (Tsunami in Thailand). ANT Office Express Co., LTD, 178 p (ISBN 978-974-225-283-0) (in Thai)

5.3 ตำรา "ธรณีสัณฐานวิทยาพื้นฐาน" ใช้ในการเรียนการสอนระดับอุดมศึกษา เผยแพร่ทั่วไปที่ศูนย์หนังสือจุฬาลงกรณ์มหาวิทยาลัย (ระบุคำขอบคุณ สกว. และรหัสโครงการ)

- Montri Choowong, 2011. ธรณีสัณฐานวิทยาพื้นฐาน (Basic geomorphology). Tienwattana Printing Co., LTD, 202 p (ISBN 978-974-496-747-3) (in Thai)

5.4 เผยแพร่บทความข้อมูลพิบัติภัยในนิตยสาร (ระบุคำขอบคุณ สกว. และรหัสโครงการ)

- มนตรี ชูวงศ์ 2555 เปิดแฟ้มพิบัติภัย หายนะโลกในรอบ 10 ปี บทสัมภาษณ์และบทความนิตยสารแพรว ฉบับวันที่ 25 พฤษภาคม 2555 หน้า 210-214

5.5 บทสัมภาษณ์และบทความเผยแพร่ในสารคดีระดับนานาชาติ (ที่ระบุคำขอบคุณ สกว. และรหัสโครงการ)

- มนตรี ชูวงศ์ 2555 ดาวเคราะห์มนุษย์ (Human Planet) บทสัมภาษณ์และบทความประกอบสารคดีบีบีซี (BBC documentary)

- มนตรี ชูวงศ์ 2556 โลกน้ำแข็ง (Frozen Planet) บทสัมภาษณ์และบทความประกอบสารคดีบีบีซี (BBC documentary)

เอกสารแนบ

1. ผลงานตีพิมพ์ในวารสารวิชาการระดับนานาชาติ จำนวน 3 บทความ (ระบุคำขอบคุณ สกว และรหัสโครงการ) ดังนี้
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Forewarning of M 7.6 earthquake at Andaman Islands: where next?

On Monday, 10 August 2009 at 19:55:39 Universal time (UT) (11 August 2:56 a.m., Thailand local time), an earthquake of surface wave magnitude (M) 7.6 occurred off the coast of Port Blair, Andaman Islands, India¹. This quake (depth at 15 km of 13.991°:93.838°E)² spawned a regional quake which was felt up to some 600 km west of its epicentre. At Thong Pha Phum, Kanchanaburi, western Thailand, the quake started at 2:57 a.m. and persisted for more than 60 s. This earthquake is located about 200 km north of the pre-2004 rupture areas related to the 1941 earthquake (Figure 1).

According to the prediction made before the 2004 Sumatran earthquake³, this recent earthquake of M 7.6 at the northern Sunda Trench was not the first of its kind⁴. An earthquake with a magnitude up to M 8.0 was expected to recur at 157 ± 43 years from the rupture zone of Car Nicobar Islands after 1881 – i.e.

between 1995 and 2081 (refs 5 and 6). At southern Sunda Trench, seismological data reveals that the recurrence of the quake at Sumatra with a magnitude $\geq M$ 9.0 may not be earlier than 140 years from 2004 (ref. 7). Though this M 7.6 earthquake was about 500 km away from the previously expected recurrent zone^{5,6}, it confirmed the probable recurrence in the pre-2004 rupture zone according to the seismological and geological predictions. To date, sedimentological evidence also extends tsunami history for the Sunda Trench region. If the youngest sand sheet beneath 2004 tsunami layer found in Thailand⁸ and Indonesia⁹ is a predecessor of the 2004 Indian Ocean tsunami, the expected recurrence with a similar magnitude of tsunamigenic earthquake at Sumatra is inferred to possibly recur in the next 600 years. These issues challenge the scientists to narrow down the prediction of the recurrence of such a potential mega-tsunamigenic earthquake

spatially and temporally along the Sumatra–Andaman subduction zone. However, the possibility of a local tsunamigenic earthquake should also be taken into account.

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

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

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

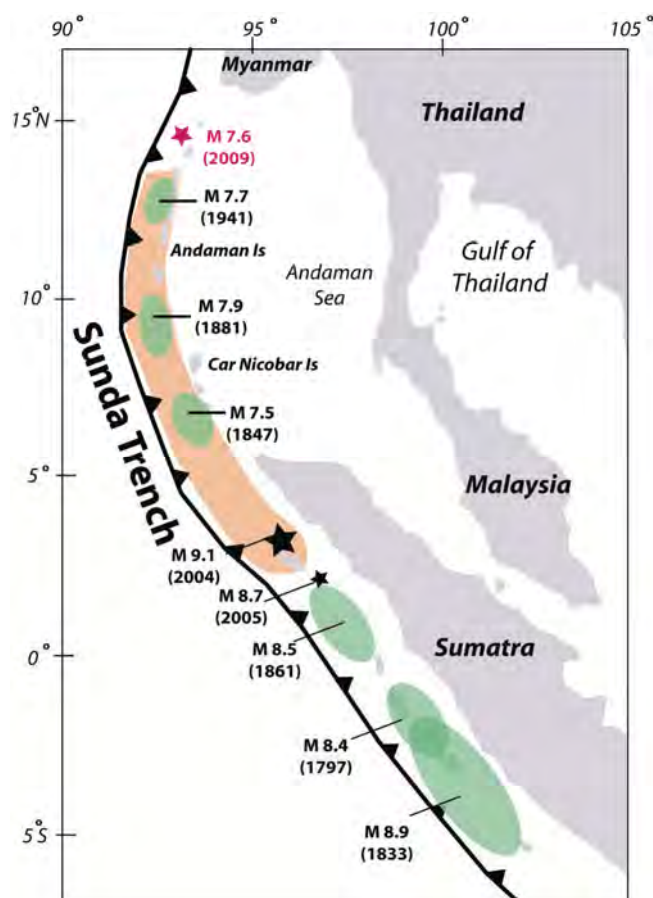


Figure 1. Historical records of submarine earthquakes along Sunda Trench^{3–6}. The 2004 ($M = 9.1$) event at Sumatra rupture extended to Andaman Islands (pale brown)^{7–9}; green circles indicate rupture zone for each event.

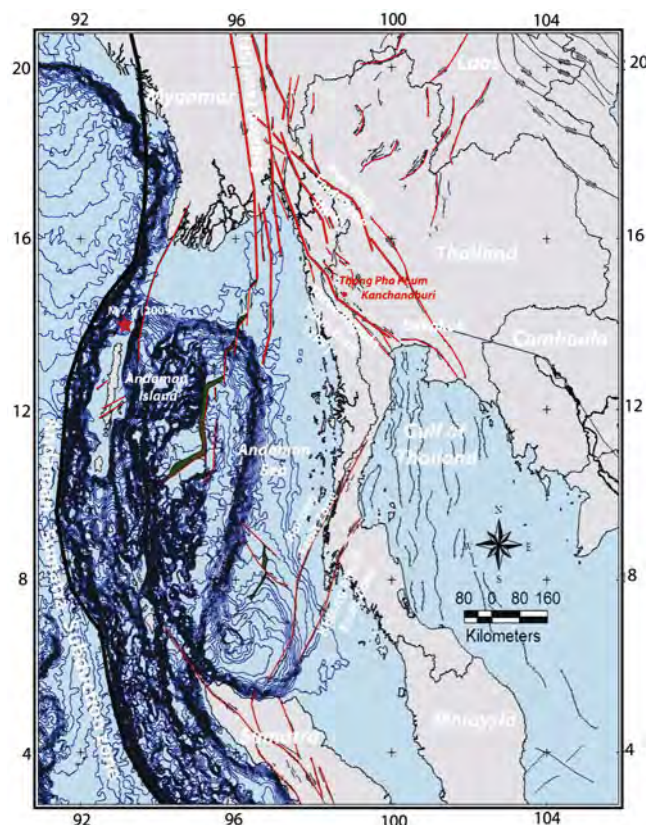


Figure 2. Major active faults (red) with their networks: Sagaing Fault (SF) in Myanmar, Mae Ping Fault (MPF) and Three Pagoda Fault (TPF) in Thailand. Red star represents the recent event of M 7.6 with the epicentre at northern Andaman Islands. Red dot shows the location of Thong Pha Phum, Kanchanaburi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

Andaman subduction zone. Within an hour of the occurrence of the quake, the Pacific Tsunami Warning Centre sent a message alerting all the countries around the Indian Ocean for a possible teletsunami. Fortunately, no teletsunami hit the coastal region and the warning message was withdrawn a couple of hours later. Most importantly, such a M 7.6 earthquake has the potential for local tsunami

generation and what would happen if an earthquake of equal or greater magnitude occurred in the night when people living in Indian Ocean coastal zone are asleep. This event, certainly, cannot be ignored and could be counted as one of the significant signs of early forewarning for future earthquakes and tsunamis that may recur at countries around Indian Ocean. These countries need to plan for the

mitigation of earthquakes and night-time tsunamis that might recur in the next hundred years.

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Tsunamis versus storm deposits from Thailand

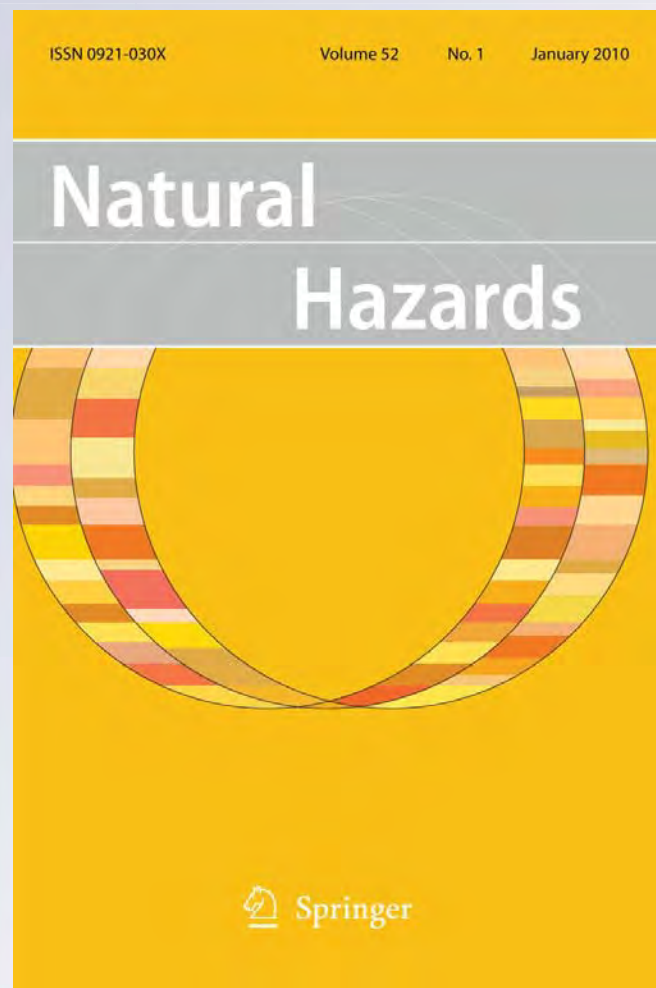
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Tsunamis versus storm deposits from Thailand

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

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

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1 Introduction

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

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

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

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

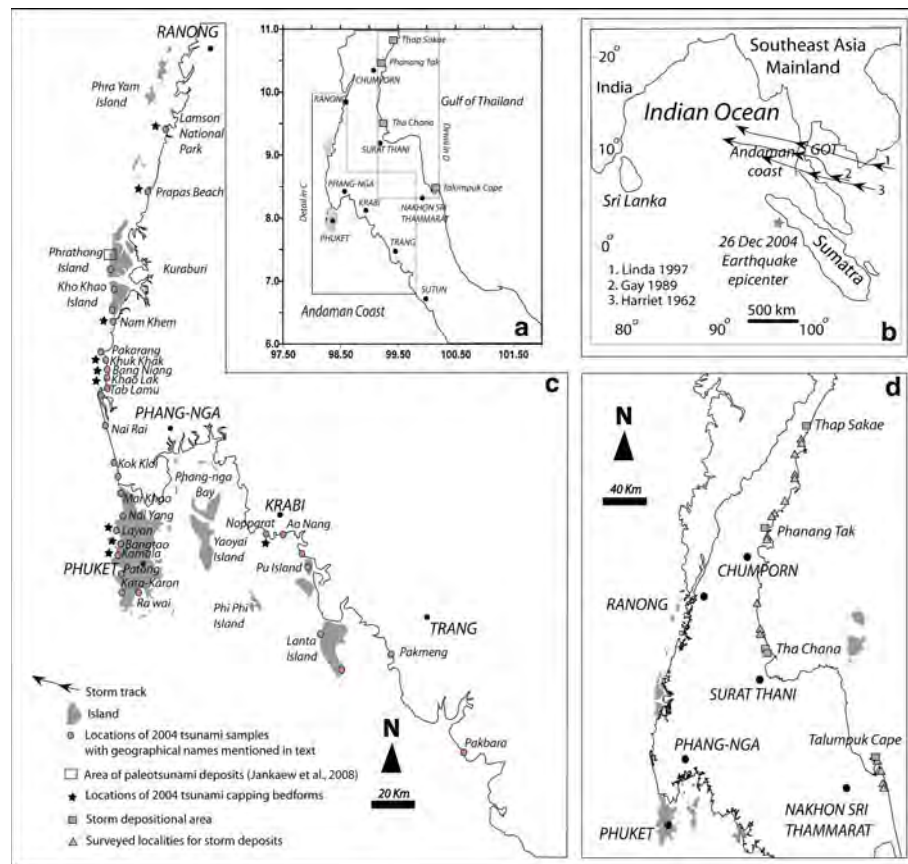


Fig. 1 Setting. **a** Location map of the main geographic provinces from the Andaman and Gulf of Thailand (GOT) coasts. **b** Physiographic map of the Indian Ocean region, the location of the 2004 earthquake epicenter, and records of the three severe storm track ways in the GOT. **c** Sample collection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

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

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

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

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

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

2 Setting and method

We analyzed the sedimentological characteristics of the 2004 tsunami and its precedents from the Andaman coast of Thailand (Fig. 1c, d), whereas, storm deposits were mostly investigated from the GOT coast (Fig. 1a, d). In the case of tsunamis, the characteristics of the 2004 tsunami deposits and its predecessor in Thailand were inferred mostly from Choowong et al. (2007, 2008a, b, 2009) and Jankaew et al. (2008). We, thus, focus in this paper the comparison of the 2004 tsunami and its precedent in one place, where both deposits were officially reported that is the Phrathong Island. In the case of storm deposits,

we based this analysis solely in places where the work by Phantu Wongraj et al. (2008, 2010), Phantu Wongraj and Choowong (2010) was reported. The localities of the geological evidence for the tsunami deposits and the storm-induced washover deposits were recorded and analyzed from more than fifty sites both at the west (Andaman) and the east (GOT) coasts (Fig. 1b, d).

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

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

3 Results

3.1 Characteristics of the 2004 tsunami and predecessor deposits

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

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

Typical 2004 tsunami stratigraphy		Observed sedimentary structures	Inferred flow conditions	
Outflow			Condition	Flow regime
Single normal grading is common		Mud cap Parallel laminae Foreset seaward inclined-laminae with mud drapes	1. Low density of sand in flow 2. High suspended mud content 3. Very low outflow velocity	Lower flow regime (Subcritical flow)
Inflow				
Multiple normal gradings are common		Mud cap Mud drapes Ripples and dunes.	1. Flow velocity } Decrease 2. Grain density } Decrease 3. Flow depth } Increase 4. Time } Increase	Lower flow regime (Subcritical flow)
Normal grading		Antidune		
Reverse grading			Inferred transitional time 1. High density turbulent 2. High flow velocity 3. Limit flow depth 4. Rapid deposition 5. Flat topography	Upper flow regime (Supercritical flow)

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

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

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

3.2 Storm deposits

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

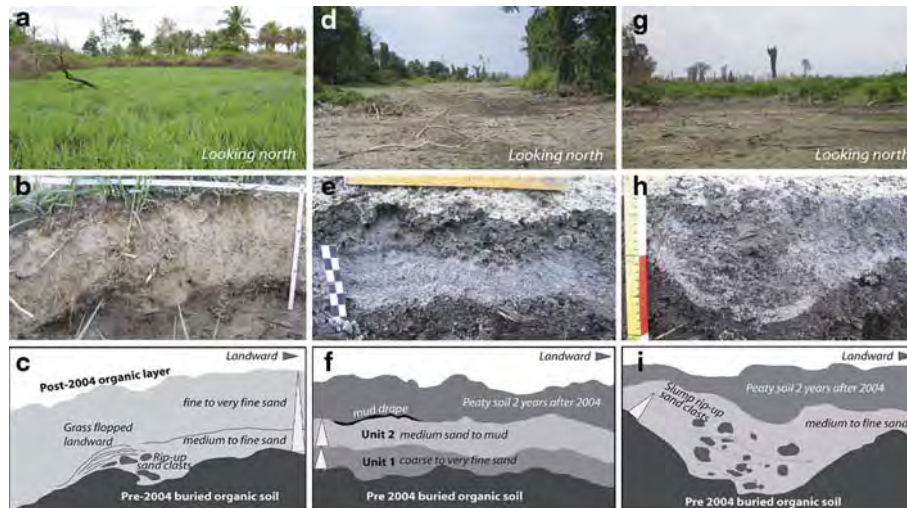


Fig. 2 Internal sedimentary structures of the 2004 tsunami deposited in wet- and dry-swales from Phrathong Island. **a** the nature of dry swale (photo taken in 2006). **b** and **c** the 2004 tsunami deposit with grasses flopped landward and rip-up sand clasts. **d** and **g** wet swale with no bioturbation.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

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

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

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

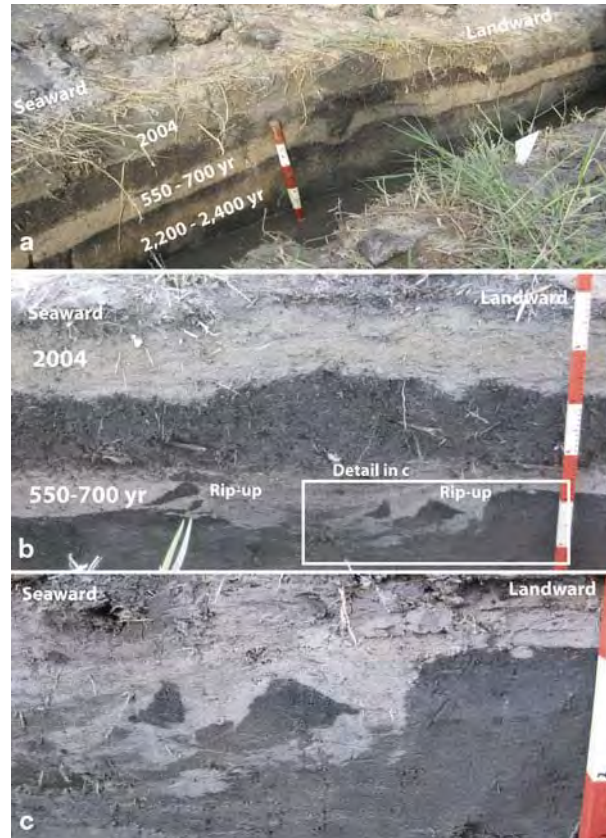


Fig. 3 Sedimentological characteristics of the pre-2004 tsunami deposits from Phrathong Island. **a** three tsunami sand sheets including 2004 on top and ancient deposits at 550–700 years, 2,200–2,400 years (Jankaew et al. 2008). **b** parallel stratifications in the 2004 tsunami, and rip-up clasts in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

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

4 Tsunami versus storm

4.1 Depositional styles and characteristics

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

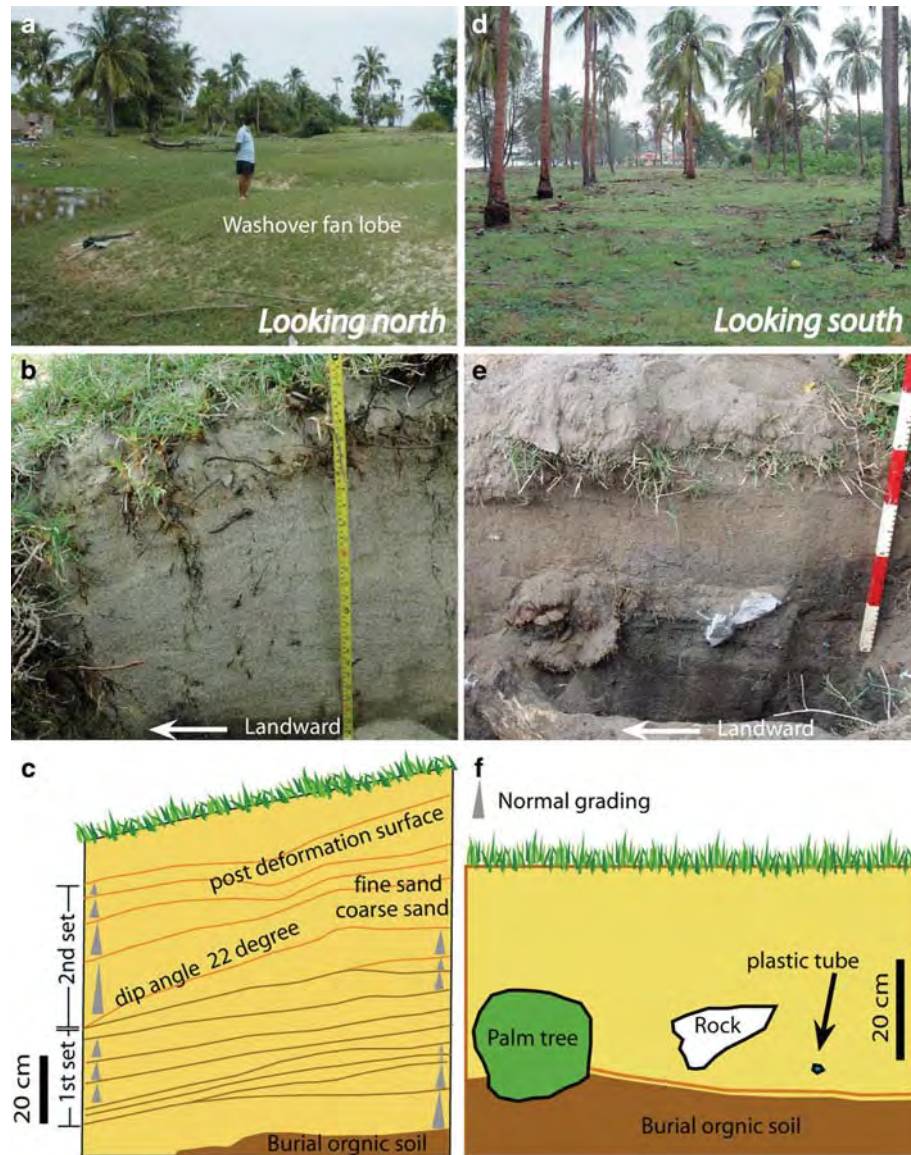


Fig. 4 Storm depositional characteristics from the GOT. **a** morphology of the washover fan lobes from Tha Chana. **b** internal stratigraphy at a distal part of the washover deposits from Tha Chana. **c** sketch of two foreset lamina from **b**. **d** and **e** setting of the area flooded by a storm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

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

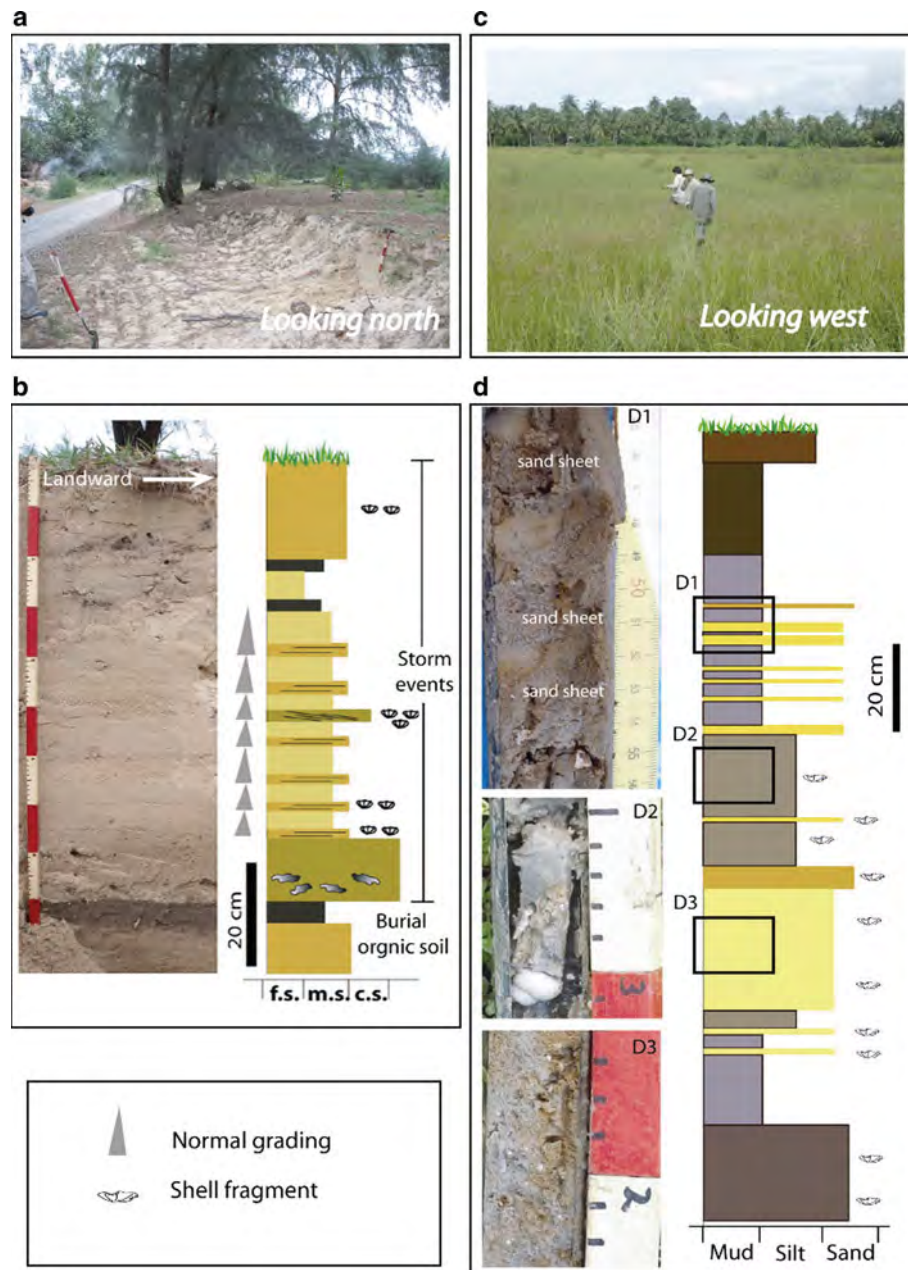


Fig. 5 Modern and ancient storm deposits from the GOT. **a** modern washover features at Talumpuk Cape sand spit. **b** multiple normal gradings in a modern storm-induced washover deposits from **a**. **c** large wet swale at Panang Tak bay. **d** nine sand sheets of candidate ancient storm deposits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

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

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

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

4.2 Flow conditions

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

During the transformation stage, we hypothesize that tsunamis likely entrained much deeper offshore and shoreface sediments than storms did. Benthic fauna found within tsunami and storm deposits may be used to confirm this hypothesis. During the depositional stage, tsunami and storm deposits are generally formed under similar flow patterns. The sedimentary features of the 2004 tsunami and those of storms mostly have similar internal

structures. Within the literature, tsunami deposits contain an enormous variability of features (e.g., planar stratification, inclined lamination, cross-laminations, imbrication of gravels, normal-graded sand, dispersed mud and mudstone clasts, hummocky cross-stratification, etc.). Likewise, many of these features could be found in storms (tempestites) as well.

4.2.1 Transformation stage

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

4.2.2 Depositional stage

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

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

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

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

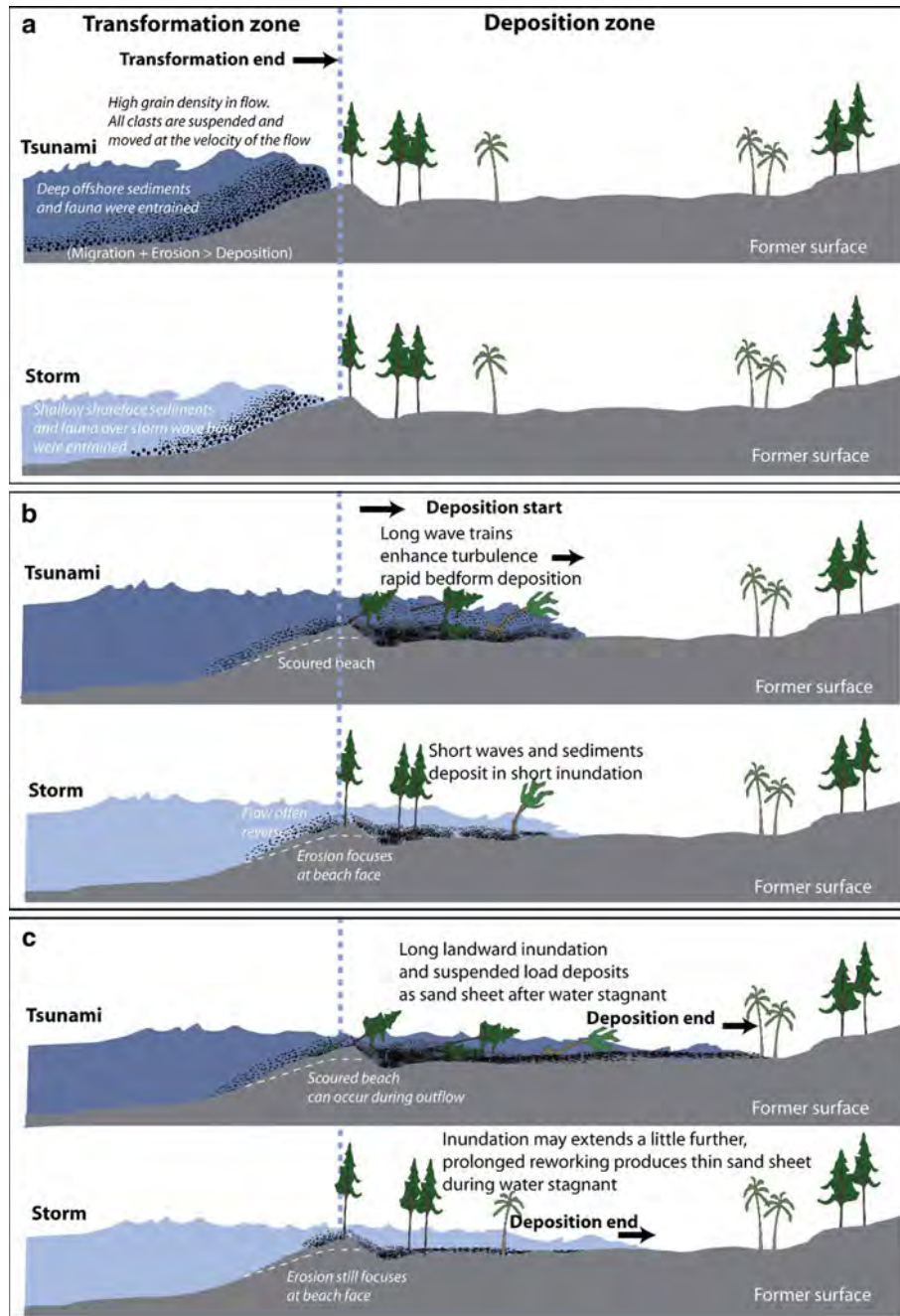


Fig. 6 Schematic model of the flow conditions for a tsunami versus that for a storm. **a** transformation stage. **b** early depositional stage. **c** the end of depositional stage (detail in *text*)

4.3 Depositional and preservation potentials

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

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

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

4.3.1 Type A: Gentle and flat topography

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

4.3.2 Type B: Tidal channel embayment

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

4.3.3 Type C: Swale and beach ridge

Type C has the highest preservation potential for both storms and tsunamis and is deposited on the beach ridge plain and in the swales. This is likely the best environment to trap both

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

4.3.4 Type D: Large-scale irregular topography

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

5 Conclusions

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

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

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

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

Table 2 continued

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

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

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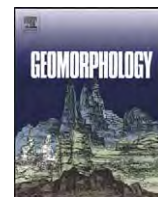
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Coastal geomorphic conditions and styles of storm surge washover deposits from Southern Thailand

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ABSTRACT

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

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1. Introduction

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

In fact, the sedimentary characteristics and physical properties of storm-induced washover deposits have been published since the

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

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

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

The coast of Thailand has also been attacked by storm surges which cause damage to coastal communities. Although, Thailand has experienced storm surges at least three times recently from tropical storms (“Harriet” in 1962, typhoon “Gay” in 1989 and typhoon “Linda” in 1997), only a few reports on the storm deposits have been published (e.g. Roy, 1990). Phantu Wongraj 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 Phantu Wongraj et al. (2010) found multiple layers of paleo-storm sand sheets in a swale located 1 km inland and far away from the present shoreline. However, more detailed studies of the sedimentary characteristics, topographical and flow conditions of the washover deposits induced by storms are still required, particularly for Thailand where so little is known.

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

differences in the sedimentary features found in storm deposits from different geological settings may help geoscientists to understand further what (and how) storms leave behind as their evidence in the geological record.

2. Setting and method

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

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

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

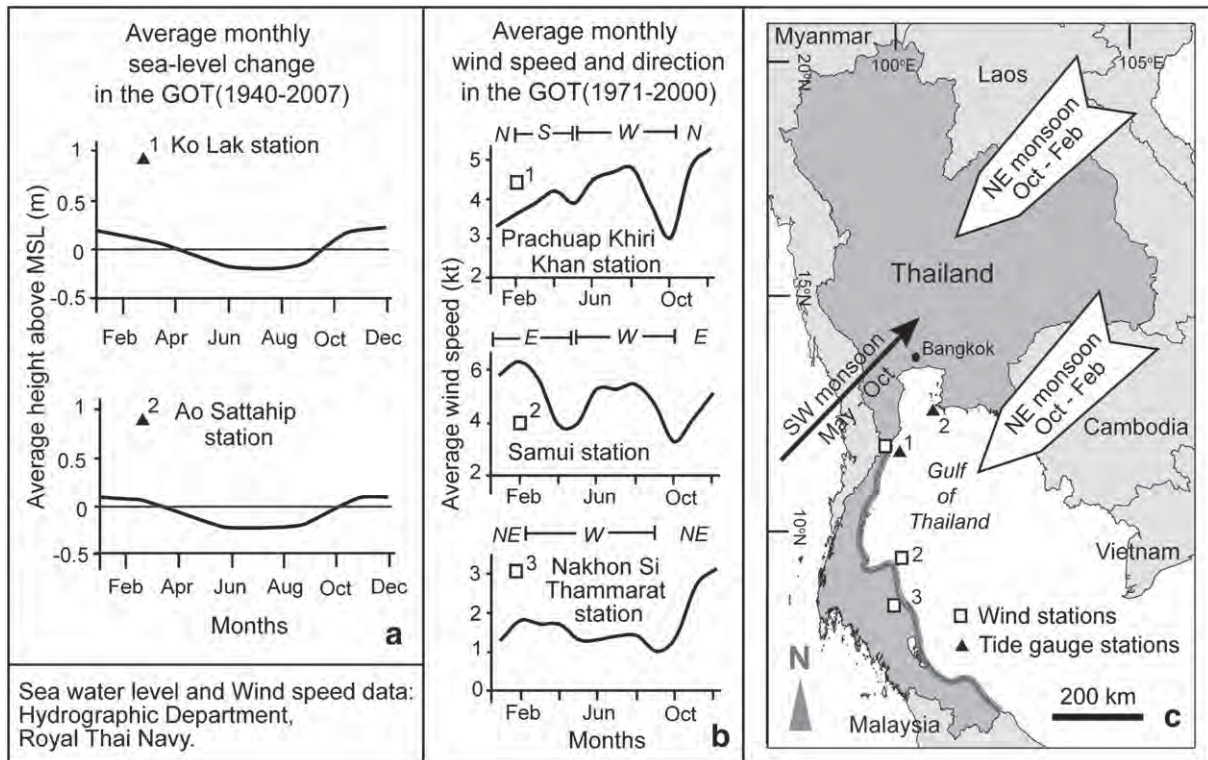


Fig. 1. (a) Average monthly sea-level change in the Gulf of Thailand (GOT) from 1940 to 2007. (b) Average monthly wind speed and direction from 1971 to 2000 from the nearest weather stations to the three study sites. (c) Map demonstrates usual NE and SW monsoon directions in Thailand and location of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

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

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

3. Results

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

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

Lang Suan tide gauge station and significant wave height data (Fig. 3). The maximum inundation distance of the 25th April 2008 storm surge was 100–300 m from the shoreline. The morphology of the wide swale between the relict strand lines also limited the flooding zone from overflow flow in this area.

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

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

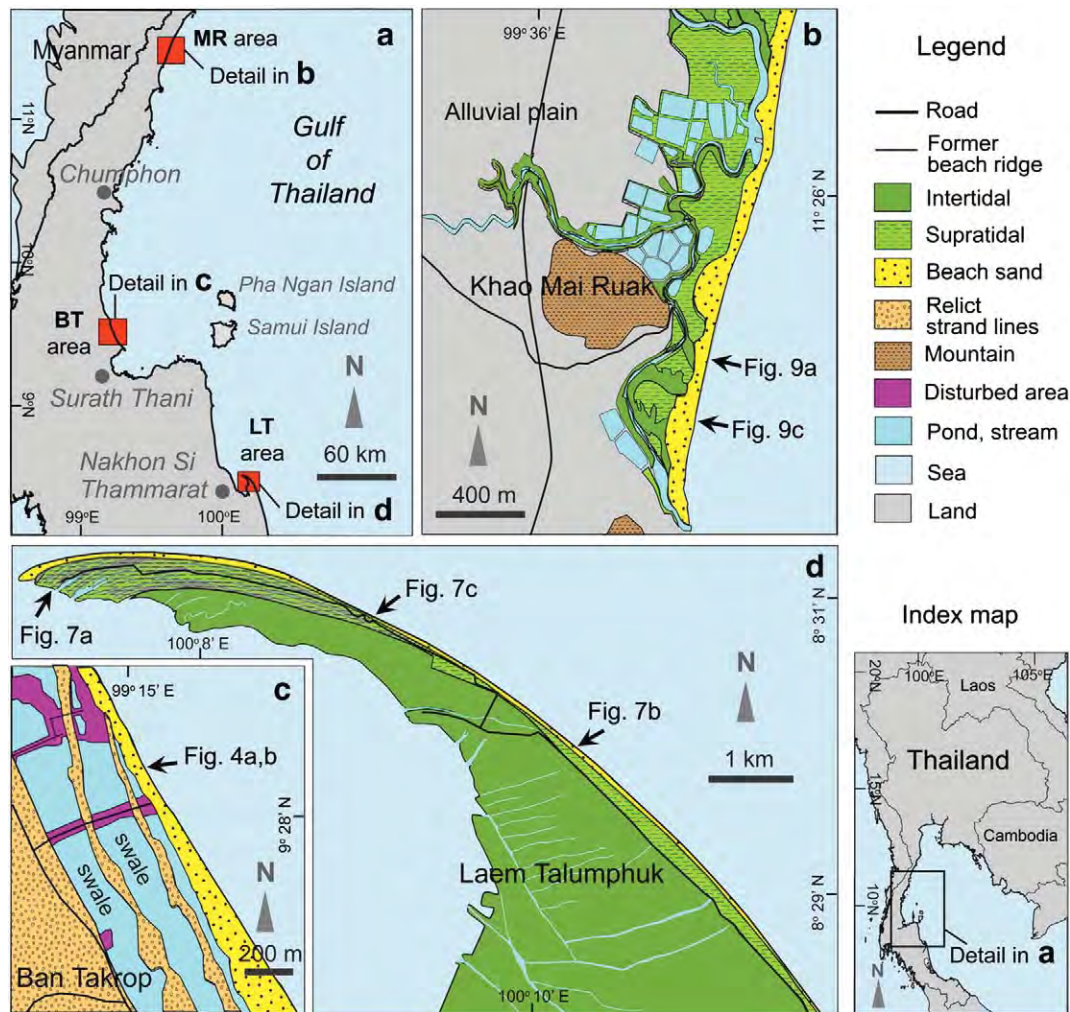


Fig. 2. Geomorphological map of the study sites. (a) The three sites along the GOT, with the geomorphic setting map at (b) Khao Mai Ruak (MR), Prachuap Khiri Khan, (c) Ban Takrop (BT), Surat Thani and (d) Laem Talumphuk (LT), Nakhon Si Thammarat. Also shown are the locations of subsequent figures.

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

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

unusual grain size distribution and grain size value of sample 7, may have resulted from the aeolian process after the storm event. This reworked surface is similar to washover sediments found in Australia that are characterized by two storm layers separated by a thin veneer of sand that has been reworked by aeolian processes (Switzer and Jones, 2008b).

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

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

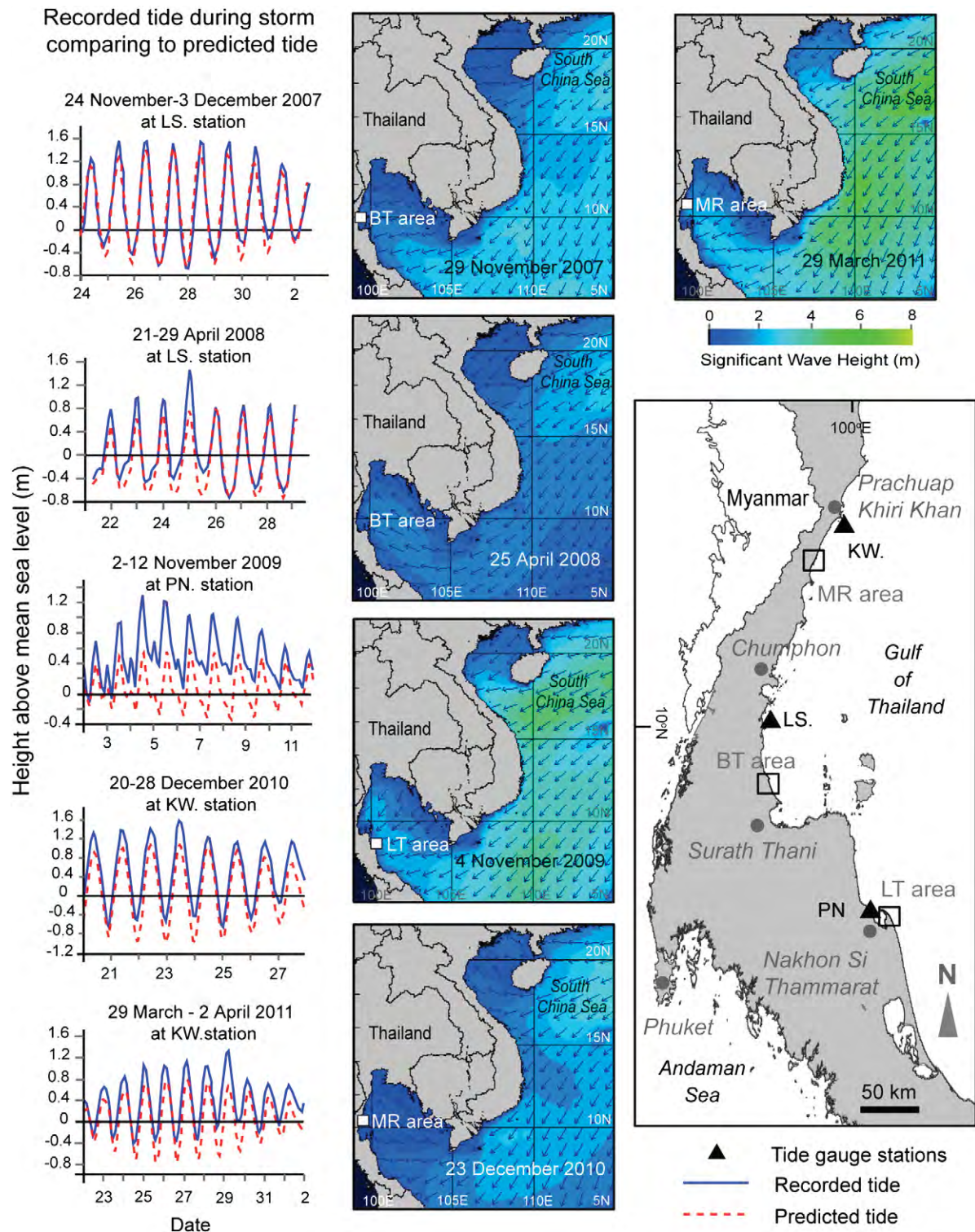


Fig. 3. Records of tide during storm surge from 2007 to 2011 in the study sites from the nearby tide gauge stations (left). Significant wave height and wave direction map in the South China Sea and the GOT during the 2008–2011 overwash events (middle). Location of tide gauge stations and the study sites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

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

LT is an active sand spit, 6 km long and 500–700 m wide with a south–north trending orientation that corresponds to the major present-day longshore current. The spit itself developed an east–west orientation of a series of former beach ridges. The distal part of the spit recurves to the west (Fig. 2d). The spit recently consists of a

relatively small modern beach ridge of about 1–1.5 m above present MSL. Subaqueous sand bars can be seen during low tide while average tidal range here is 0.5 m. During the spring tide, the interval between high and low water level is 0.9 m. During the 4th–5th November 2009, a storm surge induced by temporary NE strong winds flooded over the LT sand spit. The potential storm tide with 2.3 m height was calculated from tide recorded and significant wave height data.

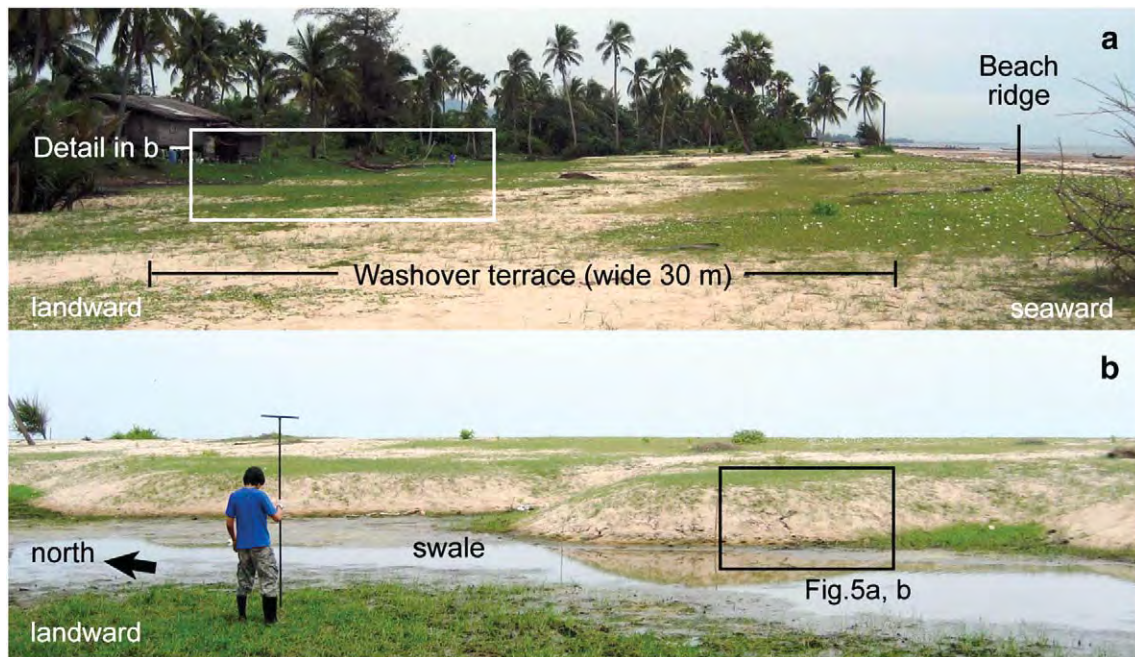


Fig. 4. (a) The washover terrace (wide 30 m cross-shore and long 600 m along-shore) at BT and (b) the washover lobes showing the avalanche face at the distal part of the terrace. Pictures were taken on 2 July 2008.

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

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



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

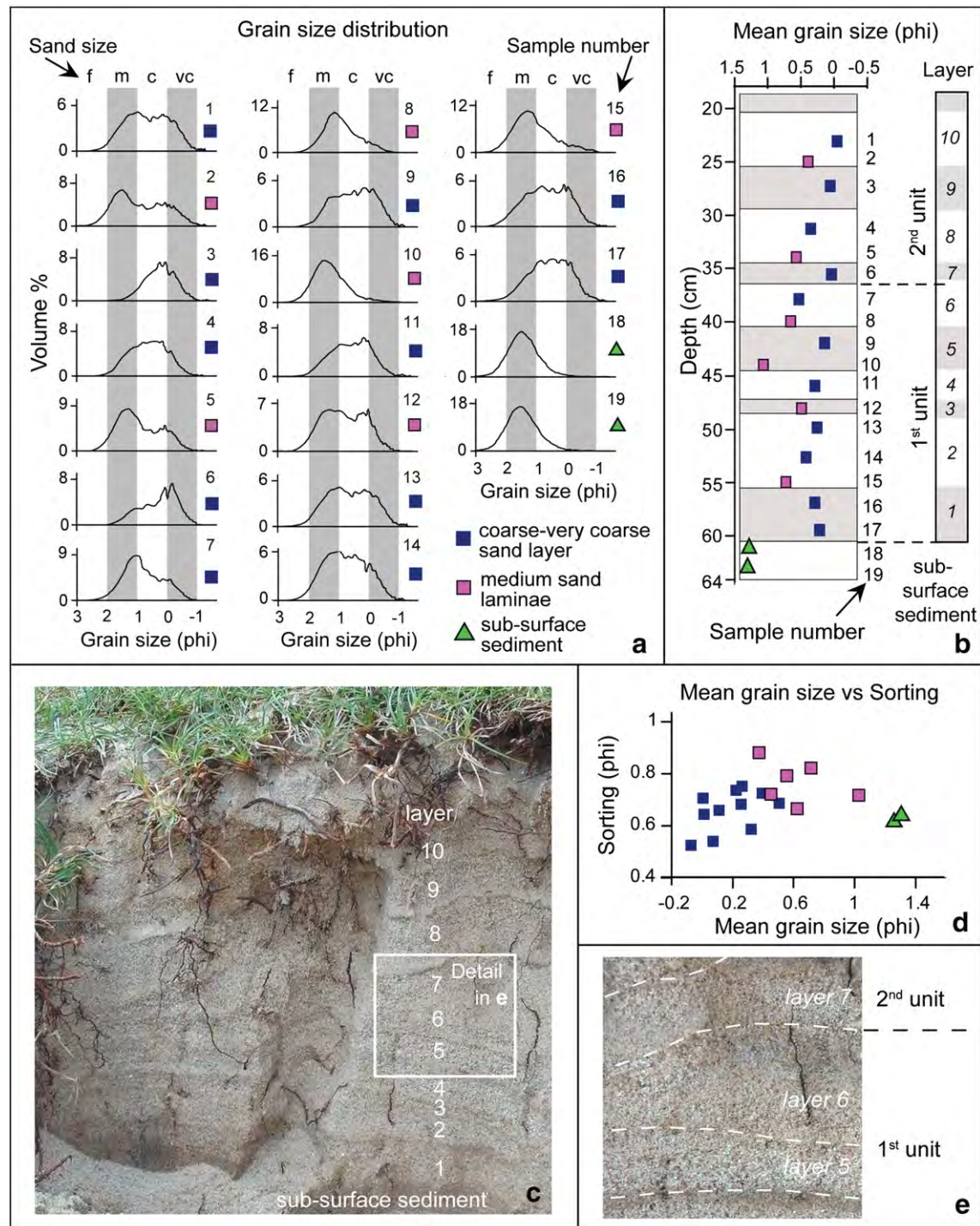


Fig. 6. (a) Grain size distribution graph of washover sediments and pre-storm surface sediments. (b) Average grain size change from top to bottom within the washover deposit and pre-storm surface sediment. (c) The sampling locations (at scour) in the washover deposit. (d) Mean grain size and sorting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

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

We made a small trench where the washover deposit was found on the road behind the beach in order to describe the physical characteristics and sedimentary structures (Fig. 7d, e). The topography behind the beach is exhibited as a slightly flat coastal plain without

swale. Apart from the forested area behind the beach, a compacted surface road 4–5 m in width was constructed parallel to the shore. Washover sediments were found as a sand sheet with a basal sharp contact overlain on the pre-surface soil and the road. Grasses buried at the bottom part of washover sediment were still green, which indicated the recent timing of the washover deposit (Fig. 7e). The dimension of washover body was 25 m in length cross-shore and 8 m in width parallel to shore. The thickness of the washover sediment was relatively uniform at about 15–20 cm on the flat topography (Figs. 7d and 8a).

Two different sedimentary textures were recognized in the washover sand, being the fine sand grain unit at the bottom and the coarse sand grain unit from the middle to the top (Figs. 7e and 8a, b). The fine sand unit was dominated by fine to medium-grained sand containing rip-up clasts of the underlying soil that were then dispersed upwards into the lower zone near the base of the unit. The erosional contact at the bottom of the first unit was found only in the forested area behind the beach but not on the road. The spatial limit of the erosional contact at the base of washover deposit that was found only in the forested area may reflect the difference in overwash flow condition. The compacted surface of the road may act essentially as an armored bed with little to no erosion relative to areas away from the road. Additionally, drag on the flow would be significantly reduced as well when compared to the forested area. The vertical change in the grain size in the unit shows a normal grading from medium sand at the bottom to fine sand at the top. Additionally, in the distal part, a thin layer of dark organic material was found in the uppermost level of unit (Fig. 8c). The source of dark organic layer may come from the sub-surface soil in the forested area behind the beach. This organic layer may indicate a period of waning flow or possibly a falling flood level. The thickness of the 1st unit was confined by the antecedent topography to about 8 cm in the depression of buried soil and 2 cm on a flat road. Subsequently, the second unit, which is composed of coarse to very coarse-grained sand, was deposited on

top of the fine to medium-grained sand unit (Fig. 8b). The coarser grain size in this unit may result from the removal of the fine grain sand from the beach surface by the initial stage of the storm surge, which was then transported to be deposited as the 1st unit and, thus, exposing the less eroded more coarse grain sand on the beach. Subsequently, these exposed coarser sediments were then eroded by the following surges to be deposited as the 2nd unit. The sedimentary characteristics of the 2nd unit was characterized as two multiple layers of coarse sand around 10 cm in thickness which were clearly separated by shell laminae at the base of each layer (Figs. 7e and 8d, e). Normal grading, from very coarse to coarse-grained sand at the bottom to medium grained sand at the top, was revealed in both layers (Figs. 7e and 8e). Dune bedforms (6 cm height and 50 cm in length), oriented perpendicular to shoreline, were recognized in the middle part of the washover deposit. Then, these dunes were gradually transformed into horizontal bedding as it extended further inland (Fig. 8b). The changing of sedimentary structure from dune bedform surface to structureless at the distal part of the washover deposit and the decrease in the overall grain size in the landward direction presumably reflects the decreased flow velocity.

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



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

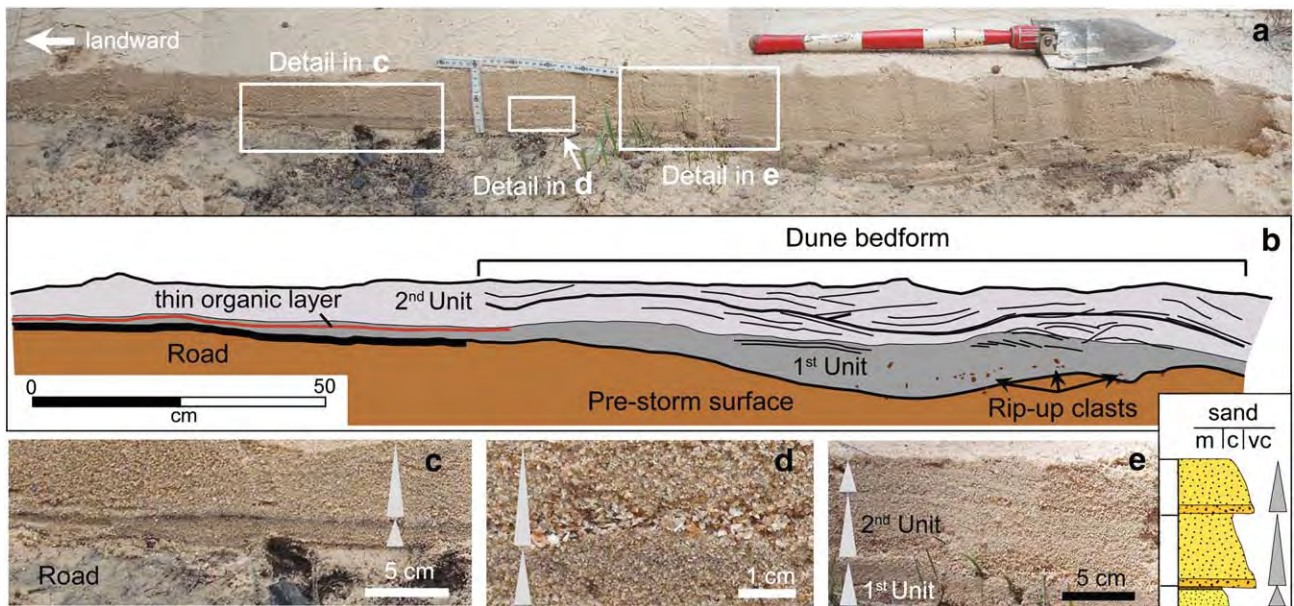


Fig. 8. (a) The internal structure of the washover deposits at LT. (b) A detail sedimentary structure in the washover deposits revealing two sediment units and a dune structure. (c) The thin organic layer found in the distal part of the washover sediment in the 1st unit and (d) shell lag laminae at the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

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

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

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

Apart from erosional features, depositional features were also recognized as washover sediment deposited behind the barrier. At the tidal floodplain behind the barrier, washover sediments were exhibited as

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

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