



รายงานวิจัยฉบับสมบูรณ์

โครงการ แผนที่เสี่ยงต่อพิบัติภัยคลื่นพายุซัดฝั่งตามแนวชายฝั่งอ่าวไทย

โดย ศาสตราจารย์ ดร. มนตรี ชูวงศ์ และ
อาจารย์ ดร. สุเมธ พันธุ์วงศ์ราช

มกราคม พ.ศ. 2562

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คณะผู้วิจัย

สังกัด

ศาสตราจารย์ ดร. มนตรี ชูวงศ์
อาจารย์ ดร. สุเมธ พันธุ์วงศ์ราช

ภาควิชาธรณีวิทยา คณะวิทยาศาสตร์
ภาควิชาธรณีวิทยา คณะวิทยาศาสตร์

สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัยและ
จุฬาลงกรณ์มหาวิทยาลัย

(ความเห็นในรายงานนี้เป็นของผู้วิจัย สกว. และจุฬาลงกรณ์มหาวิทยาลัย
ไม่จำเป็นต้องเห็นด้วยเสมอไป)

บทคัดย่อ

เหตุการณ์พิบัติภัยทางธรรมชาติได้เกิดขึ้นในหลายภูมิภาคของโลกในช่วงกว่าสิบปีที่ผ่านมา โครงการนี้มีเป้าหมายเพื่อทำการวิเคราะห์ความเสี่ยงต่อพิบัติภัยคลื่นพายุซัดฝั่งของพื้นที่ชายฝั่งอ่าวไทย เน้นไปที่คลื่นจากมรสุมและพายุไต้ฝุ่นที่มีโอกาสเกิดขึ้นบ่อยครั้ง ที่จำเป็นต้องวิเคราะห์ถึงสาเหตุ ผลกระทบในเชิงพื้นที่เพื่อนำมาออกแบบการเตรียมการป้องกันบรรเทาภัยที่จะเกิดขึ้นในอนาคต ระเบียบวิธีการดำเนินงานของโครงการเริ่มจากการค้นหาประวัติในอดีตว่าพื้นที่ใดเคยเกิดเหตุการณ์คลื่นพายุซัดฝั่งท่วมขึ้นมาในแผ่นดินโดยใช้หลักฐานทางตะกอนวิทยาหรือชั้นตะกอนที่เกิดการสะสมตัวในช่วงพายุมาเป็นตัวกำหนด ได้ทำวิจัยพื้นฐานในการสร้างองค์ความรู้ในเรื่องการวิเคราะห์ประวัติของพื้นที่ชายฝั่งในเชิงวิวัฒนาการการเกิดของพื้นที่ที่สัมพันธ์กับการเปลี่ยนแปลงของระดับน้ำทะเลในอดีตควบคู่ไปกับการค้นหาตะกอนพายุ โดยมีผลการวิจัยโดยสรุป คือพบชั้นตะกอนพายุในอดีตในหลายพื้นที่โดยเฉพาะพื้นที่เศรษฐกิจ พื้นที่ชุมชน แหล่งท่องเที่ยวและเกษตรกรรมในปัจจุบัน ได้ผลการวิเคราะห์ประวัติของพื้นที่ในเชิงวิวัฒนาการชายฝั่งแล้วหลายพื้นที่ ได้แก่ พื้นที่ชายฝั่งทะเลจังหวัดเพชรบุรี พื้นที่อุทยานแห่งชาติเขาสามร้อยยอด จังหวัดประจวบคีรีขันธ์ โดยผลงานที่เป็นเป้าหมายหลักของโครงการคือการกำหนดพื้นที่เสี่ยงต่อคลื่นพายุซัดฝั่งในรูปของแผนที่แสดงความเสี่ยงต่อพิบัติภัยคลื่นพายุซัดฝั่งในเบื้องต้นที่บูรณาการข้อมูลตั้งแต่อดีตมาจนถึงปัจจุบันได้ในบริเวณชายฝั่งทะเลอ่าวไทยตอนบน โดยหลักการรวมถึงวิธีการในการสำรวจทางธรณีวิทยาของคลื่นพายุซัดฝั่งนี้จะเป็นต้นแบบให้นักวิจัยรุ่นหลังสานต่อเพื่อวิจัยในระดับลึกได้ต่อไป

คำสำคัญ พายุหมุนเขตร้อน วิวัฒนาการชายฝั่ง ตะกอนคลื่นฝั่ง แผนที่เสี่ยงต่อพายุ

Abstract

In the past decades, natural hazards have been occurring all around the world. This research project aimed at analyzing the risk from tropical storm and monsoon surges in the coastal area of the Gulf of Thailand. The detail study focusing on the cause and spatial effect is necessary for modeling the future mitigation plan. The work methodology involved the search for the history of overwash process (i.e. storm surge) that induced flooding into the coastal zone using sedimentological and additional geological evidences. Sedimentological clues are of significant geological evidences to indicate the area where there used to attack by storm. Not only recurrence period of storm surges was studied in this work, but also inclusive of basic geological background of the area, i.e., the evolution. As a result, this project was successfully described the evolution of the storm attacked areas from Petchaburi and Sam Roi Yot national park, Prachuap Khiri Khan as the case study. Definitely, although the main final output was set up to create the preliminary mapping of storm attacked area in the past to present, the standard method of geological survey regarding how to recognize storm depositional layers is also the additional output that can be the analog for young researcher to further the similar work in the future.

Keywords: Tropical storm, coastal evolution, washover deposit, storm hazard map

Executive Summary

Project title: Storm Surge Hazard Map along the Coast of the Gulf of Thailand

Principle Investigator: Professor Dr. Montri Choowong

Co-investigator: Dr. Sumet Phantuwongraj

Research problem and its significance

Currently, coastal communities along the Gulf of Thailand (GOT) are suffering from the natural hazards in different levels, especially severe erosion by unusual surge from tropical storm and monsoon surge. The recent protection is prioritized in place where economic zone is addressed first. Several patterns of breakwater sea walls were limited for solving the coastal erosion problem, not really inclusive of severe unusual surge like storm. However, the need for detail analysis may arise from (1) a lack of the better understanding in coastal processes and (2) lack of reliable oceanographic and geologic analyses. As long as both data sets have not been systematically studied, the mistake on mitigation and protection plan would be frequently occurred. The systematic research methodology as mentioned earlier was, therefore, carried out in this project in order to better understand coastal process within each selected small coastal sector. We mostly emphasized on the analysis in behavior of wave, longshore current in relation to bathymetry and morphology in each coastal sector. The storm hazard map was preliminary created from site specific area where storms used to inundate into the coastal lowland area.

The successful discovery of paleo-tsunami deposits at the Andaman west coast has inspired that Thailand has been hit by such a large catastrophic event back about several thousand years ago. On the other side, the east coast of Thailand, bordering the GOT, is seemingly subject to only large damaging typhoon strikes. Most typhoons affecting Thailand originate in the northwestern Pacific Ocean and move in a westerly or northwesterly direction. Many strike the Philippines or China, but some travel west into the South China Sea, making landfall in Vietnam or Thailand. Notable typhoons or tropical storms (powerful cyclonic storms with wind speeds below the threshold for typhoon status) to make landfall on the east coast of Thailand in recent decades include: Tropical Storm Harriet (1962) causing 769 fatalities in southern Thailand; Typhoon Gay (1989), a Category 3 typhoon at landfall which caused over 800 fatalities in Thailand; and Tropical Storm Linda (1997) causing 164 fatalities in Thailand. Therefore, a long-term record of tropical cyclone strikes will enable significant improvement in the estimated recurrence interval of large, damaging typhoon strikes and will represent a step towards a regional database of paleotempestological records for Southeast Asia.

According to Thai's literatures, the paleotempestological research (the study of geological proxies indicating ancient storm deposit) was little conducted, even though this coastline is subject to intense tropical storm struck. Since then, only two international geological publications have been published for Thailand that both are corresponded by the principal investigator of this project (i.e. Phantu Wongraj and Choowong, 2012; Phantu Wongraj *et al.*, 2013). A paleotempestology research in Thailand has been initiated since Phantu Wongraj *et al.* (2008) has firstly published the record of paleo-storm deposit in several locations along the GOT coast. For example, sand sheets of suspected storm surge origin were reported from coastal marshes near Surat Thani and Laem Talum Puk in southern Thailand. Subsequent findings (e.g. determination of the age of the sand sheets) has been published (Phantu Wongraj and Choowong, 2012; Phantu Wongraj *et al.*, 2013). Definitely, this research was a "proof of concept" or a pioneer work among the geological science of coastal hazards of Thailand.

Objectives

The objective of the proposed basic research was to create coastal storm hazard maps in place where paleotempestological studies confirmed the occurrence of storm. The maps will be created mostly from a successful result of identifying and dating geological evidence of historical and the pre-historical tropical cyclone (typhoon) strikes preserved in coastal marshes on the GOT side.

Methodology

This work was carried on subsequently following the international research collaboration between the Thai (Chulalongkorn University) and the University of North Texas (UNT), USA. The work involved the investigation of long-term tropical cyclone strike records for the Thailand coast, which is so-called "paleotempestology". Paleotempestology studies from this project have focused mainly on identifying and dating washover sand layers in coastal marsh sequences located immediately landward of sandy barriers. This geologic proxy approach is based on the premise that, unlike normal storms and tides, a tropical cyclone storm surge overtops the barrier and transports littoral and offshore sand onto a muddy, organic-rich marsh to form an anomalous sand layer. Over time, multiple tropical cyclones are recorded by multiple sand layers separated by muddy, organic-rich sediments. These subsurface sand layers were revealed by trenching and/or coring a coastal marsh along transects oriented perpendicular to the coastline. Tropical cyclone storm surge deposits present in the subsurface were distinguished by a coarser texture and lower organic content than enclosing marsh sediments, by a sharp basal contact, by marine microfossils and by a wedge-shaped profile that thins and fines landward. Identified storm surge deposits were

readily dated by radiocarbon dating because the buried marsh under the deposit usually contains abundant organic material.

Summary of Result

Preliminary reconnaissance

Preliminary reconnaissance of field sites along the GOT conducted in August 2013 and the more survey was then carried out within this project time span by a combination of trenching by spade, gouge coring and vibracoring suggest some more potential sites possible for this research. Shallow trenches excavated by spade provide good exposure of sand beds at a shallow depth; gouge coring (~1-m-long, 1-inch-diameter cores) is a rapid reconnaissance tool, indicating the presence of subsurface sand beds, which are then exposed by trenching or vibracoring.

Detail field investigation and laboratory

In 2013, preliminary field survey was conducted. Several swampy and marsh locations along the coast of GOT were dug by gauge coring. Three sites at Prachuap Khiri Khan and Phetchaburi provinces were dug using vibracoring equipment (a motorized coring device) provides 10-cm-diameter cores several meters in length by driving aluminum core tubes into marsh deposits. It was firstly carried out in middle 2013 and will be conducted and extended more in 2014-2016 in place where candidate layers of paleo-storm are proofed, i.e., Chumphon. Sediment cores are extracted from vibracores by cutting the aluminum tube lengthwise, ensuring the sediment remains undisturbed and providing a large amount of material for sampling.

Sampling, logging and photographing of sand beds revealed by trenching will be conducted in the field. They will transport to Department of Geology, Chulalongkorn University to be opened, logged, photographed and sampled. Specific samples will be collected from sand beds and enclosing marsh deposits for analysis of particle size, organic content and. Additional samples of organic material will be collected from within or immediately below sand layers for radiocarbon age determinations (to be sent out to oversea labs). TL and OSL lab for age dating will be determined at Chulalongkorn University.

Storm surge hazard maps and relate storm events to sea level change

Apart from a result of detail research on paleotempestology, the final product of this project, series of “storm hazard map” that was created mostly based on the occurrence of the historical and pre-historical records of storm or washover deposits. Some coastal sectors of the GOT are not subject to modern storm effect at all, but there may have been hit by pre-historical storm. The evaluation was performed in relation with the records of modern and

ancient storms to find the best coastal sectors for making the preliminary storm hazard map. Unusual storm deposits may reflect the variation in sea level change especially throughout the Holocene when the records of sea level change were confirmed extensively along the coastal zone of the GOT. The discovery of unusual storm events from this project, however, will increase our understanding in change of sea level through time and may extend to help understanding the climate variation in some senses.

Conclusion

1. As for our first step of literature reviews and field reconnaissance, we found some unusual sand layers deposited in swale of Chumphon estuary. We tested our hypothesis that the storm layers may preserve well in paleo-landforms such as swale in between ridges. As a result, we made the study of coastal evolution at Chumphon as the case study area and successfully published 1 paper in "ScienceAsia" journal.
2. We have successfully discovered for the first time the ancient storm records underground at Cha-am, Petchaburi and Kui Buri (south of Sam Roi Yot National Park), Prachuap Khiri Khan. As a result, we published one paper in "Marine Geology" journal with collaboration from Professor. Dr. Harry Williams, University of North Texas. And one manuscript was submitted and under review at "Natural hazards" journal.
3. Two sites mentioned above are selected for detail mapping of ancient storm records together with sea level change and the study of coastal evolution, in particular Sam Roi Yot National Park where the preservation of geological proxies of evolution is high potential. As a result, we have successfully published two papers from this site.
4. We attempted to make preliminary storm hazard map at Petchaburi and Prachuap Khiri Khan coastal areas using our record of ancient storm discovery. However, the map is not 100% completed, but it shows some progressive work that integrated such a detail scientific geological and biological and geographical survey.

ส่วนที่ 1

กล่าวนำ

1.1 ความสำคัญ และที่มาของปัญหา

พิบัติภัยคลื่นพายุซัดฝั่งส่งผลกระทบต่อชุมชนชายฝั่งของประเทศไทยตลอดมา และได้สร้างแรงกระตุ้นให้นักวิจัยทางธรณีวิทยาในการค้นหาคำตอบว่าเหตุการณ์คลื่นพายุซัดฝั่งมีกระบวนการเกิดอย่างไร มีกลไกทางธรณีวิทยาและสมุทรศาสตร์เป็นอย่างไร และมีโอกาสเกิดเหตุการณ์เช่นนี้อีกหรือไม่ในอนาคต โดยสภาพภูมิประเทศของอ่าวไทยนั้นอยู่ในเส้นทางของพายุหมุนเขตร้อน (Tropical storm) ที่ในอดีตได้พัดผ่านสร้างความเสียหายมาแล้วหลายลูก อย่างไรก็ตาม ด้วยเทคโนโลยีปัจจุบัน การคาดการณ์การเกิดพายุมีความก้าวหน้าไปอย่างมาก สามารถระบุได้ถึงวันและเวลาการเคลื่อนตัวของพายุได้อย่างชัดเจน ซึ่งเป็นสิ่งที่ดีในการวางแผนป้องกันและบรรเทาสาธารณภัยในพื้นที่ชายฝั่งได้ อย่างไรก็ตาม ในวงวิชาการธรณีวิทยา ยังมีความจำเป็นที่จะต้องวิเคราะห์ช่วงเวลาคาบวิบัติซ้ำของการเกิดพายุเพื่อการวางแผนในระยะยาว เพื่อเตรียมรับมืออย่างเป็นระบบตามระดับความเสี่ยงของแต่ละเหตุการณ์ที่คาดการณ์ได้ โดยเฉพาะข้อมูลวิจัยระดับลึกที่เป็นที่ยอมรับในสากลสามารถนำมาเป็นพื้นฐานกำหนดเป็นแผนยุทธศาสตร์และกำหนดนโยบายป้องกันและบรรเทาภัยได้อย่างยั่งยืน

ด้วยความก้าวหน้าของการวิจัยทางวิชาการธรณีวิทยาในประเทศไทยจนถึงปัจจุบัน ผู้วิจัยมีความมั่นใจว่าถึงเวลาแล้วที่ต้องรวบรวมนำผลการวิจัยระดับลึกมาเผยแพร่และถ่ายทอดให้กับสังคมส่วนรวมเพื่อให้ทราบข้อมูลระดับลึกที่แท้จริง ที่สำคัญเป็นข้อมูลที่ผ่านการกลั่นกรองทางวิชาการวิทยาศาสตร์กายภาพแล้ว มีความน่าเชื่อถือทางวิชาการมากที่สุด ผ่านกระบวนการวิจัยเชิงลึกอย่างแท้จริง และที่สำคัญกระทำโดยนักวิจัยไทยที่ตั้งใจสำรวจและวิเคราะห์ข้อมูลอย่างละเอียด เป็นกลุ่มนักวิจัยที่วิเคราะห์อย่างเป็นระบบ ทั้งนี้เพื่อเป้าหมายในการนำข้อมูลเหล่านี้มาสังเคราะห์และบูรณาการกับศาสตร์ต่างๆ ในการวางแผนป้องกันและบรรเทาพิบัติภัยในอนาคตได้อย่างเต็มประสิทธิภาพและมีประสิทธิภาพอย่างแท้จริง ที่สำคัญเป็นผลงานที่เกิดจากนักวิจัยไทยที่จะเป็นต้นแบบให้มีการพัฒนาองค์ความรู้เพื่อเป็นแนวทางให้กับนักวิจัยในประเทศกลุ่มอาเซียนด้วยกัน เพื่อให้ประเทศไทยเป็นศูนย์กลางการศึกษาวิจัยพิบัติภัยของภูมิภาคอาเซียนในอนาคต

1.2 วัตถุประสงค์ของการวิจัย

1. รวบรวมและจัดทำระบบข้อมูลผลการวิจัยพิบัติภัยคลื่นพายุซัดฝั่งในประเทศไทยและภูมิภาคอาเซียนบางส่วน
2. ศึกษาประวัติคลื่นพายุซัดฝั่งด้วยข้อมูลทางธรณีวิทยา
3. จัดทำแผนที่เสี่ยงต่อพิบัติภัยคลื่นพายุซัดฝั่งในพื้นที่เฉพาะตามแนวชายฝั่งอ่าวไทย

1.3 ขอบเขตของการวิจัย

โครงการนี้ได้เน้นวิเคราะห์ข้อมูลเชิงลึกของคลื่นพายุซัดฝั่ง วิวัฒนาการชายฝั่งที่เคยได้รับผลกระทบจากคลื่นพายุซัดฝั่ง การกำหนดอายุธรณีสัณฐานชายฝั่งในอดีตที่สัมพันธ์กับหลักฐานตะกอนวิทยาที่บ่งชี้ชัดว่าเป็นพื้นที่เคยเกิดคลื่นพายุซัดฝั่ง

1.4 วิธีการดำเนินการวิจัย และสถานที่ทำการทดลอง/เก็บข้อมูล

1. ค้นคว้า สืบหารายงาน บทความวิชาการ รายงานวิจัยที่เกี่ยวข้องกับพิบัติภัยคลื่นพายุซัดฝั่งในประเทศไทยจากหน่วยงานในประเทศและต่างประเทศ วารสารวิชาการระดับชาติและนานาชาติ
2. จัดกลุ่มข้อมูลแยกชนิดของคลื่นพายุซัดฝั่งและวิเคราะห์ในเชิงกระบวนการเกิด สาเหตุ และผลกระทบ
3. สำนักรวบรวมวิทยานิพนธ์ ฐานข้อมูลวิทยานิพนธ์อย่างละเอียดในพื้นที่จังหวัดเพชรบุรีและประจวบคีรีขันธ์ที่ได้รับการคัดเลือกเพื่อเป็นต้นแบบพื้นที่ศึกษา
4. วิเคราะห์สมบัติตะกอน ซากบรรพชีวิน และกำหนดอายุตะกอน
5. สรุปและจัดทำรายงานและข้อเสนอทางวิชาการ

1.5 สรุปรายชื่อรายงานวิจัยและบทความวิจัยทางธรณีวิทยาที่ใช้วิเคราะห์คลื่นพายุซัดฝั่งของโครงการ

รายชื่องานวิจัยโดยนักวิจัยไทยเป็นผู้วิจัยหลัก และบทความจากนักวิจัยนานาชาติ มีดังต่อไปนี้

1. มนตรี ชวงษ์ และวิโรจน์ ดาวฤกษ์ 2545 วิวัฒนาการธรณีสัณฐานชายฝั่งทะเลอ่าวไทยและทะเลอันดามัน รายงานวิจัย ฉบับสมบูรณ์ กองทุนรัชดาภิเษกสมโภช จุฬาลงกรณ์มหาวิทยาลัย 120 หน้า
2. มนตรี ชวงษ์ และปัญญา จารุศิริ, 2548, อัตราการกัดเซาะชายฝั่งจากฝั่งทะเลอันดามันและชายฝั่งอ่าวไทย, รายงานฉบับสมบูรณ์ เสนอต่อ คณะกรรมการการอุดมศึกษาและสำนักงานกองทุนสนับสนุนงานวิจัย (สกว.), 96 หน้า
3. ปัญญา จารุศิริ มนตรี ชวงษ์ จุติมา เจริญจิตรัตน์ วิชัย จุฑะโกสิทธิ์กานนท์ เครือวัลย์ จันทร์แก้ว และ พิษณุ พงศ์ กาญจนพยนต์ 2548 การประเมินผลกระทบทางธรณีวิทยาและกายภาพในพื้นที่ประสบพิบัติภัยเพื่อการฟื้นฟูและการเฝ้าระวังเตือนภัย รายงานวิจัยฉบับสมบูรณ์ เสนอต่อกระทรวงทรัพยากรธรรมชาติและสิ่งแวดล้อม 451 หน้า
4. มนตรี ชวงษ์ ฐาสินี เจริญจิตรัตน์ สุเมธ พันธวงศ์ราช เครือวัลย์ จันทร์แก้ว วิชัยจุฑะโกสิทธิ์กานนท์ และ ปัญญา จารุศิริ ปี ๒๕๕๐ การประเมินผลการฟื้นฟูทางกายภาพภายหลังเหตุการณ์สึนามิ และการสำรวจตะกอนสึนามิปัจจุบันและในอดีตเพื่อประเมินค่าการวิบัติซ้ำของแผ่นดินไหวในทะเลที่ก่อให้เกิดสึนามิ รายงานฉบับสมบูรณ์ เสนอต่อ จุฬาลงกรณ์มหาวิทยาลัย จำนวน ๑๑๕ หน้า
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ส่วนที่ 2

ผลการดำเนินงาน

2.1 ข้อมูลพื้นฐานของคลื่นพายุพัดถล่มฝั่ง

พายุ เป็นปรากฏการณ์ทางชั้นบรรยากาศเกิดขึ้นมาจากการเคลื่อนที่ของอากาศอย่างรวดเร็วและรุนแรง อันเนื่องมาจากอากาศ 2 บริเวณมีอุณหภูมิต่างกัน ทำให้มีความกดอากาศที่ต่างกันอย่างมาก ซึ่งอากาศที่ร้อน (อุณหภูมิสูง และ ความกดอากาศต่ำ) จะลอยตัวสูงขึ้น ตามมาด้วยอากาศที่เย็น (อุณหภูมิต่ำ และ ความกดอากาศสูง) แทรกตัวเข้ามาในแนวราบทำให้เกิดการปะทะกันระหว่างอากาศ 2 อากาศขึ้น ซึ่งผลต่อมาทำให้เกิดการหมุนของอากาศจนเป็นสาเหตุที่ทำให้เกิดพายุ โดยปกติพายุที่พบในประเทศไทยแบ่งเป็น

1. พายุฝนฟ้าคะนอง (Thunderstorm) เกิดขึ้นในบริเวณที่มีอากาศร้อน และมีความชื้นมากพอสมควร โดยปกติแล้วเกิดขึ้นในบริเวณพื้นที่เขตร้อนในแถบเส้นศูนย์สูตร เมื่ออากาศได้รับความร้อนและลอยตัวสูงขึ้นและมีไอน้ำในบริเวณนั้นมาก ประกอบกับการลดลงของอุณหภูมิ จึงทำให้เกิดการกลั่นตัวควบแน่นของไอน้ำ เกิดเป็นพายุฝนฟ้าคะนอง ซึ่งมักจะมีทั้งลมแรง ฟ้าแลบ ฟ้าร้อง และมีฝนตกหนักเกิดขึ้นพร้อมกัน

2. พายุหมุนเขตร้อน (Tropical cyclone) เป็นพายุหมุนที่เริ่มก่อตัวมาจากหย่อมความกดอากาศต่ำที่เกิดขึ้นในเขตร้อนบริเวณเส้นศูนย์สูตร โดยส่วนมากมักเกิดบริเวณผิวน้ำทะเลและมหาสมุทรที่มีอุณหภูมิสูงอย่างน้อย 26.5 องศาเซลเซียส มีลักษณะเป็นพายุหมุนขนาดใหญ่ ที่มีเส้นผ่านศูนย์กลางประมาณ 100 กิโลเมตรขึ้นไป เกิดขึ้นพร้อมกับลมที่พัดรุนแรงมาก ลมที่พัดเวียนเข้าหาศูนย์กลางจะมีทิศทางการหมุนแบบทวนเข็มนาฬิกาหากเกิดในซีกโลกเหนือ (Northern Hemisphere) หรือเหนือเส้นศูนย์สูตร (Equator) แต่ถ้าหากเกิดในซีกโลกใต้ (Southern Hemisphere) หรือใต้เส้นศูนย์สูตรจะมีทิศทางการหมุนแบบตามเข็มนาฬิกาเนื่องจากแรงคอริโอลิส (Coriolis force) และมีความเร็วสูงสุดอยู่ที่ 120 – 200 กิโลเมตรต่อชั่วโมง ในการพิจารณาความรุนแรงของพายุนั้น เราใช้เกณฑ์ความเร็วลมสูงสุดที่บริเวณใกล้ศูนย์กลางพายุในการแยกแยะเป็น

2.1 พายุดีเปรสชัน (Tropical depression) เกิดขึ้นจากพายุโซนร้อนที่มีความเร็วลดลง โดยมีความเร็วลมสูงสุดใกล้ศูนย์กลางไม่ถึง 63 กม./ชม. (34 นอต) ถ้ามีฝนตกหนักมาก อาจจะทำให้เกิดน้ำท่วมได้ พายุระดับนี้จะเห็นเป็นกลุ่มเมฆหนาที่บ เป็นวงกลม ยังไม่มีแนวเขตเป็นเกลียว หรือ ตาพายุ ชัดเจน

2.2 พายุโซนร้อน (Tropical storm) เกิดขึ้นเมื่อพายุหมุนเขตร้อนขนาดใหญ่อ่อนกำลังลงขณะเคลื่อนตัวในทะเล และความเร็วที่จุดศูนย์กลางลดลงเมื่อเคลื่อนเข้าหาฝั่ง มีความเร็วลมสูงสุดใกล้ศูนย์กลาง 63 กม./ชม. ขึ้นไป (34 นอต) แต่ไม่ถึง 118 กม./ชม. (64 นอต) ฝนที่ตกอย่างหนักทั้งวันทั้งคืนอาจทำให้เกิดน้ำป่าและแผ่นดินถล่ม

2.3 พายุไต้ฝุ่น หรือ เฮอริเคน (Typhoon or Hurricane) มีความเร็วลมสูงสุดใกล้ศูนย์กลางตั้งแต่ 118 กม./ชม. ขึ้นไป (64 นอต) มีระดับความรุนแรงมากที่สุด ในทะเลมีคลื่นลมแรงจัดมาก และอาจมีคลื่นใหญ่ซัดชายฝั่ง ทำให้ระดับน้ำทะเลสูงขึ้นมากจนท่วมอาคารบ้านเรือนริมทะเลได้ พายุระดับนี้มักจะเกิด “ตาพายุ” ขึ้นตรงศูนย์กลางพายุ เป็นบริเวณที่มีความกดอากาศต่ำมากที่สุด ลมสงบ ท้องฟ้าโปร่ง อาจมีเมฆและฝนบ้างเล็กน้อย สำหรับพายุหมุนเขตร้อนที่เคลื่อนเข้าสู่ประเทศไทยส่วนใหญ่เป็นพายุดีเปรสชัน เนื่องจากพายุได้อ่อนกำลังลงก่อนถึงประเทศไทย ส่วนพายุที่กำลังแรงขนาดพายุโซนร้อนหรือไต้ฝุ่นมีโอกาสเคลื่อนเข้าสู่ประเทศ

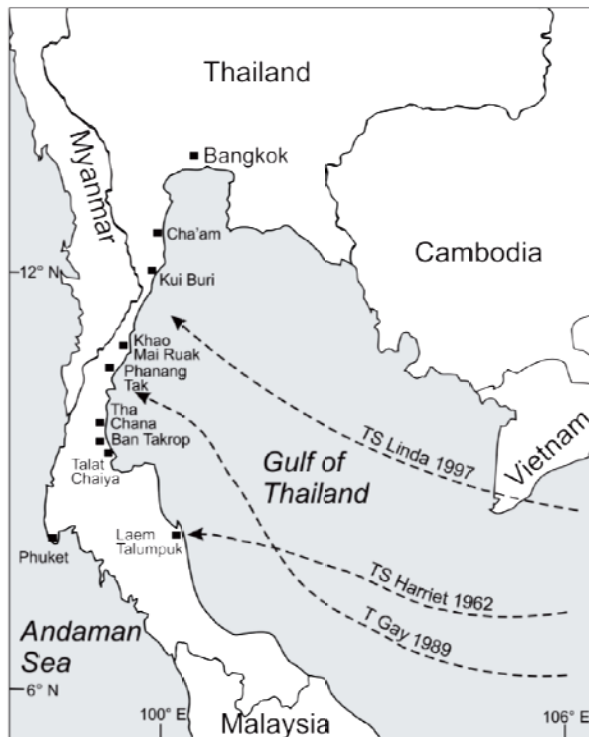
ไทยน้อยมาก พายุเริ่มเคลื่อนเข้าสู่ประเทศไทยตั้งแต่เดือนพฤษภาคมเป็นต้นไป และเดือนตุลาคมเป็นเดือนที่พายุมีโอกาสเคลื่อนเข้าสู่ประเทศไทยมากที่สุด รองลงไปคือเดือนกันยายน

2.2 งานวิจัยทางธรณีวิทยาที่เกี่ยวข้องกับคลื่นพายุซัดฝั่งที่สำคัญ

สำหรับการศึกษาวิจัยทางด้านพายุโบราณนั้น (paleotempestology) เป็นศาสตร์ใหม่ที่ใช้ในการศึกษาเรื่องราวกิจกรรมของการเกิดพายุในอดีตในช่วงเวลาระดับ 100 ปี ถึง 1,000 ปี ซึ่งในอดีตไม่เคยมีการบันทึกทางประวัติศาสตร์ไว้มาก่อนเลย โดยใช้วิธีทั้งทางด้านธรณีวิทยา และเทคนิคในการหาอายุ วิธีการวิจัยอันดับแรก คือ การค้นหาตะกอนที่น้ำทะเลท่วมข้ามแนวสันทรายหรือพื้นที่ชายฝั่งที่ปกติดูต่ำกว่าระดับน้ำขึ้นสูงสุด (washover deposit) ซึ่งเป็นตัวบ่งชี้หลักในกรณีที่เกิดพายุหรือ เหตุการณ์ที่มีพลังสูง (high energy event) โดยกระบวนการของมันก็คือ เมื่อเกิดพายุขึ้น แรงของพายุจะยกน้ำทะเลทำให้มีคลื่นสูงผิดปกติ คลื่นเหล่านี้เรียกว่า คลื่นพายุซัดฝั่ง (storm surge) คลื่นจะพัดเข้ามาบริเวณชายหาดเกิดการกัดเซาะ และพัดพาตะกอนทรายที่ถูกกัดเซาะซึ่งอยู่นอกชายฝั่ง และ/หรือบริเวณชายหาด มาสะสมตัวบนบกในทิศทางเข้าหาชายฝั่ง ซึ่งอาจจะเป็นพื้นที่ต่ำเช่น ที่ราบลุ่มต่างๆ เกิดการสะสมตัวของทรายเกิดขึ้น ในช่วงระยะเวลาผ่านไปหลายปีที่ราบลุ่มต่างๆ เกิดการสะสมตัวขึ้นในสภาพแวดล้อมของตัวเอง เช่นที่ราบลุ่มที่มีแอ่งน้ำขัง จะมีการสะสมตัวแบบตะกอนโคลน แต่หากเราเจาะสำรวจบริเวณชายฝั่งละพบการแทรกตัวของชั้นทรายผิดปกติในการสะสมตัวแบบตะกอนโคลนเกิดขึ้นมา

งานวิจัยที่เกี่ยวข้องกับการค้นหาประวัติของคลื่นพายุซัดฝั่งในประเทศไทยโดยเฉพาะฝั่งทะเลอ่าวไทยเกิดขึ้นในปี ค.ศ. 2008 โดย ดร. สุเมธ พันธุ์จักราช (ในขณะนั้นกำลังศึกษาปริญญาเอก อยู่ที่ภาควิชาธรณีวิทยา คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย) และคณะอาจารย์ที่ปรึกษา ได้รายงานการค้นพบชั้นตะกอนทรายที่แทรกตัวในตะกอนโคลน บ่งชี้ความผิดปกติของการสะสมตัวและได้สรุปว่าเป็นตะกอนที่ถูกนำพามาจากคลื่นพายุซัดฝั่งในช่วงมรสุม ในการประชุมวิชาการนานาชาติ (GREAT 2008) หลังจากนั้น Williams และคณะ (ทีมวิจัยไทยประกอบด้วยผู้วิจัยในโครงการนี้) เผยแพร่บทความการค้นพบในวารสาร Marine Geology ในปี ค.ศ. 2016 ได้ศึกษาค้นหาประวัติของตะกอนพายุตามแนวชายฝั่งอ่าวไทย โดยเป็นการเผยแพร่การศึกษาพายุโบราณที่สมบูรณ์ที่สุดงานแรกในประเทศไทย จากแท่งตะกอนจากพื้นที่ 2 พื้นที่ตามแนวชายฝั่งอ่าวไทย ชายฝั่งชะอำ และที่ลุ่มต่ำ (swale) กุยบุรี พบหลักฐานทางธรณีวิทยาของพายุไต้ฝุ่นที่เข้าปะทะมากถึง 19 ลูกในช่วงระยะเวลา 8,000 ปีที่แล้ว และได้วิเคราะห์ว่าความถี่ของการเข้าปะทะของพายุนั้นเพิ่มขึ้นเป็นหลายเท่าในช่วงอายุตั้งแต่ประมาณ 4,000 ถึง 8,000 ปี

ทีมงานได้ทำการต่อยอดการสำรวจพื้นที่ที่พบการสะสมตัวของตะกอนพายุบนพื้นผิวและใต้ดินได้จากการเจาะสำรวจโดยใช้เครื่องเจาะแบบหมุนมือ (gauge core) เพิ่มเติม โดยได้สรุปพื้นที่ที่จะดำเนินการสำรวจในระดับรายละเอียดคือ ตั้งแต่บริเวณอำเภอชะอำ ของจังหวัดเพชรบุรี อำเภอหัวหิน ปราณบุรี สามร้อยยอด กุยบุรี ของจังหวัดประจวบคีรีขันธ์ และในปีถัดไปได้วางแผนสำรวจเรื่อยไปทางใต้จนถึงตัวเมืองจังหวัดชุมพร ผลการเจาะพบชั้นตะกอนที่มีโอกาสเป็นตะกอนพายุหลายพื้นที่ นอกจากการสำรวจชั้นตะกอนพายุในอดีตแล้ว ทีมงานได้ตั้งโจทย์วิจัยในประเด็นการศึกษาวิวัฒนาการของพื้นที่ที่สัมพันธ์กับการเปลี่ยนแปลงของระดับน้ำทะเลในอดีตไว้ด้วย โดยได้ผลการวิจัยเป็นที่น่าสนใจ



รูป 1 ตำแหน่งพื้นที่สำรวจระดับรายละเอียด และแนวเส้นทางการเคลื่อนตัวของไต้ฝุ่น และพายุหมุนเขตร้อนในอดีตที่ส่งผลกระทบต่อพื้นที่ชายฝั่งเพชรบุรีและประจวบคีรีขันธ์โดยตรง (Williams และคณะ ค.ศ. 2016)

สำหรับผลการดำเนินงานในช่วงปีที่สองของโครงการ นักวิจัยได้เจาะสำรวจเพื่อเก็บตะกอนคลื่นพายุซัดฝั่งในพื้นที่บริเวณแนวที่ลุ่มต่ำหลังแนวสันทราย (swale behind beach ridge) บริเวณตอนใต้ของอุทยานแห่งชาติเขาสามร้อยยอด และพื้นที่ด้านตะวันออกของอำเภอกุยบุรีที่ติดกับชายฝั่งทะเล พร้อมทั้งทำการวัดระดับพื้นที่ตามแนวเจาะสำรวจ และการสำรวจธรณีฟิสิกส์ระดับตื้นโดยสัญญาณเรดาร์ (Ground Penetrating Radar: GPR) (รูป 2 ถึง 5) ได้ผลการสำรวจเป็นที่น่าพอใจเป็นอย่างยิ่ง คือ พบชั้นตะกอนทรายแทรกสลับกับชั้นตะกอนดินโคลนที่คาดการณ์ว่าเกิดจากการสะสมตัวโดยพายุในอดีตหลายชั้น และพบชั้นตะกอนที่เกิดจากการท่วมของน้ำแผ่เป็นรูปพัดบนแนวสันทราย (Washover deposits on top of normal beach ridge) ขณะนี้กำลังดำเนินการประมวลผลและแปลผลสัญญาณธรณีฟิสิกส์

2.3 ผลการสำรวจธรณีฟิสิกส์

จากการออกภาคสนามในวันที่ 20 พฤษภาคม 2559 ที่อำเภอกุยบุรี จังหวัดประจวบคีรีขันธ์ เพื่อทำการสำรวจโครงสร้างการสะสมตัวของสันทรายโดยใช้ GPR- Ground Penetrating Radar ซึ่งเป็นวิธีการทางธรณีฟิสิกส์ โดยการส่งผ่านคลื่นแม่เหล็กไฟฟ้า (Electromagnetic Waves) ลงไปใต้ผิวดิน และรับสัญญาณสะท้อนกลับเพื่อแปลผลจากสัญญาณคลื่นที่ได้ซึ่งแสดงผ่านทางจอคอมพิวเตอร์ โดยในการสำรวจครั้งนี้ได้มีการวางแนว Transect ทั้งสิ้น 4 Transects โดยมีทิศทางตั้งฉากกับชายฝั่งในปัจจุบัน (รูป 2) และแต่ละ Transect ถูกกำหนดด้วยค่าพิกัดจาก GPS และใช้สัญญาณคลื่นความถี่ทั้ง 200 MHz และ 400 MHz ดังนั้นผลลัพธ์จากการทำการสำรวจที่ได้ออกมาจะมีทั้งสิ้น 8 ผล (รูป 3 และ 4) โดยแบ่งเป็น Transect ที่ใช้สัญญาณคลื่น 200 MHz 4 ผล และ Transect ที่ใช้สัญญาณคลื่น 400 MHz 4 ผล โดยความแตกต่างของสัญญาณคลื่น

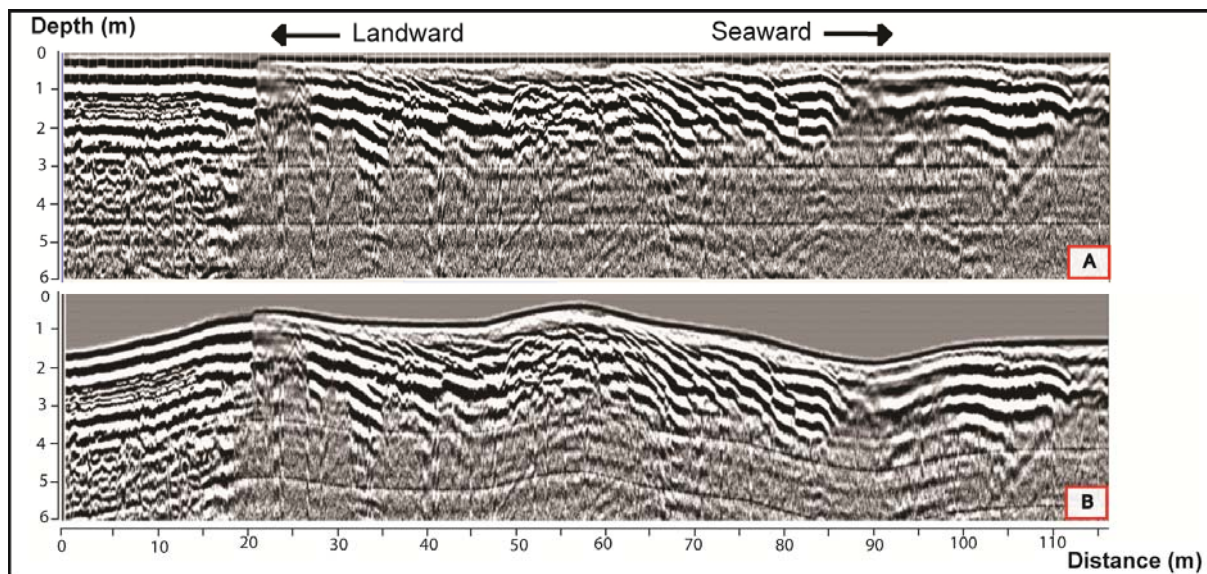
ทั้ง 2 คือ คลื่นสัญญาณ 200 MHz สามารถปล่อยสัญญาณลงไปได้พื้นดินได้มากถึง 6 เมตร ในขณะที่คลื่นสัญญาณ 400 MHz สามารถปล่อยสัญญาณได้เพียง 3 เมตร



รูป 2 ตำแหน่ง Transect ทั้ง 4 ที่ทำการสำรวจโดยใช้ GPR



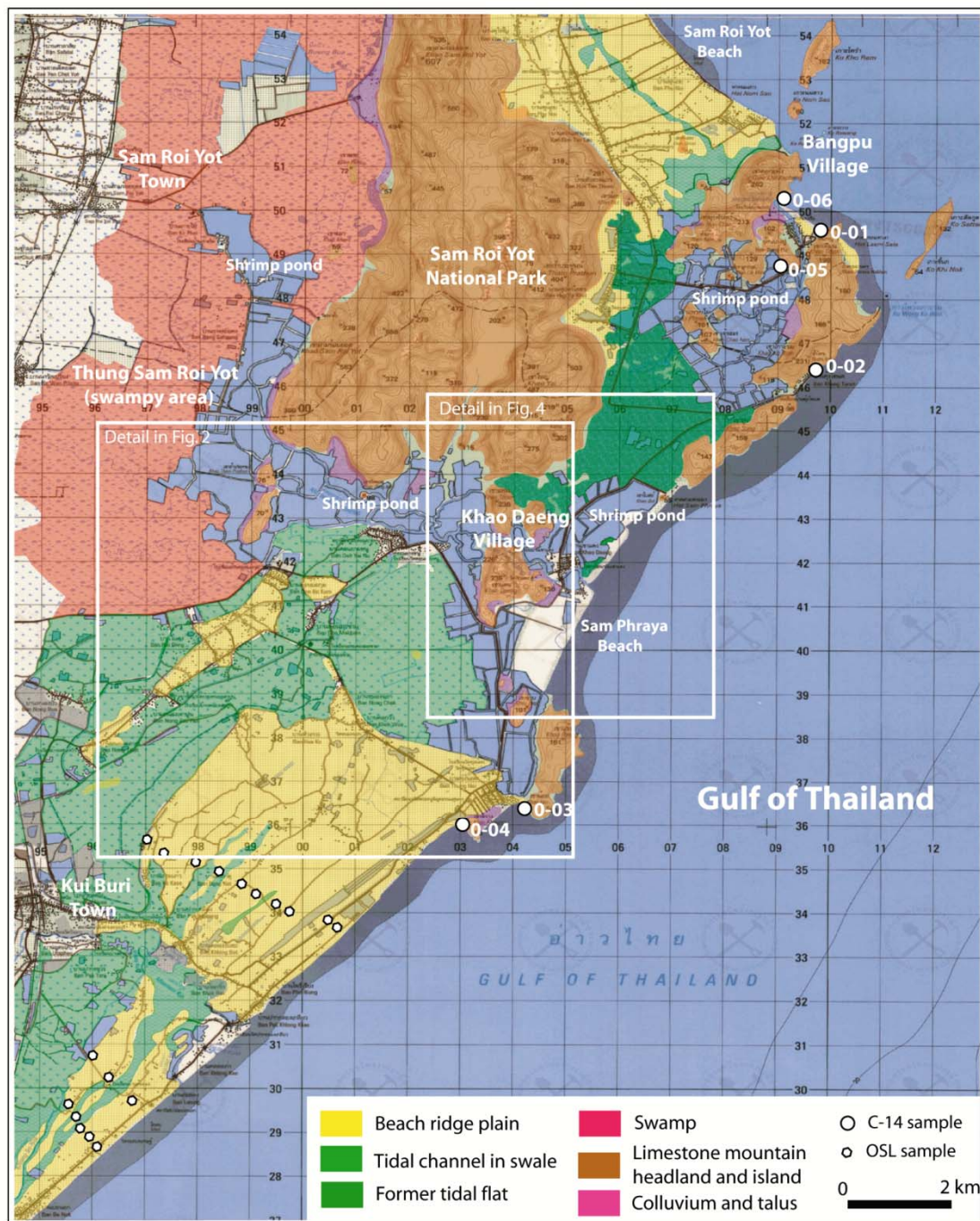
รูป 3 แสดงการลากสำรวจตาม Transect โดยใช้ตัวส่งสัญญาณคลื่น 400 MHz B. ตัวส่งสัญญาณคลื่น 200 MHz C. จอแสดงผลการรับสัญญาณ



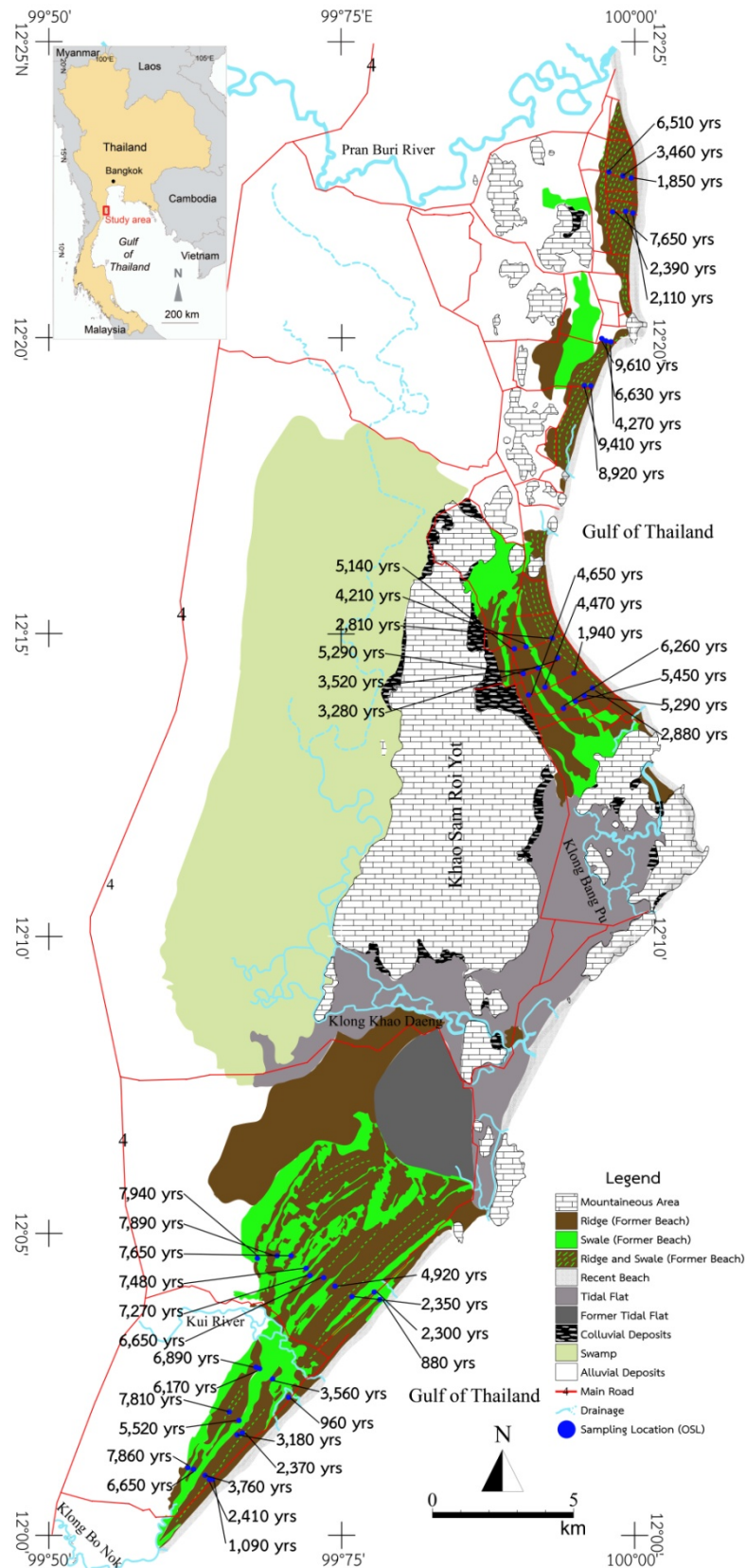
รูป 4 ตัวอย่างภาพผลจากการทำสำรวจโดยที่ยังไม่ได้ปรับแก้ลักษณะภูมิประเทศ (ภาพบน) และภาพผลจากการทำสำรวจโดยที่ปรับแก้ตามลักษณะภูมิประเทศ (ภาพผลจาก Transect ที่ 1 โดยใช้ความถี่ 200 MHz)

2.4 ผลการกำหนดอายุซากบรรพชีวินและตะกอน

ผู้วิจัยได้ทำการเก็บตัวอย่างฟอสซิลที่เกาะผนังของรอยเว้าในหินปูน (Sea notch) และเก็บตัวอย่างทรายเพื่อนำมากำหนดอายุตะกอนโดยวิธีเรืองแสงความร้อน ที่ผลการกำหนดอายุคาดว่าจะทำให้ทราบอายุของแนวสันทรายและสามารถบอกวิวัฒนาการของพื้นที่ที่สัมพันธ์กับการเปลี่ยนแปลงของระดับน้ำทะเลได้ (รูป 5) และตาราง 1 และ 2 และเก็บตะกอนจากบริเวณแนวสันทรายตั้งแต่ปากน้ำปราณบุรี ถึงแนวสันทรายกุยบุรี เพื่อกำหนดอายุโดยการเรืองแสงความร้อน ได้ผลวิวัฒนาการของพื้นที่สำรวจระดับรายละเอียด คือ อุทยานแห่งชาติเขาสามร้อยยอดดังแสดงในรูป 6



รูป 5 แผนที่แสดงพื้นที่อุทยานแห่งชาติเขาสามร้อยยอดที่คณะวิจัยได้ทำการเก็บข้อมูลเชิงลึก เพื่อศึกษาวิวัฒนาการของพื้นที่ชายฝั่งโดยการกำหนดอายุแนวสันทรายและฟอสซิลที่ฝังร่อยვე้าหินปูนที่สามารถช่วยอธิบายประวัติการเปลี่ยนแปลงของระดับน้ำทะเลในอดีตได้



รูป 6 แผนที่แสดงตำแหน่งเก็บตัวอย่างตะกอนและผลการหาอายุด้วยวิธีเรืองแสงความร้อนในบริเวณปราณบุรี ถึงกุยบุรี จังหวัดประจวบคีรีขันธ์

ตารางที่ 1 แสดงผลการกำหนดอายุโดย Radiocarbon (C-14) (ดูตำแหน่งเก็บตัวอย่างในรูป 5)

Sample no.	Notch level	Altitude (m a MHW)	Lab code	Material	$\delta^{13}\text{C}$ (‰)	Conventional Age (yr BP)	Cal. Age (a BP) (2SD)	Mean Cal Age (a BP)
Khao Thian								
O-01	Middle	2.0	IHLC3917	oyster	-12.00	3,400±170	2789 – 3610	3216
Ban Khung Tanot								
O-02	Lower	1.0	IHLC3918	oyster	-12.00	2,480±150	1714 – 2477	2100
Ban Thung Noi								
O-03-1	Middle	1.4	IHLC3919	oyster	-12.00	5,160±160	5062 – 5854	5476
O-03-2	Middle	1.2	IHLC3920	oyster	-12.00	2,140±210	1255 – 2202	1702
O-03-3	Lower	1.0	IHLC3921	oyster	-12.00	1,380±150	641 – 1216	902
Khao Khwang								
O-04	Middle	2.0	IHLC3922	oyster	-12.00	2,680±200	1858 – 2806	2352
Khao Luk Klom								
O-05	Middle	2.5	IHLC3923	oyster	-12.00	3,090±110	2596 – 3159	2851
Ban Bang Pu								
O-06-1	Middle	2.6	IHLC3924	oyster	-12.00	780±180	45 – 633	366
O-06-2	Middle	2.3	IHLC3925	oyster	-12.00	1,060±180	288 – 940	617
O-06-3	Middle	2.0	IHLC3926	oyster	-12.00	2,420±120	1741 – 2314	2028

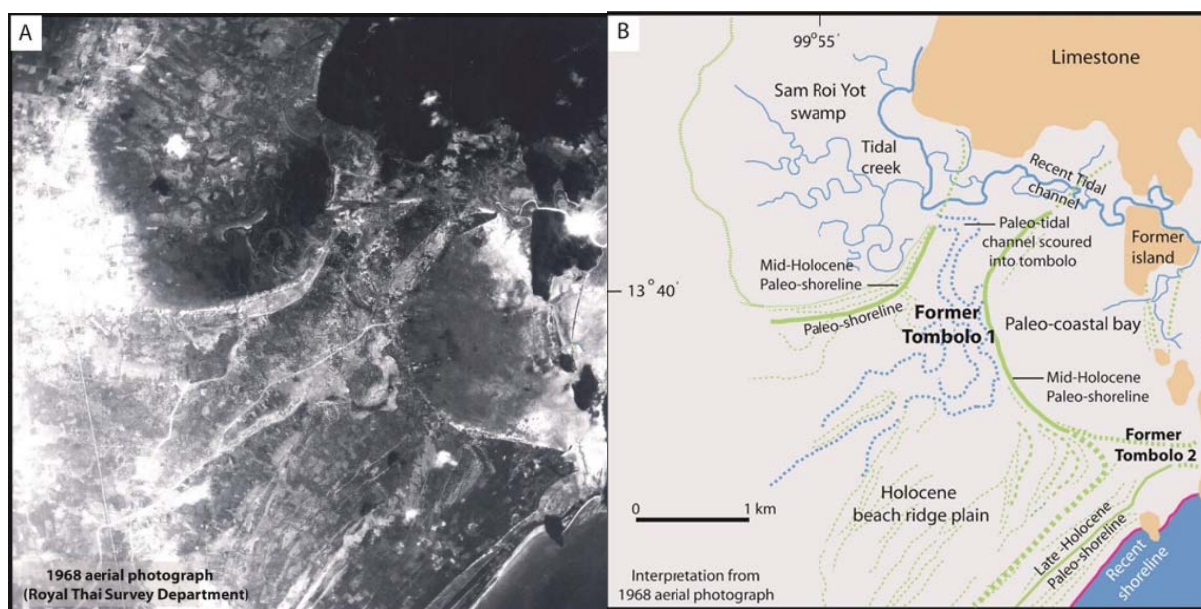
ตารางที่ 2 ผลการกำหนดอายุแนวสันทรายโดยวิธีเรืองแสงความร้อน (ดูตำแหน่งเก็บตัวอย่างในรูป 5)

Sample no.	Lab code	Distance from shoreline (m)	U (ppm)	Th (ppm)	K (%)	Water (%)	De (Gy)	Age (years)	Age (BP)
Transect 1									
K1-1	K1-1	320	0.8±0.1	2.1±0.1	0.4±0.01	5.4	0.92±0.09	1,490±280	1,424±280
K1-2	K1-2	380	0.7±0.1	2.3±0.1	0.5±0.01	22.1	1.41±0.11	2,650±535	2,584±535
K1-3	K1-3	550	0.8±0.1	2.8±0.1	0.3±0.01	2.2	2.91±0.06	4,398±668	4,332±668
K1-4	K1-4	930	0.8±0.1	1.7±0.1	0.3±0.01	4.9	4.39±0.08	7,997±1,460	7,931±1,460
K1-5	K1-5	1070	0.7±0.1	2.4±0.1	0.3±0.01	1.2	3.95±0.02	6,385±1,030	6,319±1,030
Transect 2									
K2-1	K2-1	550	0.8±0.1	2.5±0.1	0.3±0.01	2.1	1.61±0.10	2,533±427	2,467±427
K2-2	K2-2	630	0.8±0.1	2.3±0.1	0.3±0.01	7.3	1.95±0.10	3,353±613	3,287±613
K2-3	K2-3	990	0.7±0.1	2.1±0.1	0.3±0.01	1.0	3.24±0.07	5,730±1,020	5,664±1,020
K2-4	K2-4	1380	0.7±0.1	2.1±0.1	0.4±0.01	4.1	5.16±0.05	8,260±1,320	8,194±1,320
Transect 3									
K3-1	K3-4	260	0.7±0.1	1.8±0.1	0.4±0.01	9.3	0.59±0.01	1,050±185	984±185
K3-2	K3-3	1080	0.8±0.1	3.5±0.1	0.4±0.01	2.0	2.87±0.04	3,597±447	3,531±447
K3-3	K3-1	1600	0.8±0.1	2.6±0.1	0.6±0.01	2.8	6.76±0.12	8,217±1,003	8,151±1,003
K3-4	K3-2	1700	0.8±0.1	2.1±0.1	0.4±0.01	1.8	4.73±0.17	6,958±1,070	6,892±1,070
Transect 4									
K4-1	K4-1	170	0.7±0.1	1.9±0.1	0.3±0.01	2.4	0.63±0.01	1,090±190	1,024±190
K4-2	K4-2	430	0.7±0.1	2.5±0.1	0.5±0.01	12.4	1.76±0.17	2,610±460	2,544±460
K4-3	K4-3	1180	1.0±0.1	2.6±0.1	0.5±0.01	3.2	1.95±0.04	2,310±270	2,244±270
K4-4	K4-4	1500	0.8±0.1	2.6±0.1	0.6±0.01	0.3	4.35±0.06	5,140±608	5,074±608
K4-5	K4-5	1900	0.7±0.1	2.5±0.1	0.5±0.01	1.4	6.08±0.06	7,603±950	7,537±950

K4-6	K4-6	2200	0.8±0.1	2.8±0.1	0.7±0.01	4.0	6.94±0.08	7,865±890	7,799±890
K4-7	K4-7	2480	0.8±0.1	2.7±0.1	0.7±0.01	1.7	6.46±0.17	6,703±713	6,637±713
K4-8	K4-8	3100	1.0±0.1	4.1±0.1	0.7±0.01	2.0	6.88±0.09	6,228±568	6,162±568
K4-9	K4-9	3500	1.2±0.1	5.1±0.1	0.8±0.01	1.8	9.18±0.18	6,830±525	6,764±525
K4-10	K4-10	3800	1.1±0.1	4.7±0.1	1.0±0.01	2.0	10.59±0.35	7,518±590	7,452±590

2.5 ผลการวิเคราะห์วิวัฒนาการพื้นที่ชายฝั่งที่มีหลักฐานคลื่นพายุซัดฝั่ง

ในบริเวณชายหาดเขาสามร้อยยอดยังพบหลักฐานรูปถ่ายทางอากาศที่แสดงให้เห็นการท่วมของน้ำทะเลจากเหตุการณ์พายุซัดฝั่งต่อเนื่องหลายปี (รูป 7) ซึ่งแนวการท่วมนี้สามารถที่จะนำมาช่วยประเมินการลากแนวขอบเขตของการการท่วมของน้ำทะเลจากคลื่นซัดฝั่งได้เป็นอย่างดี นอกจากนี้ผลการหาอายุซากบรรพชีวินและอายุตะกอนในพื้นที่สามร้อยยอดอย่างละเอียด สามารถสร้างแบบจำลองภูมิประเทศเชิงพื้นที่ที่แสดงวิวัฒนาการของชายฝั่งทะเลที่สัมพันธ์กับการเปลี่ยนแปลงของระดับน้ำทะเลได้ (รูป 8)



รูป 7 หลักฐานแสดงการท่วมของน้ำทะเลจากพายุต่อเนื่อง 3 ปี คือ ค.ศ. 1968-1970 บริเวณหาดสามพระยา อุทยานแห่งชาติเขาสามร้อยยอด จังหวัดประจวบคีรีขันธ์ (ภาพบน) และระบบการสะสมตัวของชายฝั่ง barrier island system ที่พบในบริเวณดังกล่าว (ภาพล่าง)

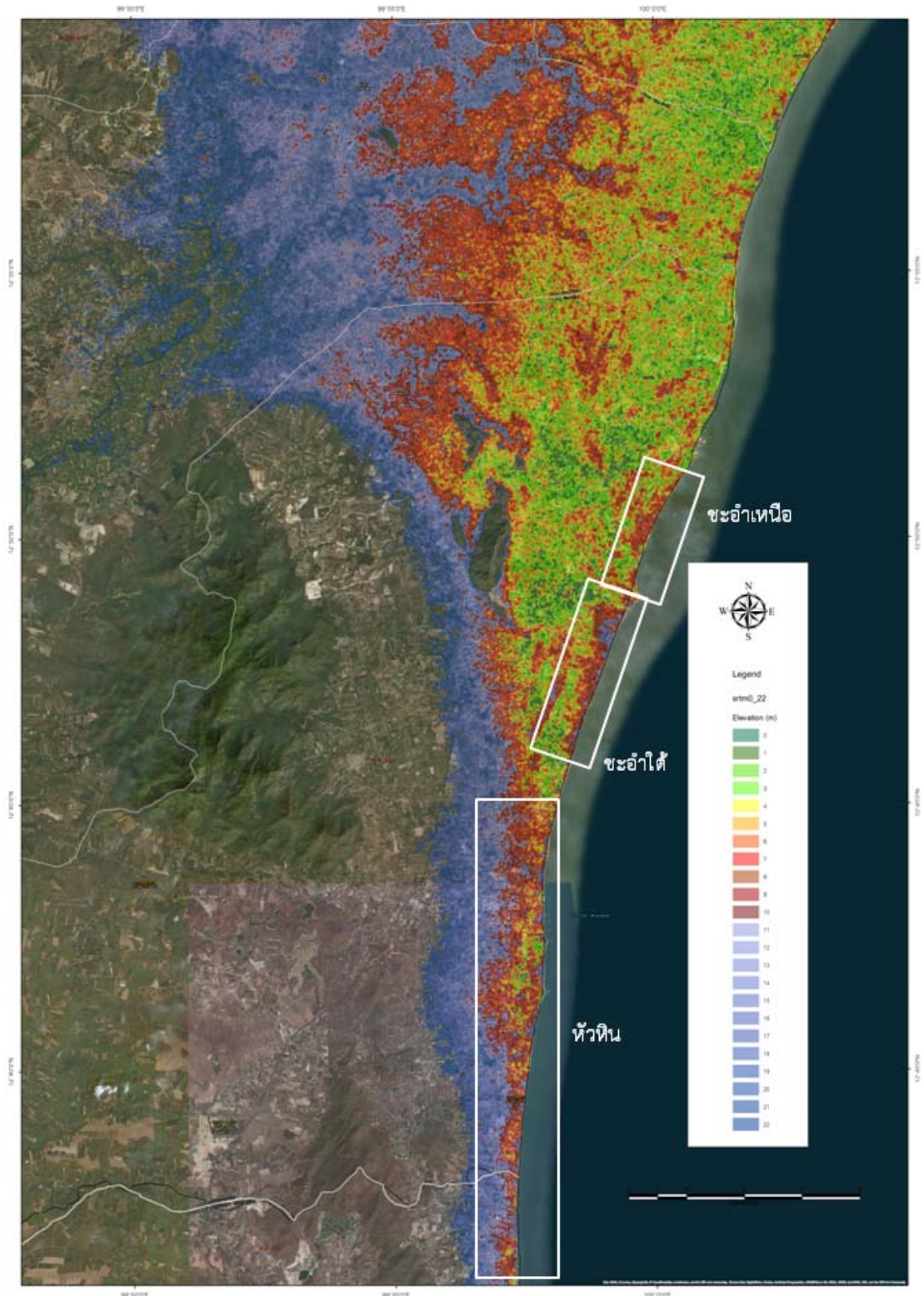


รูป 8 แบบจำลองภูมิประเทศแสดงวิวัฒนาการเชิงพื้นที่ที่สัมพันธ์กับการเปลี่ยนแปลงของระดับน้ำทะเลในช่วงอายุต่างๆ จากบริเวณสามร้อยยอด จังหวัดประจวบคีรีขันธ์

2.6 ผลการกำหนดกรอบพื้นที่จัดสร้างแผนที่เสี่ยงต่อภัยคลื่นพายุซัดฝั่ง

เนื่องจากเป้าหมายหลักของโครงการนี้คือการจัดสร้างแผนที่แสดงความเสี่ยงต่อภัยคลื่นพายุซัดฝั่งโดยทางโครงการได้คัดเลือกพื้นที่จังหวัดเพชรบุรีและจังหวัดประจวบคีรีขันธ์ในการเป็นกรณีศึกษาและตัวอย่างของการจัดทำแผนที่อย่างเป็นระบบตามหลักการสำรวจทางธรณีวิทยา คือ เริ่มตั้งแต่การสำรวจหาประวัติของคลื่นพายุซัดฝั่งในอดีต (paleotempestology) จากหลักฐานทางตะกอนวิทยา โดยหลักการสำรวจนี้ต้องอาศัยข้อมูลพื้นฐานในเรื่องวิวัฒนาการชายฝั่งประกอบด้วยเนื่องจากภูมิประเทศชายฝั่งในแต่ละช่วงอายุ (ตั้งแต่ตอนกลางสมัยโฮโลซีนถึงปัจจุบัน) มีความแตกต่างกันอย่างมาก หลักฐานที่แสดงการสะสมตัวของตะกอนพายุในแต่ละธรณีสัณฐานจึงมีความแตกต่างกันไปตามชนิดของธรณีสัณฐานชายฝั่ง หลักการนี้เป็นหลักการสากลที่จำเป็นต้องศึกษาให้รู้ก่อนว่าพื้นที่ไหนเคยได้รับผลกระทบจากคลื่นพายุซัดฝั่งมาก่อนแล้วซึ่งจะสามารถนำไปประเมินคาบวิบัติซ้ำ (recurrence) ได้อย่างสมเหตุสมผล ทำให้การดำเนินงานสร้างแผนที่เสี่ยงต้องใช้ความละเอียดของข้อมูลเป็นอย่างมากและต้องประเมินด้วยความละเอียดอ่อนเป็นอย่างยิ่ง โดยเฉพาะในพื้นที่เศรษฐกิจเนื่องจากอาจส่งผลต่อพื้นที่ในหลายมิติ

อย่างไรก็ตาม ในโครงการนี้เมื่อประมวลผลการสำรวจในทุกมิติทางธรณีวิทยาแล้วรวมกับการวิเคราะห์สภาพพื้นที่ปัจจุบัน ได้แก่ การใช้พื้นที่ อาคารสิ่งก่อสร้าง และระดับความสูงของภูมิประเทศ จึงสามารถจัดทำแผนที่แสดงความเสี่ยงในเบื้องต้นได้ในพื้นที่กรณีศึกษา ดังแสดงในรูป 9 (ดูแผนที่ฉบับขยายในรูปดิจิทัลไฟล์ที่แนบมากับรายงานฉบับนี้)



รูป 9 ตัวอย่างแผนที่แสดงกรอบพื้นที่เสี่ยงต่อพิบัติภัยคลื่นพายุซัดฝั่งบริเวณหาดชะอำถึงหาดหัวหินตอนเหนือ เมื่อนำมาวิเคราะห์ร่วมกับแบบจำลองสภาพภูมิประเทศ (DEM: Digital Elevation Model) โดยสีแดงแสดงพื้นที่และอาคารสิ่งก่อสร้างที่มีความสูงตั้งแต่ 5-10 เมตร สีเขียวแสดงพื้นที่ต่ำกว่า 5 เมตรที่คลื่นพายุอาจนำพาน้ำทะเลเข้าท่วมได้ อย่างไรก็ตามแผนที่นี้แสดงกรอบในมาตราส่วนขนาดใหญ่เพื่อเป็นข้อมูลเบื้องต้นในการวิเคราะห์ระดับรายละเอียดต่อไป

ส่วนที่ 3

สรุปผลการดำเนินงานโครงการ

ผลงานที่เผยแพร่แล้วและกำลังพิจารณาโดยวารสาร

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2. **Choowong, M. and Phantuwongraj, S.**, 2014. Past and current in-depth coastal hazard researches in Thailand. *The 40th Congress on Science and Technology of Thailand, 2 - 4 December 2014*

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บทความที่ประยุกต์วิธีการวิจัยโครงการนี้ไปใช้ในงานวิจัยอื่นและมีการขอบคุณที่สทวน สกว.*

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4. บทความที่เผยแพร่ได้รับการตอบรับและปัจจุบันออนไลน์
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Evidence of Holocene sea level regression from Chumphon coast of the Gulf of Thailand

Parisa Nimnate^a, Vichai Chutakositkanon^{a,*}, Montri Choowong^{a,b}, Santi Pailoplee^{a,b}, Sumet Phantu Wongraj^a

^a Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330 Thailand

^b Earthquake and Tectonic Geology Research Unit (EATGRU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330 Thailand

*Corresponding author, e-mail: vichai.c@yahoo.com

Received 15 Oct 2014

Accepted 1 Dec 2014

ABSTRACT: Sets of beach ridge plains located as far as ten kilometres inland at the Chumphon estuary area, southern peninsular Thailand, provide evidence of an ancient sea-level change. Relict coastal landforms including former beach ridge plains, old lagoons, swales, and former tidal flats between beach ridges are found inland at elevations of 1–5 m above the present sea level. Ancient beach ridges here comprise three sets and all are inferred to have been deposited during the Holocene. The orientation of the inner beach ridge plains confirms their deposition by south to north longshore currents, whereas the middle and outer ridges were probably formed by north-to-south currents. Grain size analysis shows that all ancient beach ridge deposits are similar and are composed of fine- to medium-grained sand with high sphericity. Likewise, the compositions are similar, with quartz as a major component and feldspar and ferromagnesian minerals as minor components, reflecting the same sediment provenance. Marine fossils found in the former tidal deposit indicate intertidal and mangrove environments. Optical stimulating luminescence dating of three sets of beach ridge plains indicate that deposition occurred 8900–5600, 5900–2700, and 3800–1600 years ago for inner, middle, and outer beach ridge plains, respectively.

KEYWORDS: beach ridge plain, progradation, sea level curve, palaeo-shoreline, Pleistocene

INTRODUCTION

Since 1980, sea level changes in Thailand have been extensively investigated on the lower central plain and Holocene palaeo-shorelines proposed^{1–10}. The Holocene sea level curve for peninsular Malaysia and Singapore were among the first pioneer curves that derived from result of radiocarbon dating of shell, wood, and coral materials in marine and brackish deposits^{11,12}. Most of the dated material comes from estuarine environment and indicates the history of sea level change during the Holocene after the post-glacial marine transgression (PGMT). In general, the sea level rose rapidly after PGMT from several meters below the present mean sea level (MSL) and reached a highstand of nearly 4 m above MSL at around 6500–7000 years before present (BP). Then sea level began to fall to the present MSL around 3000 or fewer years ago^{11,13}. From southern Thailand, Sconffin and Tissier also confirmed this history of sea level changes from a study of fringing reefs growing in the muddy waters of southeast Phuket¹⁴. The results indicated that

reefs commenced to grow 6000 years ago when the sea level (low spring tide) was at 1 m above present MSL¹⁴. Moving northwards to the upper Gulf of Thailand, an indicator of Holocene marine transgression is found in the lower central plain from the deposition of the Bangkok clay formation¹⁵. However, fluctuations of sea level were also reported locally from Thailand and peninsular Malaysia during sea-level regression after the sea reached the mid-Holocene highstand^{12,16}. A sea-level curve in the Gulf was firstly established by Sinsakul¹⁶. Radiocarbon dating suggest that sea level rose rapidly from –12.75 m below MSL to reach a maximum highstand at about 3.5 m above present MSL at around 6500 to 4000 years ago^{17,18}.

Well accepted evidence of sea level changes is provided by muddy deposition especially from marine and brackish fossils. Relict of coastal landforms preserved inland are significant evidence rarely discovered. In this study, we focus on our discovery on the Chumphon estuary area, southern Thailand where the relict beach ridge plains remain as far as ten kilometres inland. The estuary area of

Chumphon preserves spectacular geomorphological landforms as the former beach ridges 6–10 km from the present shoreline. These beach ridge plains are geographically bordered by the highland in the west and the present coastline in the east (Fig. 1). In the middle part of the area, the Thatapaow canal runs throughout Muang district and flow down south to reach the coastal zone joining Sawi and Langsuan rivers at Sawi and Langsuan districts, respectively. Terrestrial sediments are transported to the Chumphon coastal zone via all these rivers.

MATERIALS AND METHODS

Geomorphological interpretation and field planning

Relict landforms including three different beach ridge plains can be recognized clearly from aerial photographs taken in 1998 by the Royal Thai Survey Department (Fig. 1a). Detail interpretation from aerial photographs provides a coastal geomorphological map with a precise boundary classification of landforms. The interpretation of palaeo-longshore current is also provided by the orientation of beach ridges. The coastal transect lines were then set up mostly perpendicular to the present shoreline for geomorphological checking and locating sampling sites. Geomorphological field check is not only aimed to examine the accuracy of interpretation, but also to make a detail topographical survey of beach ridge plains by high accuracy digital GPS. Samples for detailed analysis of sedimentary deposits from each beach ridge were collected by digging small excavation pit as well as hand augering. Apart from beach ridges, sediment samples were also taken from several landforms including a former lagoon, former tidal flat, and modern beach. At the top of each beach ridge, shallow pits were done at foreshore zone and sand samples were collected for optically stimulated luminescence (OSL) dating. Marine and brackish shell fossils were also collected from former tidal flats and swales for systematic faunal classification (also see location in Fig. 1b).

Laboratory analysis

A total of 115 samples from 22 auger cores of the former sandy beach ridges, and the recent beach were analysed. Distribution of grain size and the statistical values of sediments were calculated by moment method modified from Boggs¹⁹ and four parameters were determined: average grain size, standard deviation, skewness, and kurtosis. The comparison of moment parameter followed Blott

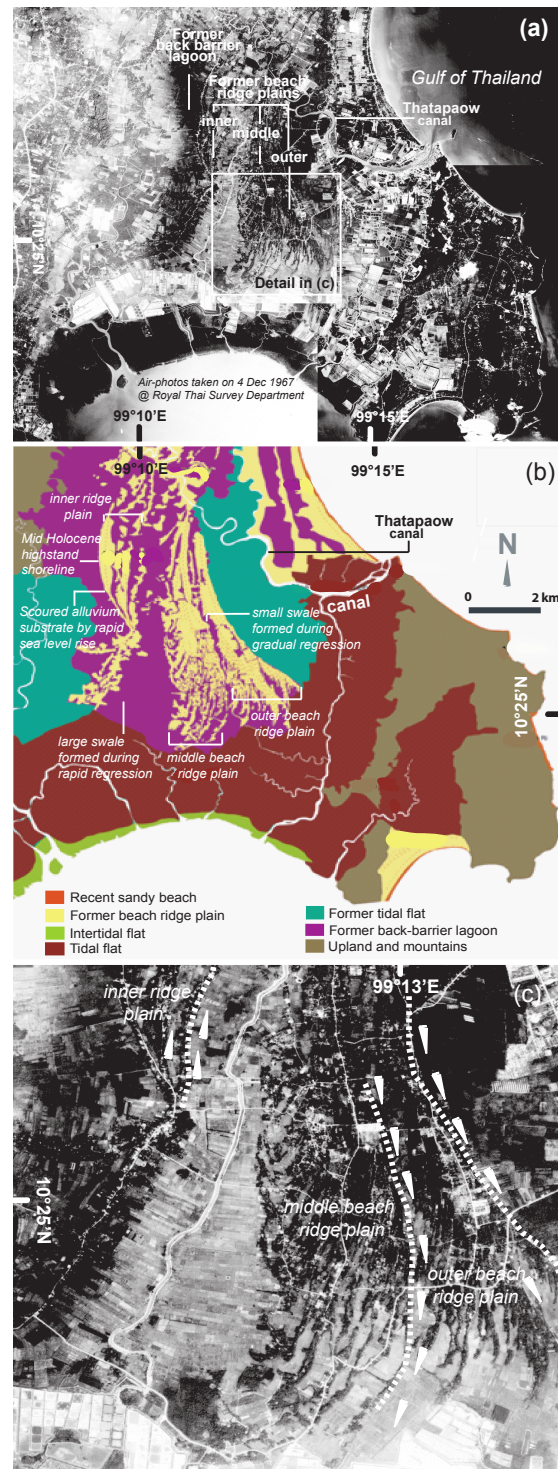


Fig. 1 (a) Aerial photographs with approximately 1:50 000 scale covering the study area (modified from Thai Royal survey Department, 1998). (b) Coastal geomorphological map displays all important landforms. (c) Close-up beach ridge plains with interpreted palaeo-longshore currents (arrows).

and Pye²⁰. Sediment was classified by binocular microscope. The percentage was estimated by comparison with the standard chart of sediment composition²¹. The classification of roundness and sphericity followed Powers²².

RESULTS

Description of landforms

The result of aerial photograph interpretation (Fig. 1a) provides a detailed geomorphological map (Fig. 1b). Coastal geomorphological units observed in this area include the old sandy beach, old lagoon, young sandy beach, old tidal flat, upland and mountain, intertidal flat, and tidal flat. Some relict coastal landforms were recognized inland as far as ten kilometres from the present shoreline, e.g., a series of ancient beach ridges. Inland beach ridges showing a strandline can be used as an indicator of the palaeo-shoreline. The former beach ridge is a relict feature left behind inland usually of interest for being evidence of sea level changes both during marine transgression and regression. Likewise, sets of strandlines indicate the past longshore current direction. The shape of the ancient beach ridge can also be related to the sea level regression at the time when the land prograded seawards. In this area, at least three series of former beach ridges were recognized with a different direction of palaeo-longshore current. The inner series showed the direction of palaeo-longshore current from the south to the north. On the other hand, the middle and outer series of former beach ridges showed the palaeo-longshore current direction from the north to the south (Fig. 1c).

Physical properties of the sediments

Plotting of statistical parameters from grain size analysis (Fig. 2) can separate the sediments into four groups based on the different landforms as inner series, middle series, outer series, and recent beach. Mean grain size of the inner series of former beach ridge is characterized as very fine to medium sand, moderately to moderately well sorted. Skewness and kurtosis values are showed as coarse to fine skewed to very leptokurtic, respectively. From the middle series, mean grain size is described as medium sand and moderately sorted. Skewness value showed as symmetrical to fine skewed, whereas kurtosis value is in the range of very leptokurtic. Mean grain size of the outer series of former beach ridges is classified as fine sand, moderately to moderately well sorted, coarse

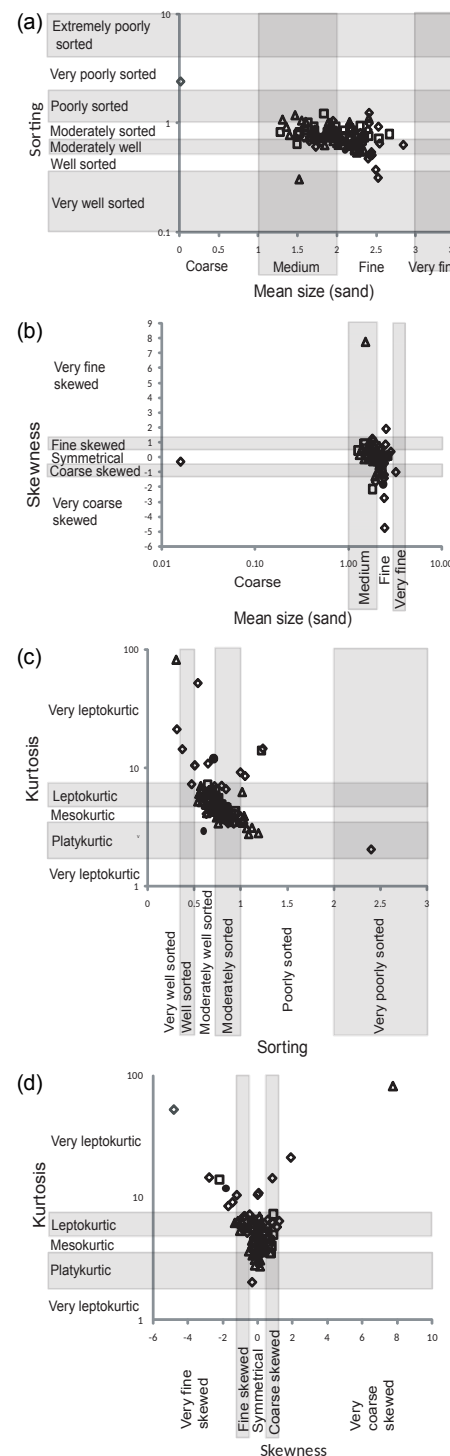


Fig. 2 Scatter plots of statistic parameter relationships: (a) mean size versus sorting, (b) mean size versus skewness, (c) sorting versus kurtosis, and (d) skewness versus kurtosis. Diamonds: inner ridge, squares: middle ridge, triangles: outer ridge, and circles: recent beach.

to symmetrical skewed, with a kurtosis value is in the range of very mesokurtic to leptokurtic. The recent beach is dominated by fine sand, moderately to moderately well sorted, symmetrical skewed, and leptokurtic.

Two-variable scatter plots include mean grain size versus sorting, mean grain size versus skewness, sorting versus kurtosis, and skewness versus kurtosis²³. Mean grain size versus sorting (i.e., standard deviation) (Fig. 2a) is commonly used to indicate the deposition environment of the sediment sample. The middle, outer ridge, and recent beach sand samples had a mean grain size between medium sand and fine sand. Sorting value was in a range of moderately to moderately well sorted. Mean grain size versus skewness in this unimodal sediment is composed of pure sand and shown positive skewed. Scatter plot of mean grain size versus standard deviation are shown in Fig. 2b. Some sand sediments at the outer ridge and the inner ridge showed extreme kurtosis values and good sorting (Fig. 2c) similar to sediments in the neritic zone. Extreme kurtosis values result from sand mode that achieves a good sorting in a high energy environment of a beach, and then it is transported a mass by storm to a neritic environment where it becomes mixed with clay and hence is finally deposited in a medium of low sorting efficiency²³.

Skewness versus kurtosis (Fig. 2d)²⁴ shows a regular path. Most of the samples are in the range of fine to coarse skewed and mesokurtic to leptokurtic. Half of all sediment samples are characteristically leptokurtic and positive skewed, indicating that they have been transported not far from the sort area.

Compositions, roundness, and sphericity

The old beach ridge at Chumphon estuary area consists mainly of quartz. All beach ridges, the inner, the middle, and the outer series of old beach contain similar composition. A minor component of the inner series of old beach consist of feldspar and ferromagnesian minerals, in a percentage higher than that of the middle and the outer ridge (Fig. 3).

Roundness of the inner beach sediments displays a subangular shape, whereas, the middle beach ridge shows an angular to subangular shape. Roundness trend from the outer former beach ridge is subangular. All of beach ridge sediments show a high sphericity shape.

Based on the composition of beach sediments, sediments in this coastal area were transported from mountains in the west and the north of this area. Rock basements are composed of Permo-

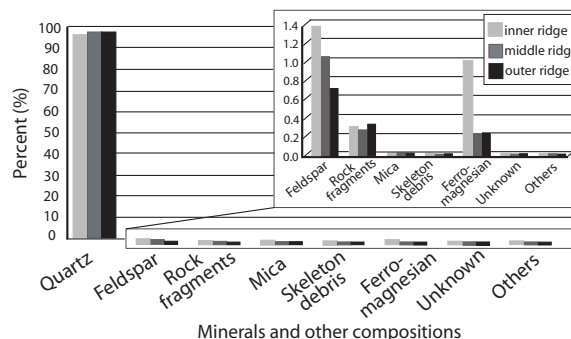


Fig. 3 Histogram of sediment composition from three sets of beach ridge plains (see text for explanation).

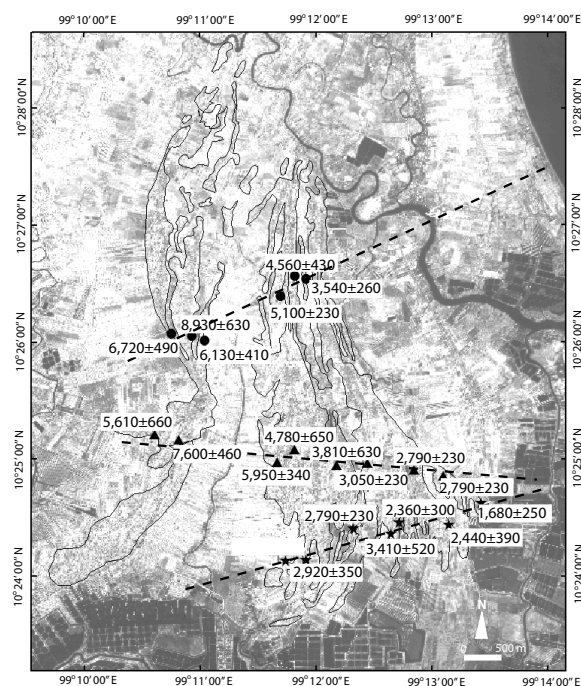


Fig. 4 Locations and results of OSL dating along three transects. Black circles indicate pit locations along transect 1, black triangles belong to transect 2, and black stars represent locations of pit along transect 3. Dark lines indicate tentative boundary of beach ridges.

carboniferous and Permian sedimentary rocks. The weathered sediments from these rock basements were transported by active fluvial systems in the north-eastern part of beach ridges and through the coastal zone by longshore currents²⁵.

Age determination of ancient beach ridges

Twenty one samples from the ancient beach ridge plains (Figs. 4 and 5a) located far from present

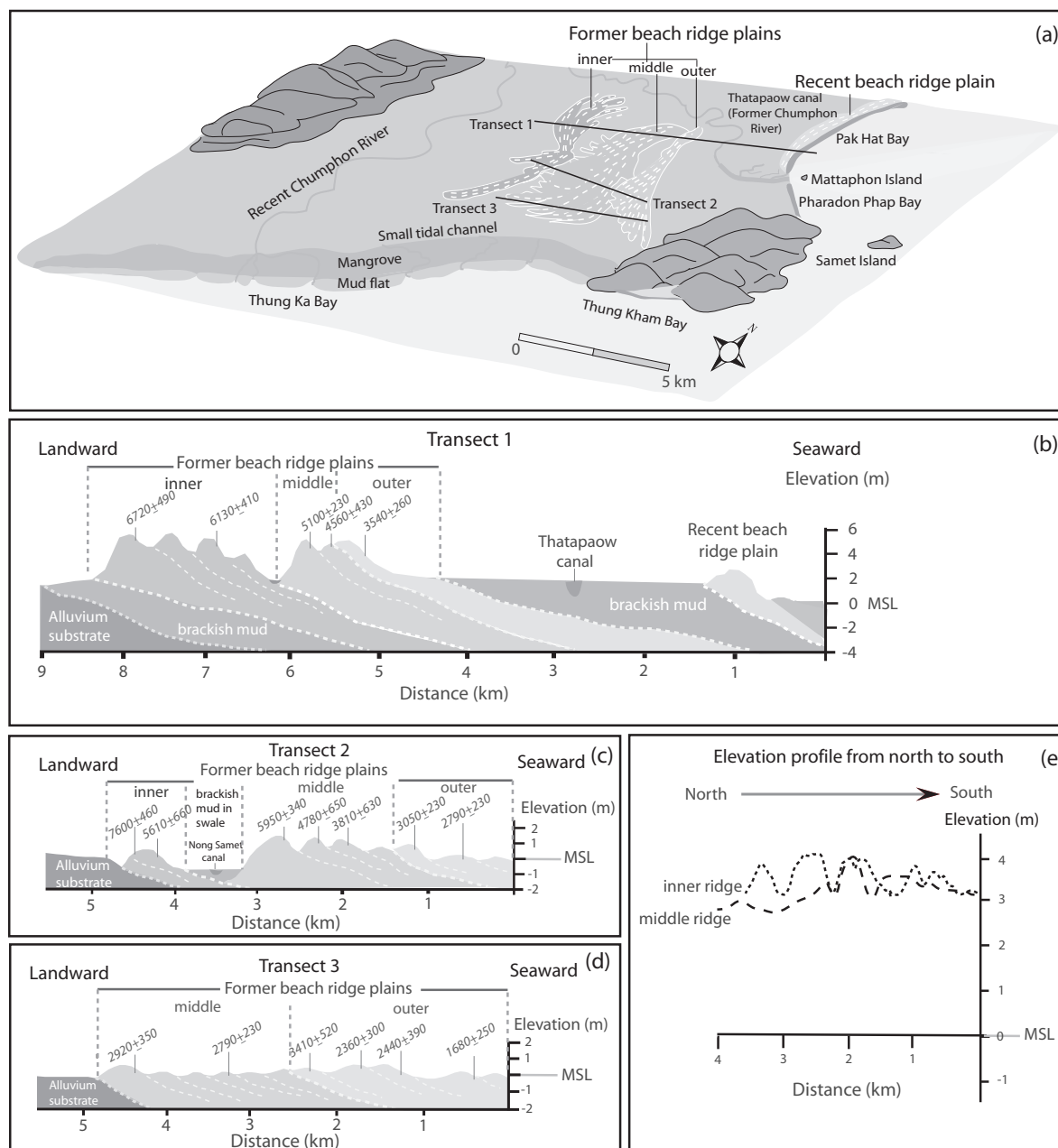


Fig. 5 Three dimensional geographical models and cross-sections with age determination. Numbers in (b) and (c) indicate the age determined by OSL dating (see text for explanation).

shoreline were analysed by the optical stimulate luminescence (OSL) dating method. The age of these beach ridges dated from all transects is shown in Table 1 and Fig. 5b–d.

At transect 1, result of OSL dating of the inner ridge series reveals an age of between 8930 ± 630 – 6130 ± 410 years BP. The middle beach ridges series have an age of between 5100 ± 230 – 4560 ± 430 years BP. Finally, the outer ridge series have a

younger age than those of inner and middle ridge plains around 3540 ± 260 years BP.

Along transect 2, OSL samples were collected from 8 locations at the inner, middle, and outer beach ridge series. The age of beach sand at the inner beach ridges ranges from 7600 ± 460 – 5610 ± 600 years BP. Whereas, the middle ridge shown the age of deposition from 5950 ± 340 , 4780 ± 650 and 3180 ± 630 years BP seawards. The

Table 1 Result of OSL dating of the beach ridges from Chumphon area, southern Thailand (see locations of sample collection in Figs. 4 and 5a–c).

Transect	Latitude (°N)	Longitude (°E)	Dist _s (km)	Depth (m)	K (%)	U (ppm)	Th (ppm)	Moist. (%)	Dose rate (mGy/a)	D _e (mGy)	Age (years)
Line 1											
1–1	10.434595	99.179238	6.49	0.15	0.156	3.70	16.0	10.2	2.53 ± 0.25	17.0 ± 1.0	6720 ± 490
1–2	10.434304	99.182170	6.30	0.55	0.377	1.27	4.94	3.72	1.58 ± 0.15	21.0 ± 1.9	8930 ± 630
1–3	10.433588	99.184089	6.10	0.60	0.155	2.69	13.3	2.04	2.08 ± 0.20	12.0 ± 0.6	6130 ± 410
1–4	10.439976	99.195011	4.75	0.65	0.449	1.64	7.14	6.59	1.98 ± 0.19	10.0 ± 0.5	5100 ± 230
1–5	10.442778	99.196986	4.33	0.55	0.517	1.09	2.86	2.62	1.68 ± 0.16	7.6 ± 1.4	4560 ± 430
1–6	10.442361	99.198686	4.20	0.45	0.402	2.23	13.6	2.62	2.51 ± 0.25	8.8 ± 0.5	3540 ± 260
Line 2											
2–1	10.415228	99.214072	7.54	0.45	0.317	6.34	34.9	8.69	4.93 ± 0.49	13.0 ± 0.1	5610 ± 660
2–2	10.414320	99.218274	7.29	0.22	0.224	1.88	4.67	3.72	1.38 ± 0.13	22.0 ± 1.0	7600 ± 460
2–3	10.420207	99.176836	6.53	0.35	0.372	2.68	8.84	2.34	2.20 ± 0.22	18.0 ± 0.8	5950 ± 340
2–4	10.419499	99.180280	6.00	0.43	0.479	1.35	4.96	7.06	1.82 ± 0.18	13.0 ± 0.5	4780 ± 650
2–5	10.416280	99.194412	5.67	0.24	0.448	1.66	7.23	5.12	1.99 ± 0.19	5.9 ± 0.9	3810 ± 630
2–6	10.418078	99.196943	5.60	0.37	0.414	1.02	5.33	2.68	1.62 ± 0.16	4.7 ± 0.2	3050 ± 230
2–7	10.415877	99.202926	5.00	0.23	0.345	1.31	5.32	3.36	1.55 ± 0.15	5.3 ± 0.5	2790 ± 230
2–8	10.416145	99.207339	4.68	0.30	0.229	2.31	10.7	7.15	1.95 ± 0.19	5.3 ± 0.5	2760 ± 320
Line 3											
3–1	10.402225	99.195655	7.48	0.33	0.519	1.42	4.21	2.23	1.86 ± 0.18	5.7 ± 0.5	3880 ± 320
3–2	10.402413	99.198606	7.22	0.25	0.395	1.99	6.87	3.90	1.93 ± 0.19	5.6 ± 0.6	2920 ± 350
3–3	10.406903	99.205451	6.36	0.40	0.329	2.13	10.5	5.38	2.10 ± 0.20	5.8 ± 0.3	2790 ± 230
3–4	10.406086	99.210814	5.92	0.44	0.383	1.29	4.75	4.46	1.58 ± 0.15	5.4 ± 0.7	3410 ± 520
3–5	10.407722	99.211984	5.38	0.55	0.663	1.68	6.35	3.07	2.39 ± 0.23	5.6 ± 0.7	2360 ± 300
3–6	10.407356	99.219119	5.23	0.35	0.313	1.02	3.65	2.90	1.28 ± 0.12	3.1 ± 0.4	2440 ± 390
3–7	10.410536	99.223762	4.42	0.50	0.308	1.46	6.68	5.33	1.61 ± 0.16	2.7 ± 0.4	1680 ± 250

Dist_s: distance to the shore. D_e: total absorbed radiation dose.

outer ridge series gave the youngest age of deposition which ranges from 2790 ± 230–2760 ± 320 years ago.

At transect 3, three samples from the middle beach ridge display the depositional age ranging from 3880 ± 320–2790 ± 280 years BP. The outer beach ridge series with sand spit shape-like show a depositional age ranging from 3410 ± 520–1680 ± 250 years BP. Based on the result of age dating by OSL method, three series of the ancient beach ridges here show a depositional pattern seawards with the oldest one located at the inner beach ridge series and the youngest one located at the outer beach ridge series.

DISCUSSION

Palaeo-shoreline and palaeo-longshore currents

The delineation of palaeo-shorelines from aerial photograph interpretation is a pioneer technique used to locate the ancient shoreline in the central plain of Thailand^{3,4}. The interpretation of aerial photographs alone however may not be reliable

enough, and needs to be combined with a detailed analysis of sedimentology and dating of marine or brackish deposits as well as the classification of fauna found within the area.

In this study area, a tentative boundary of the westernmost palaeo-shoreline is indicated by the occurrence of an innermost beach ridge located far approximately 6 km inland from the present shoreline. However, the innermost beach ridge may have occurred either during the rapid transgression or regression; therefore, the back-barrier lagoon found in the west of innermost beach ridge (10 km inland) may help to confirm that the sea invasion occurred before the mid-Holocene.

Three sets of beach ridge plains were recognized in the study area as mentioned earlier. All the former beach ridges were prograded seawards. The orientation of the three beach ridge plains is parallel to the present shoreline and reflects a different direction of palaeo-longshore current during the time they were formed. The shape of the inner beaches shows that the deposition prograded northwards. They suggest that the longshore current direction

was likely from south to north. On the other hand, the middle and the outer beaches show a spit shape with the end of each beach curved at the end; therefore, they were formed by the southwards direction of longshore current (also see Fig. 1c).

Sediment characteristics of the beach ridge

Differences in statistical parameters can be detected from each of beach ridge. Grain size distribution is one of the physical properties that reflect the energy during the depositional processes. However, grain size distribution could not be used alone for sedimentary environment identification, but it needs to be combined with the other lines of evidence (i.e., roundness, sphericity, and heavy minerals, biogenic components)²⁶.

Scatter plots of mean grain size versus standard deviation (sorting) shows a narrow range of grain size (very fine to coarse sand) and moderately to moderately well sorted values (also see Fig. 2). This indicates a high energy environment of the beach zone²³. Based on the plot of sorting versus skewness, some samples from the outer and the inner beaches showed an extreme kurtosis and were well sorted indicating a neritic origin. The result of skewness versus kurtosis scatter plot reveals that half of all sediment samples are characterized by leptokurtic and are positively skewed. It indicates that the sediments were transported not so far from the source provenance²³. Skewness and kurtosis plot is identified as the indicator of selective action of the transporting agent²⁷. Additionally, all of sand generally yields a negative skewness that is common for a beach.

In this study, beach sand with fine- to coarse skewed indicates an environmental change between calm condition (stable current) and storm condition (variable current velocities and turbulence during deposition). Poorer sorting indicates variable current velocities and turbulence during deposition while good sorting indicated smooth and stable currents. Local shoaling in a shallow marine environment may produce a complex current flow patterns, eddying, and wave-generated turbulence causing sand to become negatively skewed for the most part²⁸.

Major beach sand composition is quartz. The rest are feldspar and ferromagnesian minerals. They are generally subangular to angular that can be classified as submature texture stage as suggested by Folk²⁹ and pointed to relatively short transportation for a considerable time and distance³⁰.

Pleistocene sea level records

Fleming et al³¹ mentioned the eustatic component of relative sea-level change in Pleistocene provides a measure of the amount of ice transferred between the continents and oceans during glacial cycles. This has been quantified for the period since the last glacial maximum (LGM) by correcting observed sea-level change for the glacio-hydro-isostatic contributions using realistic ice distribution and earth models. During the LGM the eustatic sea level was at 125 ± 5 m lower than the present day³².

In Southeast Asia, Hanebuth et al⁹ proposed a sea-level curve for the Sunda shelf derived from shoreline facies. On the proximal part of the Sunda shelf transect, the late-glacial transgression could be directly identified between a water depth of 70 and 126 m. Pedogenesis on the late Pleistocene land surface indicates a low sea-level still stand in the LGM at 22 ka. This surface is overlaid by transgressive coastal sediment and marine sands then cover the transgressive sediments after a hiatus⁹. Ages from *Rotalia* sp. from mud layer vary widely from 12.4 to 4.1 ka and indicate that shelf sediments were reworked and mixed up to recent times.

A sea level curve in the Pleistocene epoch from the Huon Peninsula, New Guinea analysed from coral terraces shown a mean eustatic sea level change³². During 12 Ma, the sea-level began to fall and show fluctuation. The sea-level was lowest than mean eustatic sea level at 120 m below present mean sea level. Likewise, we infer that sea level records during LGM from the Gulf of Thailand is linked to the history of the Sunda Shelf.

Holocene sea level records and revised sea level curve

History of sea-level change in Southeast Asia during the Holocene was shown as sea level curve in Fig. 6a³³. The curves were compiled from the Holocene records in Malacca strait, Indonesia³⁴, Malay-Thai peninsula, and Sunda shelf⁹, and the Huon peninsula, Papua New Guinea from Chappell and Polach³⁵. However, we will discuss only the previous work regarding Thai-Malay peninsula. Tjia¹² studied abrasion platforms, sea-level notches and oyster beds in peninsular Malaysia. The sea-level curve revealed the two Holocene highstands at 5000 and 2800 ¹⁴C years BP³³. However, sea-level in Thailand is mentioned to have fluctuated at least three times from mid/late Holocene highstands at 6000, 4000, and 2700 ¹⁴C years BP³³. Intertidal reef-flat corals (microatolls) formed in

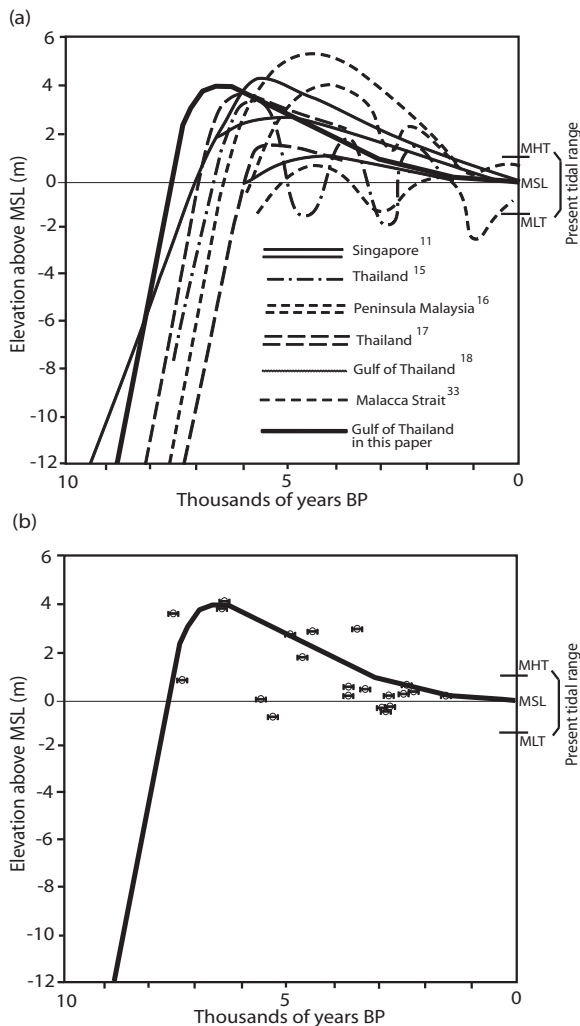


Fig. 6 (a) Sea-level curves from southeast Asia³³. (b) A new revised sea level curve for Thailand proposed in this paper. Circles with horizontal lines represent the plots of age dating from OSL.

mid/late Holocene highstands were reported from Phuket, Southern Thailand¹⁴. The evidence there suggested a single Holocene highstand with a constant rate of sea level fall since 6000 years BP. The first sea-level curve for Thailand was proposed by Sinsakul et al¹⁶. The curve shows two Holocene highstands at 5000 and 2800 years BP¹⁶. In general, the sea-level curve for Thailand and Malaysia indicated three probable rebound phases during the mid- to Late Holocene with highstands at 6, 4, and 2.7 ka^{12,16}. A revised sea-level envelope for the Gulf of Thailand was proposed by Choowong et al¹⁷, which corresponded well with the sea-level curves subsequently constructed by Horton et al¹⁸

for the Thai-Malay peninsula. The curves show an upward trend of rising Holocene sea level to the mid-Holocene highstand, and then a gradual fall of sea level to the present.

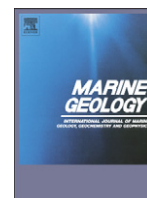
The interpretation of the former sea level has been commonly based on the coastal geomorphology, fossils, and absolute age dating. Here, we have done OSL dating of former beach ridge plains. We propose a revised sea level curve for Thailand (Fig. 6b). Together with the other geological evidence such as the occurrence of sea notches in different level and bio-erosion found at the wall of limestone, they all help to confirm that Chumphon estuary area was invaded by the sea during the Holocene. Sea level has reached almost 5 m above the present sea level. The alignment of the innermost beach ridges at highest elevation of 5 m indicates the highstand. Then the sea started to prograded seawards leading to the gradual formation of beach ridge plains at highstand elevation to the present MSL that can be inferred as marine regression (also see elevation change in Fig. 5e).

Acknowledgements: The 90th Anniversary of Chulalongkorn University Fund supported P.N. The Thailand Research Fund (BRG5780008) and Ratchadapiseksomphot Endowment Fund (RES560530028CC) provided funds to M.C. Thanks are also to EATGRU for OSL dating. Authors would like to express sincere acknowledge to editor-in-chief and anonymous reviewers that greatly improved the quality of manuscript.

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Geologic records of Holocene typhoon strikes on the Gulf of Thailand coast



Harry Williams^{a,*}, Montri Choowong^b, Sumet Phantu Wongraj^b, Peerasit Surakietchai^b,
Thanakrit Thongkhao^b, Stapana Kongsen^b, Eric Simon^a

^a University of North Texas, United States

^b Chulalongkorn University, Thailand

ARTICLE INFO

Article history:

Received 25 August 2015

Received in revised form 14 December 2015

Accepted 23 December 2015

Available online 24 December 2015

Keywords:

Tropical cyclone

Paleotempestology

Washover

Storm surge

Gulf of Thailand

ABSTRACT

Washover sedimentation resulting from modern typhoon strikes on the Gulf of Thailand coast forms anomalous sand layers in low-energy coastal environments including marshes, ponds and swales. The primary diagnostic for recognizing prehistoric typhoon-deposited sand layers in the geologic record are sharp upper and lower contacts between coarser-grained transported sand layers and finer-grained in-situ sediments. In this first paleotempestology study in Thailand, cores from two low-energy settings on the Gulf of Thailand coast – a coastal marsh near Cha-am and beach ridge plain swales near Kui Buri – reveal geologic evidence of up to 19 typhoon strikes within the last 8000 years. The sand layers have sharp upper and lower contacts with enclosing finer sediments. Some sand layers also contain other evidence of a sudden powerful landward-directed surge of ocean water, including gravel-sized clasts, offshore foraminifera, abundant shell fragments, plant debris and mud rip-up clasts. Sand layers record eleven typhoon strikes at Cha-am, ranging in age from AD 1952 to 7575 cal. yr. BP, and eight typhoon strikes at Kui Buri, ranging in age from 4075 to 7740 cal. yr. BP. Bayesian age–depth models, derived from eight AMS radiocarbon dates, suggest that the frequency of typhoon strikes was 2–5 times greater from 3900 to 7800 cal. yr. BP compared to 0–3900 cal. yr. BP. Possible explanations for this variability in the typhoon record are that typhoons were more frequent and/or more intense in Southeast Asia in the mid-Holocene because of climatic changes associated with the Mid-Holocene Warm Period or that the record reflects site sensitivity changes resulting from a mid-Holocene sea-level highstand. The preliminary finding of a possible link between warmer conditions and a greater frequency of intense typhoon strikes could have important societal implications, given possible consequences of ongoing global warming.

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1. Introduction

The devastating impact of 2013's Typhoon Haiyan in the Philippines highlighted the need for improved understanding of tropical cyclone risk and impacts for vulnerable coastlines throughout Southeast Asia. A major factor in making Haiyan the Philippines' deadliest typhoon, with 6300 fatalities, was its unusually large storm surge, estimated at 5–7 m near landfall in the Gulf of Leyte (NDRRMC, 2014; Paciente, 2014). There are reports that many local residents may have ignored government warnings and calls for evacuation because they were not aware of the potential danger of a large storm surge, having never experienced a comparable event in their own lifetimes (Mullen, 2013; Paciente, 2014).

Many countries in the region lack long-term records of tropical cyclone strikes which could be used to more reliably estimate landfall recurrence intervals and tropical cyclone risk, and to ascertain if tropical

cyclone activity displays centennial to millennium-scale variability, possibly related to climate changes (Elsner and Liu, 2003; Fan and Liu, 2008). This kind of information is valuable because it can be used to better inform public policy, guiding formulation, maintenance and execution of appropriate preparedness plans (Nott, 2007). Linking typhoon activity to climate changes improves prediction of future typhoon activity in response to ongoing global warming. In Thailand, reliable meteorological records of typhoon strikes cover only about the last 70 years – too limited a time span to provide insights into centennial to millennial-scale tropical cyclone variability (Joint Typhoon Warning Center, 2014). In response to these shortcomings in historical data, the new science of paleotempestology (study of ancient storms) has emerged as a way to obtain much longer prehistorical records from chemical, biologic and geologic proxies of tropical cyclone strikes (Donnelly and Woodruff, 2007; Emery, 1969; Lane et al., 2011; Liu and Fearn, 1993, 2000a, 2000b; Yu et al., 2009).

Paleotempestology studies have focused primarily on identifying and dating washover sand layers in coastal marshes located immediately landward of sandy barriers (Donnelly, 2005; Donnelly and Webb,

* Corresponding author.

E-mail address: HarryF.Williams@unt.edu (H. Williams).

2004; Donnelly et al., 2001a, 2001b, 2004; McCloskey and Keller, 2009; Scileppi and Donnelly, 2007; Williams, 2011, 2013). This geologic proxy approach is based on the premise that a tropical cyclone storm surge overtops the barrier and wind-driven waves transport dune, beach, intertidal and sub-tidal sand onto a muddy, organic-rich marsh to form an anomalous sand layer (Williams, 2011). Over time, during which normal marsh aggradation occurs, multiple tropical cyclones are recorded by multiple sand layers separated by muddy, organic-rich marsh sediments (Williams, 2011, 2013). Tropical cyclone storm surge deposits present in the subsurface are typically distinguished by a coarser texture and lower organic content than enclosing marsh sediments, by sharp upper and lower contacts, by marine microfossils and by a wedge-shaped profile that thins and fines landward. Identified storm surge deposits can be readily dated by radiocarbon dating because the buried marsh under the deposit usually contains abundant organic material.

The east coast of Thailand, bordering the Gulf of Thailand, is subject to large damaging typhoon strikes. Most typhoons affecting Thailand originate in the northwestern Pacific Ocean and move in a westerly or north-westerly direction. Many strike the Philippines or China, but some travel west into the South China Sea, making landfall in Vietnam or Thailand. Notable typhoons or tropical storms (powerful cyclonic storms with wind speeds below the threshold for typhoon status) to make landfall on the east coast of Thailand in recent decades include: Tropical Storm Harriet (1962) causing 769 fatalities in southern Thailand; Typhoon Gay (1989), a Category 3 typhoon at landfall, which caused over 800 fatalities in Thailand; and Tropical Storm Linda (1997) causing 164 fatalities in Thailand (Fig. 1).

There has been relatively little research on storm surge sedimentation in Thailand. Phantu Wongraj et al. (2008), examining shallow coastal sediments near Talat Chaiya, Tha Chana and Laem Talumpuk, describe sand

sheets, in otherwise muddy environments, tentatively attributed to Tropical Storm Harriet, Typhoon Gay and Tropical Storm Linda. The sand sheets, found in non-active tidal channels and swales behind beach ridges, vary from four to sixty cm in thickness, generally fine and thin inland and extend up to 90 m from shore. The key distinguishing criteria are sharp top and basal contacts with enclosing muds. Phantu Wongraj et al. (2013) describe washover deposits near Ban Takrop, Laem Talumpuk and Khao Mai Ruak resulting from small-scale, monsoon-driven storm surges occurring along the southern peninsular coast of the Gulf of Thailand in 2007, 2008, 2009, 2010 and 2011. The washover deposits formed washover terraces, perched fans and sheetwash lineations. The deposits vary from fifteen to eighty cm in thickness, extend up to 100 m inland and have sharp basal contacts. Phantu Wongraj et al. (2010) found sand sheets, tentatively attributed to prehistoric typhoons or tropical storms, in paleo-lagoon deposits, 1.2 km inland near Phanang Tak in Chumphon Province (Fig. 1). The sand sheets are typically 2–3 cm thick, but range up to 35 cm in thickness and have sharp contacts with enclosing muds.

This paper reports on a study to identify and date geological evidence of prehistoric typhoon strikes preserved in coastal marshes on the Gulf of Thailand coast. Currently, there are no published long-term records of typhoon strikes on the Gulf of Thailand, even though this coastline is subject to intense tropical cyclone strikes, including 1989's Typhoon Gay (Fig. 1). Typhoon Gay originated in the Gulf of Thailand in November 1989 and intensified rapidly, resulting in 11-m-high swells and 275 offshore fatalities from capsized vessels. The storm caused high winds and swells along much of the Gulf of Thailand coast. Winds increased to 185 km/h at landfall, elevating the typhoon to Category 3 status. There was widespread destruction close to landfall in Chumphon Province, where around 450 deaths were directly attributed to the storm. Fatalities totaled more than 800, making Typhoon Gay one of the deadliest tropical cyclones in Thailand's history.

2. Study area

Reconnaissance coring, using a gouge corer to probe to ~2 m depth, was conducted at a number of potential sites on the Gulf of Thailand coast. Two sites were selected for this study where gouge coring revealed multiple sand layers at depth with sharp contacts with enclosing predominantly fine-grained sediments: a coastal marsh near Cha-am (site designation HW1) and two beach ridge plain swales near Kui Buri (site designation SRY) (Fig. 1). The coastal marsh occupies about 0.5 km² of undeveloped land 4 km south of the city of Cha-am. The marsh surface is between 2 and 2.5 m above mean sea level (a.m.s.l.), slopes gently seaward and is drained by a branching tidal creek network which flows into the Gulf of Thailand through a breach in a sandy barrier beach. Trees and shrubs line the creek network and low-lying herbaceous plants cover parts of the marsh surface between creek channels. The rest of the marsh surface is unvegetated sand to muddy sand, is slightly lower than vegetated areas and prone to shallow flooding during rain (Fig. 2 a, b, c). The beach ridge plain swales are part of a large beach ridge plain near Kui Buri (Fig. 1). The first swale is about 150 m inland, 50 m wide and is landward of a small beach ridge with a crest about 1.6 m a.m.s.l. The floor of the swale is about 0.6 m a.m.s.l. The second swale is 550 m inland, 40 m wide and has a floor about 0.8 m a.m.s.l. The beach ridge immediately seaward of the swale rises to about 2.4 m a.m.s.l. (Fig. 2 d, e, f). Both swales are floored by fine-grained sediment, were sparsely vegetated when visited and are largely cut off from tidal influence by numerous road beds, which form barriers to tidal inflow. Sediments in the swales seemed relatively undisturbed by human activities, although they are presumably used for growing crops during part of the year. Both swales are also presumably subject to flooding during periods of rain.

A number of studies have documented evidence of a mid-Holocene highstand on the Thai–Malay Peninsula resulting from the Post-Glacial

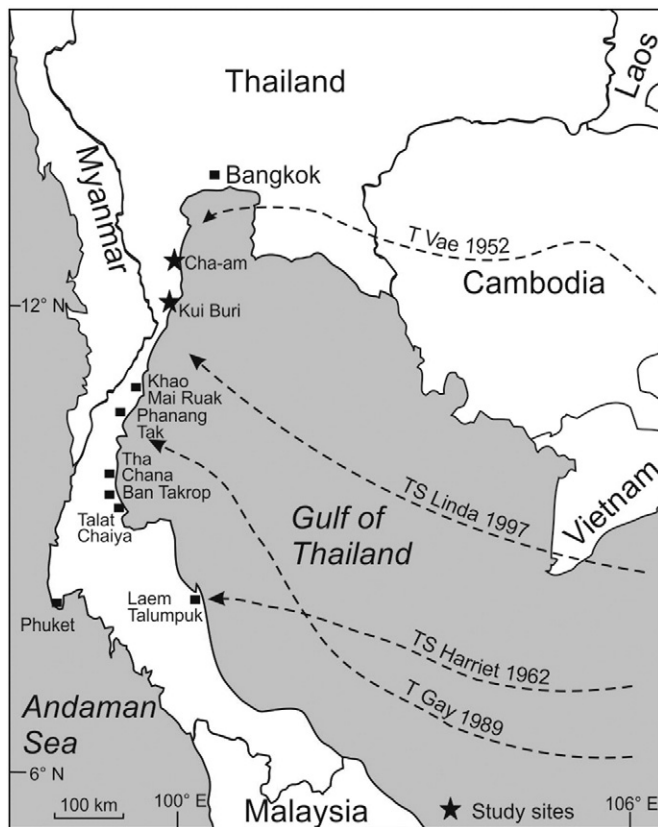


Fig. 1. Location map showing study areas at Cha-am and Kui Buri, sites of documented washover sedimentation and tracks of recent notable tropical cyclones in the Gulf of Thailand (TS: Tropical storm, T: Typhoon).

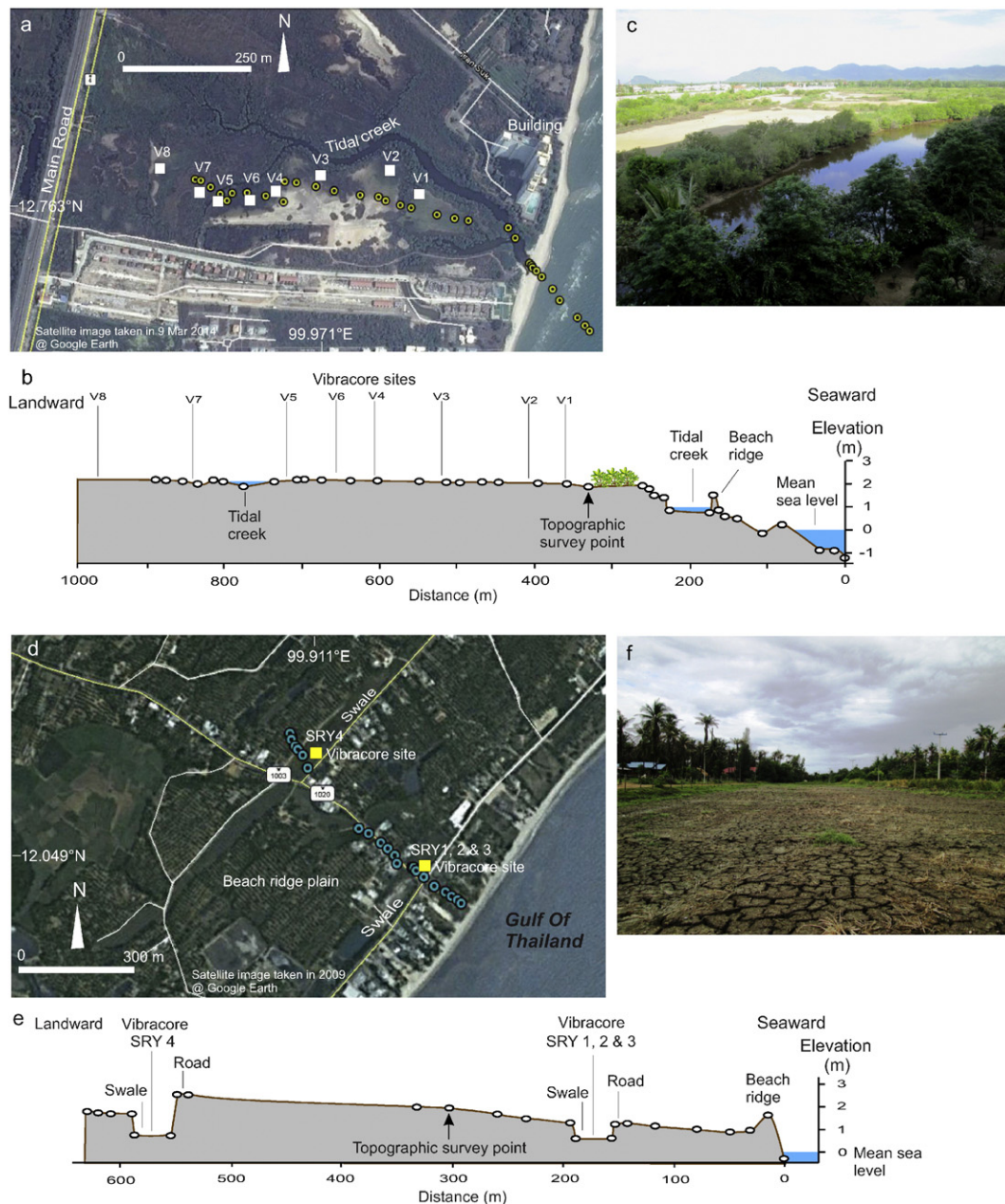


Fig. 2. a. Coastal marsh at Cha-am showing topographic survey points (yellow circles) and vibracore sites (white squares) (Google Earth image, 2014); b. topographic profile across Cha-am marsh; c. view of marsh showing tidal creek (foreground), vegetated and unvegetated marsh surface (view from building shown in Fig. 2a); d. beach ridge plain at Kui Buri showing topographic survey points (blue circles) and the two swales where vibracores were collected (yellow squares) (Google Earth image, 2014); e. topographic profile across Kui Buri beach ridge plain; f. view of the swale at vibracore site SRY4, looking northeast.

Marine Transgression (Geyh et al., 1979; Hesp et al., 1998; Sinsakul, 1990, 1992; Somboon and Thiramongkol, 1992; Streif, 1979; Thiramongkol, 1984; Tjia, 1996). There is wide agreement amongst these studies of rapid sea level rise in the early Holocene, culminating in a mid-Holocene highstand, followed by a more gradual fall of the sea to its present level. However, more recent studies have emphasized the considerable temporal and spatial variability in both the timing and magnitude of the highstand, driven mainly by hydro-isostasy (Horton et al., 2005; Scheffers et al., 2012). Whereas a maximum highstand of about 5 m has been reported for the Straits of Malacca (Geyh et al., 1979), dating of geologic and biologic sea-level indicators and geophysical modeling suggests the highstand in the study area was probably substantially lower. Choowong (2002) and Choowong et al. (2004),

for example, combining new data and a summary of earlier study results, estimated a maximum highstand of about 3.5 m for the Gulf of Thailand (although there are elements of uncertainty and spatial variability in the summarized data). Reinterpretation of two radiocarbon-dated sea-level index points indicate a sea level in the study area of 2 ± 0.7 m a.m.s.l. at 4400–3400 cal. yr. BP and 1.5 ± 0.7 m a.m.s.l. at 3200–2400 cal. yr. BP (Horton et al., 2005). These two index points presumably record the gradual retreat of the sea from its mid-Holocene (ca. 6000 cal. yr. BP) highstand. Geophysical modeling conducted by Horton et al. (2005) appears to overpredict sea level between ca. 8000–4000 cal. yr. BP at this site and most other sites around the Thai–Malay Peninsula, suggesting that the highstand in the study area was probably on the order of 2–3 m a.m.s.l. (Fig. 3).

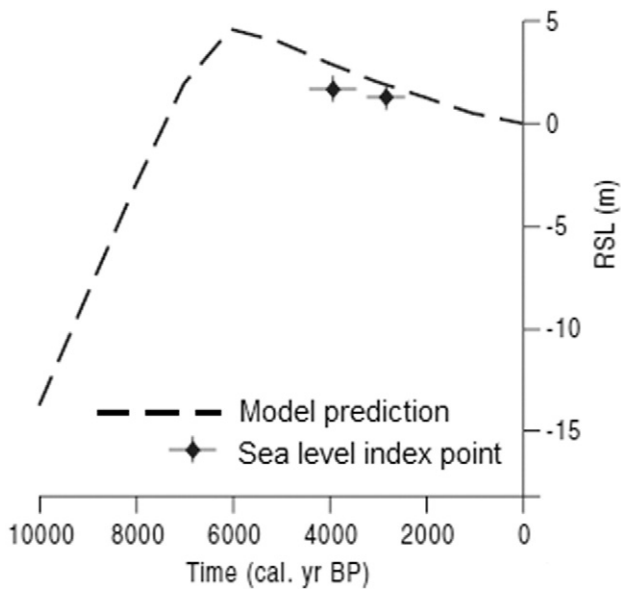


Fig. 3. Geophysical model prediction of Holocene sea-level behavior and radiocarbon-dated sea-level index points for Kui Buri region, Gulf of Thailand (modified from Horton et al., 2005; error bars on sea-level index points represent temporal and sea-level uncertainty).

3. Methods

3.1. Topographic profiles

Surveying was conducted by total station, providing spatial coordinates and elevations for all surveyed points. Topographic profiles were referenced to local tide level at the time the surveys were made. Elevations were converted to meters a.m.s.l. using tide tables obtained from tide gauge stations at Hua Hin, about 24 km south of Cha-am, and Ko Lak, about 25 km south of Kui Buri (Thai Royal Navy, 2014). At Cha-am, mean sea level is 1.76 m above the tide datum of mean lowest low water (m.l.l.w.). Mean tidal range is 1.26 m. At Kui Buri, mean sea level is 1.61 m a.m.l.l.w. and mean tidal range is 1.03 m.

3.2. Marsh stratigraphy

Spade pits, ~40 cm deep, were used to examine shallow sediments at all sites. Coring was used to reveal and sample the deeper stratigraphy. Vibracores were obtained by driving thin-walled 7.5-cm-diameter aluminum tubes into marshes until coring was stopped by resistance. At Cha-am, a series of eight cores was obtained along a transect approximately perpendicular to the coastline, extending about 800 m inland from the beach (Fig. 2 a, b; cores V1 – V8). At Kui Buri, three cores were obtained from the swale closest to the coastline, all within ~10 m of each other – cores 2 and 3 were attempts to penetrate deeper into the swale deposits (Fig. 2 d, e; cores SRY 1, 2, & 3). Another core was obtained from the second swale, farther inland (Fig. 2 d, e; core SRY 4). All cores were checked for compaction by measuring the distance between the top of the core inside the coring tube and the ground surface. Compaction was found to be negligible, presumably because the sediments were not readily compactible, consisting mostly of dense mixtures of mud and clay or mud and sand, with relatively low organic contents. Most cores were in the range of 1–2 m in length. Core tubes were sealed upon extraction and transported to a lab at Chulalongkorn University where the tubes were cut lengthwise and the sediment cores within were split into two halves longitudinally. Cores were logged in the lab, photographed and sampled at selected depths for textural analysis, foraminiferal analysis, and radiocarbon age determinations. Sediment samples were also collected from the beach and shallow off-shore (~1 m depth at the time of collection) at both study areas, because

these locations represent potential sediment sources of washover deposits.

3.3. Textural analysis

Sediment samples were collected from selected cores from within, below and above suspected typhoon-deposited sand layers for textural and microfossil analyses to help document contrasts in lithology and microfossil content between the sand layers and the enclosing sediments. All samples were divided into two subsamples for analysis. One subsample was weighed and then oven-dried at 105 °C for the determination of moisture content (% wet weight). The other subsample was weighed and then wet-sieved through a 63- μ m sieve to retain the sand fraction. The sand fraction was air-dried and weighed. The measured moisture content was used to calculate the dry weight of the sieved sample, and the weight of the sand fraction was then used to calculate sand content (% dry weight).

Particle size analysis was conducted on sand fractions from sand layers of suspected typhoon origin using sieves at 0.25 phi unit intervals from –1 phi (2 mm) to 4 phi (63 μ m). A few samples contained fine-gravel-sized clasts in the 2 mm sieve. The sieve data was analyzed using the GRADISTAT program (Blott and Pye, 2001), which provided particle size parameters using graphical procedures proposed by Folk and Ward (1957).

3.4. Microfossil analysis

Sand fractions derived from wet sieving were examined under a dissecting microscope to identify and count foraminifers. If the sand fraction was small (<1 g), the entire sample was examined for foraminifers; if the sand fraction was large (>1 g), a subsample (typically 0.2–0.5 g) was examined and foraminiferal counts were multiplied accordingly to estimate the number of specimens in the entire sample. The total number of foraminifers in the sample was used to calculate the number of foraminifers per gram of dry sediment.

3.5. Radiocarbon dating

None of the twelve cores collected for the study contained large amounts of organic material; for example, no peat layers were encountered. Modern roots and rhizomes, penetrating down into the sediment, were found in parts of some cores, but this material was not abundant. Small shell fragments were common in some cores and wood/plant fragments were rare, but present, in some cores. Wood and plant fragments were selected for AMS radiocarbon dating on the assumption that these relatively delicate materials were less likely to survive extensive reworking and would more closely date the age of enclosing sediments than the generally more robust shell fragments. Samples were obtained from within some suspected typhoon-deposited sand layers and from within enclosing finer-grained sediments. Eight samples were submitted for radiocarbon age determinations – five samples from the coastal marsh at Cha-am and three samples from the swales at Kui Buri. Samples were submitted to the NSF AMS radiocarbon dating lab at the University of Arizona.

4. Results

4.1. Marsh stratigraphy, texture and microfossils

Cha-am coastal marsh: all eight cores from the Cha-am marsh site contained at least one, and up to seven, anomalous sand layers, with sharp upper and lower contacts with enclosing finer-grained, more organic-rich, deposits. The sand layers contain between 58% and 98% sand (> 63 μ m fraction); the intervening deposits range from 1% to 53% sand content. Texturally, the sand layers vary from well sorted to poorly sorted and very fine sand to sandy very fine gravel (Table 1).

Table 1
Cha-am tidal marsh: textural characteristics and foraminiferal contents.

Core number and depth (cm)	Sedimentary unit	Sand %	Mean grain size (um)	Folk and Ward (1957) textural description	Foraminiferal content (number/g)
V1 3	Sand layer	78	151	Moderately well sorted fine sand	0
V1 7	Marsh ^a	32	N/A	N/A	0
V1 24	Sand layer	96	159	Well sorted fine sand	0
V1 26	Marsh	17	N/A	N/A	0
V2 1	Sand layer	69	128	Moderately well sorted very fine sand	0
V2 3	Marsh	53	N/A	N/A	0
V2 37	Marsh	48	N/A	N/A	0
V2 41	Sand layer	83	459	Moderately sorted medium sand	0
V2 47	Marsh	3	N/A	N/A	0
V2 53	Sand layer	87	405	Moderately sorted medium sand	0
V2 55	Marsh	32	N/A	N/A	0
V3 15	Sand layer	73	242	Moderately well sorted fine sand	0
V3 18	Marsh	36	N/A	N/A	0
V3 39	Sand layer	84	186	Well sorted fine sand	0
V3 43	Marsh	30	N/A	N/A	0
V4 50	Marsh	41	N/A	N/A	0
V4 56	Sand layer	75	446	Poorly sorted coarse sand	0
V4 67	Marsh	16	N/A	N/A	0
V4 99	Sand layer	80	242	Moderately sorted fine sand	0
V5 102	Marsh	10	N/A	N/A	0
V5 107	Sand layer	58	344	Poorly sorted coarse sand	0
V5 110	Marsh	3	N/A	N/A	0
V5 117	Sand layer	79	727	Very fine gravelly coarse sand	0
V5 119	Marsh	1	N/A	N/A	0
V5 128	Sand layer	95	1041	Very fine gravelly coarse sand	0
V5 131	Marsh	8	N/A	N/A	0
V5 136	Sand layer	91	520	Slightly very fine gravelly coarse sand	0
V5 157	Marsh	16	N/A	N/A	0
V5 162	Sand layer	90	1127	Sandy very fine gravel	0
V5 166	Marsh	31	N/A	N/A	0
V5 168	Sand layer	90	954	Sandy very fine gravel	0
V5 170	Marsh	2	N/A	N/A	0
V6 79	Marsh	27	N/A	N/A	0
V6 84	Sand layer	94	360	Moderately sorted medium sand	0
V7 74	Marsh	51	N/A	N/A	0
V7 89	Sand layer	98	462	Moderately well sorted medium sand	0
Cha-am beach	Beach	100	438	Moderately sorted medium sand	0
Cha-am offshore	Shallow marine	98	236	Moderately sorted fine sand	22

^a Because of the mid-Holocene sea-level highstand, "marsh" deposits in deeper, older parts of cores are probably intertidal/subtidal deposits (see discussion section).

In addition to sharp upper and lower contacts, there are other indications of a high-energy storm-surge origin for the sand layers. Five sand layers in core V5 contain gravel-sized clasts (> 2000 um). Two of these layers have a textural classification of sandy very fine gravel (Table 1). A coarse sand layer in core V5 at a depth of 1.1 m contains abundant large plant fragments; another sand layer in the same core at a depth of 1.58 m contains a large wood fragment at the top of the layer. The presence of organic detritus within or on top of sand layers suggests the sand and organic debris were both transported by the same mechanism, presumably a large storm surge. Sand layers in cores V3 and V5 contain large mud rip-up clasts (~1–2 cm), apparently derived from erosion of underlying deposits (Figs. 4, 5).

A sample from the beach at the Cha-am site contained 100% sand and was classified as moderately sorted medium sand. A sample from offshore (~1 m water depth at the time of collection) contained 98% sand and was classified as moderately sorted fine sand. Neither sample contained gravel-sized clasts. Shell fragments were common in both samples. Texturally, the samples from the beach and shallow offshore are similar to many of the sand layers found at this site, with the exception of the five sand layers containing gravel-sized clasts in core V5. The source of this gravel is uncertain, but it may be that the beach and shallow offshore zones contained coarser sediment in the past, which is reflected in these washover sand layers. Another possibility is that storm surges eroded gravel-sized clasts from older coarser-textured sediments underlying the marsh deposits, perhaps exposed in the floors of tidal channels.

With the exception of the sample from the shallow offshore zone, all samples at the Cha-am site were barren of foraminifera (Table 1). The modern marsh surface is frequently flooded by freshwater from rain runoff; if similar conditions prevailed at times in the past, this could explain the lack of foraminifera in some of the marsh deposits (i.e. they are primarily freshwater deposits). It is not uncommon for beaches, particularly if coarse-grained, to lack foraminifera.

The shallow offshore sample contained 22 specimens of foraminifera per gram of sediment, all common calcareous marine species. This is a low concentration of foraminiferal tests. If conditions were similar in the past and the sand layers in the marsh consist of beach and shallow offshore sediments transported inland by a storm surge, this could explain the lack of foraminifera in these deposits. It is also possible that foraminiferal tests were initially present, but not preserved in the marsh deposits because of dissolution of calcareous tests, bacterial degradation of agglutinated tests, or metazoan ingestion (Williams, 2010).

Kui Buri swale sites: the four cores from the Kui Buri swale sites all contained anomalous sand layers with sharp upper and lower contacts with enclosing finer-grained swale deposits. The number of sand layers varied from two (in core SRY 2) to eight (in core SRY 3). All sand layers were found in the deeper parts of the cores, between 0.79 and 2.06 m depth; there were no sand layers in the fairly uniform fine-grained swale deposits above this interval. The sand layers contain between 63% and 98% sand; the intervening swale deposits range from 2% to 68% sand content. Texturally, the sand layers at Kui Buri are more

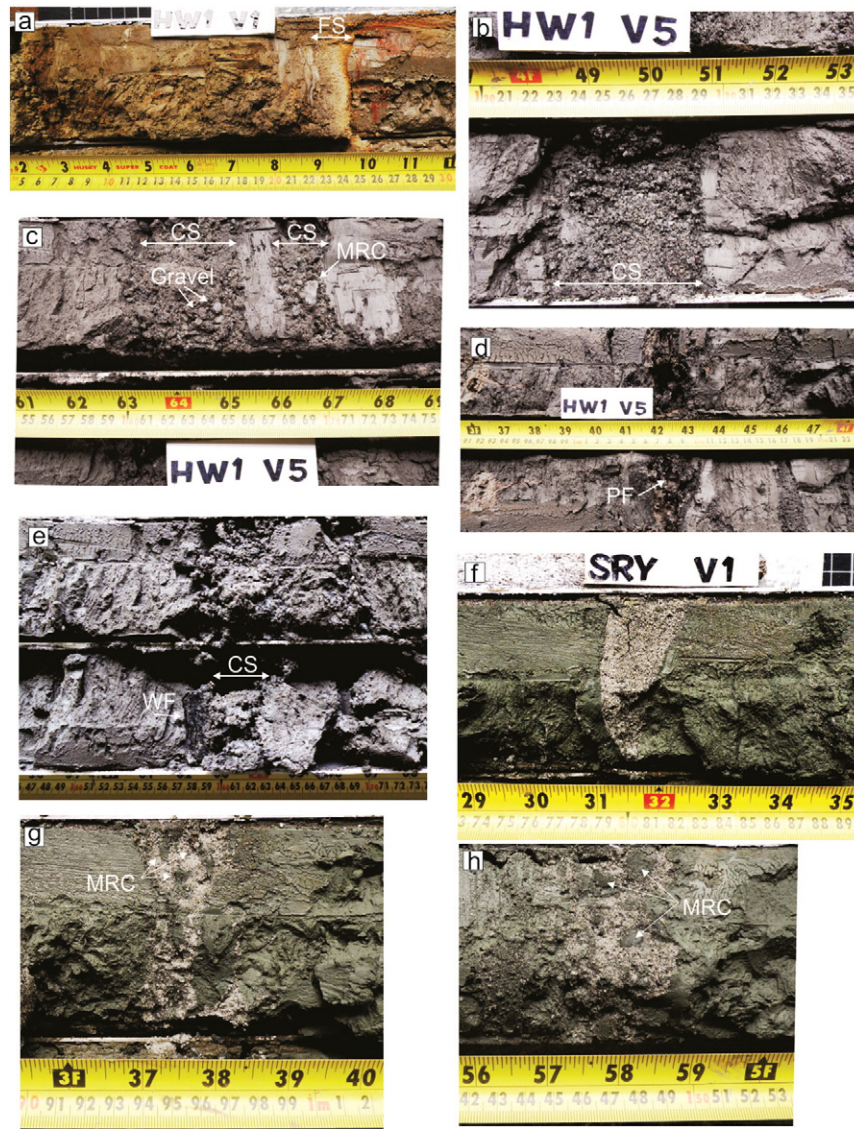


Fig. 4. a. Fine sand layer, with sharp upper and lower contacts, in core HW1 V1, depth 0.25 m; b. coarse sand layer, with gravel-sized clasts and sharp upper and lower contacts, in core HW1 V5, depth 1.25–1.29 m; c. two coarse sand layers in core HW1 V5, depth 1.6–1.72 m. Both layers have sharp contacts and gravel-sized clasts. The deeper layer contains a large mud rip-up clast (MRC); d. layer of sand and large plant fragments in core HW1 V5, depth 1.1 m. The layer has sharp contacts with enclosing fine sediments; e. large wood fragment (WF) on top of a coarse sand layer (CS) in core HW1 V5, depth 1.58 m; f. sand layer with abundant fine shell fragments in core SRY V1, depth 0.8 m. The layer has sharp contacts with enclosing swale deposits; g. multiple mud rip-up clasts (MRC) in a sand layer in core SRY V1, depth 0.95 m; h. multiple mud rip-up clasts (MRC) in a sand layer in core SRY V3, depth 1.48 m. Ruler has cm and inch markings.

uniform than those found at Cha-am; all layers fall into the classifications of well sorted or very well sorted fine sand (Table 2).

Other indications of a high energy storm surge origin include abundant fine shell fragments in a sand layer in core SRY 1 and sand layers

containing multiple mud rip-up clasts in cores SRY 1 and SRY 3 (Fig. 4). A sample from the beach at the Kui Buri site contained 99% sand and was classified as very well sorted very fine sand. A sample from offshore (~1 m water depth at the time of collection) contained 96% sand and was also classified as very well sorted very fine sand. Texturally, the samples from the beach and shallow offshore are similar to all the sand layers found at this site. Assuming the beach and shallow offshore zones had similar sediment characteristics in the past when the sand layers were deposited, the beach and/or offshore zone may have been the source of these sand layers; the slight increase in mean grain size in the sand layers compared to the beach and offshore zone, could have resulted from sorting of the sand during transport and deposition. In contrast to the Cha-am site, none of the sediment samples from the Kui Buri site contained gravel-sized clasts.

All sediment samples from the Kui Buri site contained foraminifera (Table 2). Concentrations range from very low (2 specimens per gram) to abundant (1034 specimens per gram). Generally, the sand layers have higher foraminiferal concentrations, but there are exceptions – the

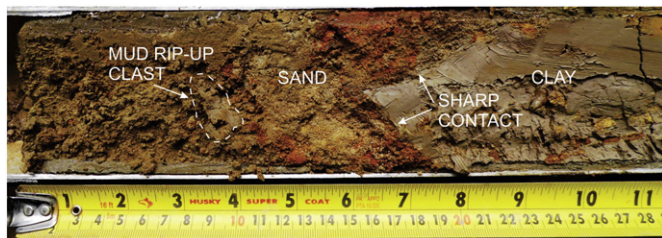


Fig. 5. Upper part of core V3 from the Cha-am coastal marsh site (see Fig. 2a for location; top of core is to the left). Sixteen centimeters of oxidized fine sand overlies clay with a sharp contact. A mud rip-up clast is enclosed within the sand layer. Ruler has inch and cm scales.

Table 2

Kui Buri Swales: Textural Characteristics and Foraminiferal Contents.

Core number and depth (cm)	Sedimentary unit	Sand %	Mean grain size (um)	Folk and Ward (1957) textural description	Foraminiferal content (number/g)
V1 79	Marsh ^a	60	N/A	N/A	188
V1 80	Sand layer	98	151	Very well sorted fine sand	443
V1 83	Marsh	2	N/A	N/A	72
V1 95	Sand layer	84	169	Well sorted fine sand	57
V1 98	Marsh	17	N/A	N/A	16
V1 121	Sand layer	97	156	Very well sorted fine sand	325
V1 124	Marsh	43	N/A	N/A	193
V1 126	Sand layer	97	143	Very well sorted fine sand	448
V1 128	Marsh	7	N/A	N/A	21
V2 101	Marsh	41	N/A	N/A	2
V2 104	Sand layer	96	183	Well sorted fine sand	100
V2 106	Marsh	6	N/A	N/A	9
V3 120	Marsh	25	N/A	N/A	6
V3 121	Sand layer	98	174	Well sorted fine sand	88
V3 123	Marsh	7	N/A	N/A	5
V3 143	Marsh	43	N/A	N/A	60
V3 147	Sand layer	97	201	Well sorted fine sand	20
V3 151	Marsh	6	N/A	N/A	2
V3 190	Marsh	8	N/A	N/A	12
V3 192	Sand layer	97	137	Well sorted fine sand	1034
V3 198	Sand layer	96	142	Well sorted fine sand	476
V3 200	Sand layer	63	142	Well sorted fine sand	760
V3 206	Sand layer	94	145	Well sorted fine sand	750
V3 208	Marsh	11	N/A	N/A	335
V4 111	Marsh	68	N/A	N/A	400
V4 114	Sand layer	96	140	Very well sorted fine sand	115
V4 117	Marsh	32	N/A	N/A	35
V4 118	Sand layer	98	157	Very well sorted fine sand	81
V4 127	Marsh	28	N/A	N/A	8
V4 128	Sand layer	98	143	Very well sorted fine sand	16
V4 131	Marsh	3	N/A	N/A	8
V4 140	Sand layer	98	144	Very well sorted fine sand	51
V4 142	Marsh	43	N/A	N/A	82
Kui Buri beach	Beach	99	114	Very well sorted very fine sand	394
Kui Buri offshore	Shallow marine	96	107	Very well sorted very fine sand	133

^a Because of the mid-Holocene sea-level highstand, “marsh” deposits in deeper, older parts of cores are probably intertidal/subtidal deposits (see discussion section).

sand layer at a depth of 1.28 m in core SRY 4 contained only 16 specimens per gram, while the swale deposit at a depth of 1.11 m in the same core contained 400 specimens per gram (Table 2).

The ubiquitous presence of foraminifera throughout the swale deposits indicates a constant marine influence on the swales as they filled with sediment, at least in the lower part of the swale deposits covered by sampling. Foraminifera found in the samples are entirely common marine calcareous forms. No agglutinated marsh forms were encountered. *Ammonia* spp., *Elphidium* spp. and *Quinqueloculina* spp. are prominent in the foraminiferal assemblages. These taxa are all common in intertidal and shallow offshore zones in the Gulf of Thailand (Melis and Violanti, 2006). *Ammonia* spp. and *Elphidium* spp. are known to be tolerant of harsh environments, for example, they can thrive in brackish water conditions caused by significant freshwater inputs. *Ammonia* spp., *Elphidium* spp. and *Quinqueloculina* spp. are also dominant in the offshore sample from the Cha-am site, but in much lower numbers.

Stratigraphy at the Cha-am marsh site was based on the assumption that the sand layers represent washover sediments transported by a storm surge and deposited into the study area. Correlation of sand layers between cores was based primarily on depth and the assumption that relief of former surfaces was similar in the past to that of the present day (~0.3–0.4 m; Fig. 2). Other criteria used in correlation were textural character of the sand layers and the presence of mud rip-up clasts. Resulting correlations suggest there are eleven washover sand layers recorded in the Cha-am marsh (Fig. 6). Layer 1, at the surface of the marsh, is found in cores V1, V2, V3, V4 and V8, and is presumably of recent origin (Fig. 5). The occurrence of this sand layer in five out of eight cores indicates that washover deposits may not be continuous over the entire marsh surface. Williams (2013) found a similar “patchy” distribution of

washover sand deposited by Hurricane Rita in a Louisiana coastal marsh. Layer 2 is found in cores V1, V2, V3 and V4, at depths ranging from 0.24 to 0.56 m. Layer 3 is found only in cores V2 and V3, at depths of 0.39 to 0.51 m. Layer 4, which appears stratigraphically below layer 3, is found only in cores V6 and V7, at depths from 0.7 to 0.8 m. Layer 5 is found in cores V4, V5, V6 and V7, at depths ranging from 0.83 to 1.05 m. This layer is relatively thick, ranging from 5 to 15 cm, which contributed to its correlation. The remaining six layers were found only in core V5, the longest core at 1.83 m. Layers 6 through 11 are found in core V5 at depths ranging from 1.17 to 1.68 m.

Stratigraphy at the Kui Buri swales site was based primarily on stratigraphic position; the first sand layer encountered in each core was correlated and assumed to represent a washover deposit which formed a sand layer on the floor of both swales. Other sand layers at increasing depths within the cores were similarly correlated (Fig. 6). The resulting correlations indicate that eight washover sand layers are recorded in the four cores taken at this site. Layers 1 through 5 are found in core SRY 1, layers 1 and 2 are present in core SRY 2, all eight layers are recorded in core SRY 3, and layers 1 through 4 are found in core SRY 4. No sand layers were found in the upper parts of the four cores, from the surface to depths ranging from 0.8 m to 1.21 m (Fig. 6).

4.2. Radiocarbon dating

The results of AMS radiocarbon dating are shown in Table 3. Ages indicated on Fig. 6 are mean values of 2-sigma calibrated age ranges. The two radiocarbon ages from core SRY 4 at Kui Buri are clearly inverted (an older date above a younger date in the same core). This has presumably resulted from reworking and re-deposition of older organic detritus

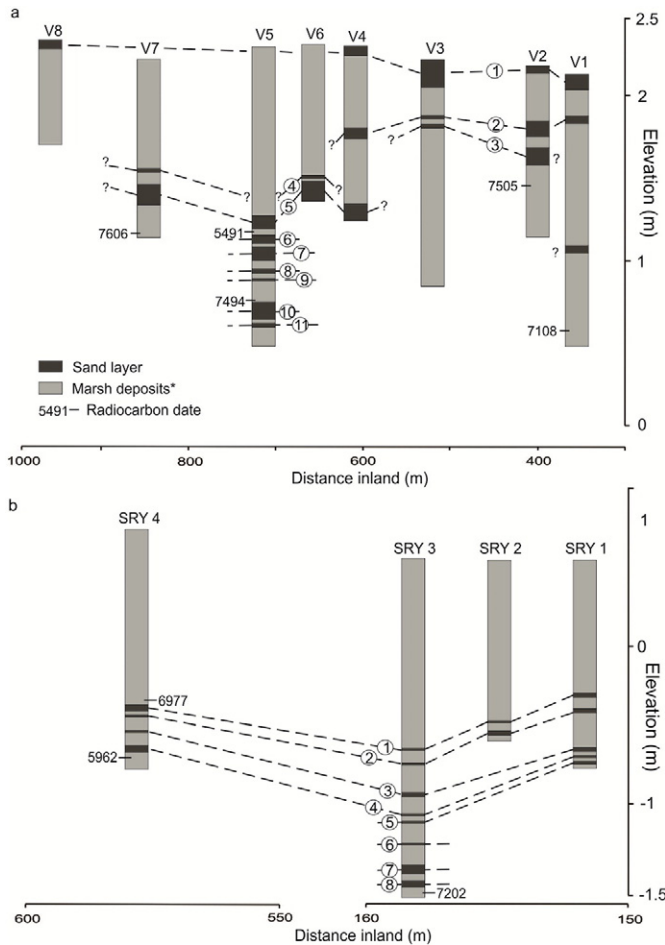


Fig. 6. Stratigraphy showing suspected storm-surge-deposited sand layers and intervening marsh deposits*, proposed correlations and radiocarbon dates, at a. Cha-am coastal marsh and b. Kui Buri swales. Radiocarbon dates are averages of 2-sigma calibrated age ranges. * Because of the mid-Holocene sea-level high stand, “marsh” deposits in deeper, older parts of cores are probably intertidal/subtidal deposits (see discussion section).

(resulting in the shallower older date) or from contamination by a root penetrating down through the sediment column from a higher level within the core (resulting in the deeper younger date). Radiocarbon dates were calibrated to calendar years using the CALIB 7.0.2 calibration program and the Reimer et al. (2013) dataset intcal13.

5. Discussion

The main diagnostic criterion for proposing a high-energy storm-surge origin for the sand layers found at Cha-am and Kui Buri are the sharp upper and lower contacts with enclosing finer-grained deposits. The sharp contacts imply abrupt transport of much coarser-grained sediment into these sites, followed by an equally abrupt return to finer-

grained sedimentation. It is unlikely that any other mechanism could have deposited the sand layers. A fluvial flood origin can be ruled out for sand layers at the Cha-am site because there are no significant fluvial sources in this area. The swale sites at Kui Buri are close to the Kui Buri River and there may well have been an open connection between the river and swales in the past, but the presence of large concentrations of marine foraminifera in the sand layers at this site argues against a fluvial origin for the sand. Slope wash or mass wasting processes from slopes surrounding the swale sites can also be ruled out because of the presence of foraminifera in the sand layers. The Cha-am site is surrounded by essentially flat terrain, making a mass wasting origin for the sand layers at this site unlikely. The migration of tidal channels at the Cha-am site could create a sharp erosional contact with underlying marsh deposits, but the transition back to marsh deposits as the channel migrated away would presumably record a more gradual return to finer-grained sedimentation, rather the abrupt sharp upper contact recorded in all of the sand layers.

Other evidence that supports a high-energy storm-surge origin includes the presence of gravel clasts and organic debris in sand layers at the Cha-am site and the inclusion of mud rip-up clasts in several sand layers at both sites, implying erosion of the local surface coincident with emplacement of the sand layers. The AMS radiocarbon dates suggest a recurrence interval for the emplacement of the sand layers on the order of centuries; this rarity of the events that deposited the sand layers also argues in favor of an infrequent, high-energy storm-surge origin. Typhoons are the rarest form of tropical cyclone to strike Thailand; for example, in the 60-year period 1951–2010, out of 185 tropical cyclones to make landfall, 171 were tropical depressions, 13 were tropical storms and only one was a typhoon (Thai Meteorological Department, 2015).

A tsunami origin for the sand layers is unlikely. There is no historical evidence for tsunami overwash on the east coast of Thailand (in contrast to the west coast, where large, destructive tsunamis do occur). Modeling of tsunamis generated at the Manila Trench, approximately 2500 km to the east, indicates a maximum wave amplitude at the coast of the Gulf of Thailand of about 0.65 m, in response to a Mw 9.0 earthquake. Attenuation of tsunami waves in the Gulf of Thailand is caused by diffraction of waves around the coast of Vietnam (Ruangrassamee and Saelem, 2009; NGI and NORSAR, 2009).

On the assumption that all 19 sand layers record typhoon strikes, age–depth models can be used to estimate the ages of typhoon strikes for each study area. The R software package BACON (Bayesian accumulation histories; Blaauw and Christen, 2011) was used to create an age–depth model for each site, using uncalibrated AMS radiocarbon dates and an age of -2 cal. yr. BP for the surface at Cha-am (AD1952 – landfall of Typhoon Vae – see discussion below) and an age of -63 cal. yr. BP for the surface at Kui Buri (AD2013 – the year the cores were collected) (Fig. 7). BACON utilizes Bayesian techniques for calibration and age modeling simultaneously. Prior information, such as stratigraphic order, is incorporated into the calibration approach ensuring that age models are consistent with sample order and that modeled ages increase with increasing depth. This approach has been shown to produce reliable age–depth models, with effective handling of outliers and with more realistic estimates of age model uncertainties (Shanahan et al., 2012).

Because the typhoon-deposited sand layers represent “instantaneous events”, thicknesses of these deposits were excluded from core depths for the purposes of age estimation. The depth of sand layers used to estimate ages was the average depth to the basal contact of each layer. These depths were used to obtain 95% probability age ranges and mean age for each typhoon strike from the age–depth models. The resulting estimated ages of typhoon strikes have large uncertainties because of the low number of radiocarbon dates used to construct the age models (Table 4).

The age and origin of sand layer 1 at Cha-am is uncertain, but its position on the surface of the marsh suggests it is a recent washover

Table 3
Radiocarbon ages and calibrated age ranges & mean.

Core number	Depth (m)	Material	14C age BP & error	2-sigma calibrated age range & mean
HW1 V1	1.50	Wood	6192 ± 47	6971–7244, 7108 cal. yr. BP
HW1 V2	0.72	Wood	6623 ± 48	7436–7574, 7505 cal. yr. BP
HW1 V5	1.10	Wood/plants	4815 ± 45	5336–5645, 5491 cal. yr. BP
HW1 V5	1.58	Wood	6564 ± 49	7419–7568, 7494 cal. yr. BP
HW1 V7	1.05	Wood	6769 ± 49	7523–7688, 7606 cal. yr. BP
SRY V3	2.09	Wood/plants	6269 ± 96	6982–7421, 7202 cal. yr. BP
SRY V4	1.10	Wood	6083 ± 47	6797–7156, 6977 cal. yr. BP
SRY V4	1.44	Wood	5174 ± 45	5754–6169, 5962 cal. yr. BP

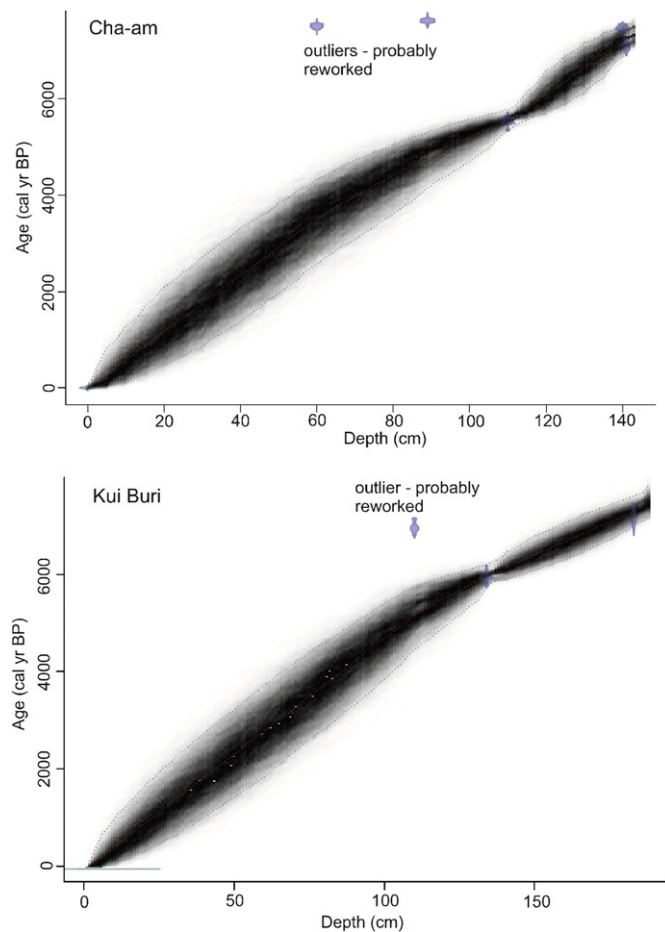


Fig. 7. Bayesian age–depth models for site HW1 near Cha-am and site SRY near Kui Buri. Blue markers represent calibrated radiocarbon dates, gray stippled lines show 95% confidence intervals; red curve shows single 'best' model based on the weighted mean age for each depth.

deposit. The oldest air photo available of the study area, from 1967, shows a bright, largely unvegetated marsh surface with what appear to be lobes of sand extending out from the marsh margins (Fig. 8).

Table 4
Estimated Ages of Assumed Typhoon Strikes for the Cha-am and Kui Buri Sites.

Study area	Sand layer	Average depth ¹ (m)	Estimated age (cal. yr. BP)	
			95% probability range	Mean age
Cha-am	1	0	–	1952 AD ²
Cha-am	2	0.308	908–2759	1789
Cha-am	3	0.32	982–2829	1863
Cha-am	4	0.75	3341–4893	4197
Cha-am	5	0.865	3990–5234	4709
Cha-am	6	1.11	5398–5821	5611
Cha-am	7	1.15	5550–6158	5804
Cha-am	8	1.21	5755–6630	6141
Cha-am	9	1.23	5831–6736	6254
Cha-am	10	1.40	6875–7526	7220
Cha-am	11	1.42	7045–7575	7294
Kui Buri	1	1.04	4075–5531	4870
Kui Buri	2	1.10	4448–5734	5151
Kui Buri	3	1.27	5245–6066	5717
Kui Buri	4	1.36	5807–6244	6004
Kui Buri	5	1.42	5910–6479	6166
Kui Buri	6	1.72	6620–7351	6990
Kui Buri	7	1.82	6949–7585	7264
Kui Buri	8	1.87	7126–7740	7427

¹ Depths exclude sand layer thicknesses; depth is to basal contact of sand layer.

² Assumed to be storm surge deposit of Typhoon Vae 1952.

These features are consistent with a recent washover deposit and suggest deposition occurred sometime prior to 1967. A likely candidate for the storm that formed this washover deposit is Typhoon Vae, which crossed the northern Gulf of Thailand in 1952 (Fig. 1). Typhoon Vae made landfall in Vietnam with typhoon-strength winds, but then, crossing land, it degraded to tropical storm status as it entered the northern Gulf of Thailand. Nevertheless, the storm caused extensive damage in Thailand due to strong winds, a storm surge of 1.2 m and waves up to 2.5 m high (Vongvisessomjai, 2007). The combination of storm surge and waves would have been sufficient to overtop the marsh, particularly if the storm occurred during high tide conditions in the study area.

The age model results raise the possibility that many sand beds at the two sites may be coeval, presumably recording washover at both sites caused by the same typhoon strikes. All eight typhoon deposits at Kui Buri overlap in age with one or more of sand beds 4–11 at Cha-am (Table 4). Williams (2012) found that Hurricane Ike deposited relatively thick sand layers into marshes along about 150 km of the Gulf of Mexico coastline and so the possibility that on up to eight occasions the same typhoon formed washover deposits at Cha-am and Kui Buri, which are about 80 km apart, is plausible. However, given the large uncertainties in age ranges, the number of coeval deposits, if any, cannot be precisely determined.

Despite the large uncertainties in ages, the frequency of typhoon strikes over the ca. 8000 year period covered by coring is clearly uneven: three or four typhoon strikes are recorded in the period 0–3900 cal. yr. BP (depending on whether sand layer 4 at Cha-am was deposited before or after 3900 cal. yr. BP), whereas as many as 16 typhoon strikes or as few as 8 typhoon strikes are recorded in the period 3900–7800 cal. yr. BP (depending on whether none, some or all of the typhoon strikes prior to 3900 cal. yr. BP are coeval between the two sites). At a minimum, there were twice as many typhoon strikes prior to 3900 cal. yr. BP compared to after 3900 cal. yr. BP (8 typhoons before 3900 cal. yr. BP, 4 typhoons after 3900 cal. yr. BP); at a maximum, there were approximately five times as many typhoons before 3900 cal. yr. BP, compared to after 3900 cal. yr. BP (three typhoons from 0 to 3900 cal. yr. BP; 16 typhoons from 3900 to 7800 cal. yr. BP) (Table 4, Fig. 9).

A possible reason for this uneven frequency of typhoon strikes is heightened site sensitivity in the mid-Holocene, increasing the chances of a nearby typhoon strike being recorded by a washover sand layer. Another possibility is that a change in climatic conditions in the mid Holocene increased the frequency and/or intensity of typhoons making landfall in the Gulf of Thailand. Higher intensity typhoons are more likely to cause overwash of coastal barriers and form a relatively thick, laterally extensive and preservable washover deposit.

Many factors influence the formation, magnitude and preservation of washover deposits at a given site, including proximity to landfall, position relative to cyclonic wind field, storm surge height, wave height, wind speed, barrier height, thickness and lithology of washover sediments and post-storm sedimentation and bioturbation (Williams, 2011, 2012; Williams and Flanagan, 2009). The mid-Holocene sea-level highstand in the Gulf of Thailand presumably increased sensitivity to typhoon strikes at both sites because their relative elevations were lower, increasing the likelihood of storm surge overwash. Geomorphology at the two sites during the mid-Holocene is uncertain, but it is probable that both sites were below sea-level at the peak of the highstand around 6000 cal. yr. BP and became elevated above sea-level in the last three to four thousand years (Figs. 3, 6).

It is possible that both sites were lagoons at the peak of the highstand and the deeper parts of cores at both sites contain fine-grained lagoonal sediments; this is consistent with the sediment record at both sites – predominantly low-energy, fine-grained sedimentation, generally low organic content, but close enough to shore to receive wood and plant fragments from land nearby, punctuated by rare high-energy inputs of sand presumably transported from sandy barriers and/or offshore deposits by typhoon storm surges. The foraminiferal

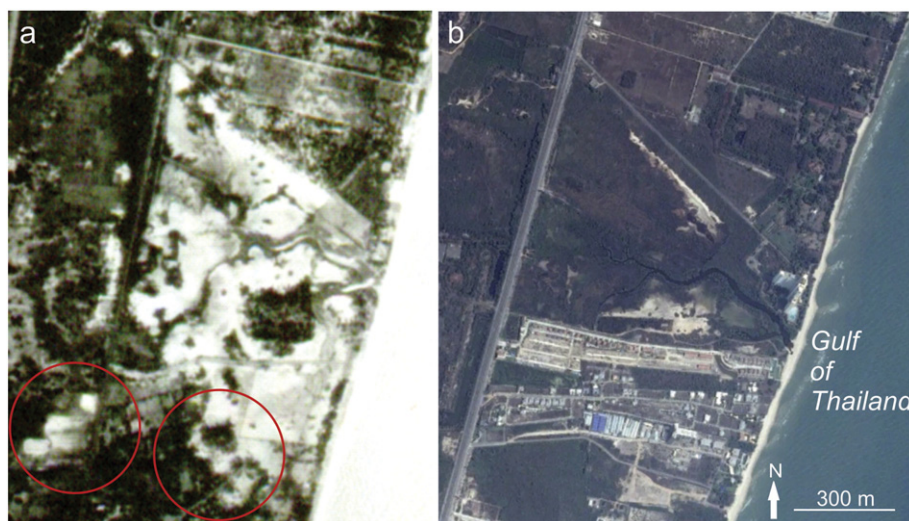


Fig. 8. a. Study area near Cha-am in 1967. The surface of the marsh appears to be largely unvegetated sand. What appears to be recent depositional lobes (circled) extend from the margins of the marsh (Royal Thai Survey image); b. the study area in 2014; the marsh is largely vegetated (Google Earth image 2014).

record at Kui Buri is consistent with this interpretation because it shows persistent marine influence throughout the sampled part of the cores, from ca. 4075 to 7740 cal. yr. BP (Table 2). The reason for the lack of foraminifers at Cha-am is uncertain: it may be that the site had strong freshwater inputs or foraminiferal tests were poorly preserved. As sea-level fell from its highstand, both sites must have transitioned from sub-tidal to supra-tidal conditions; however, there are no apparent lithologic changes within the cores to mark this transition.

Falling sea-level in the late-Holocene presumably decreased sensitivity to typhoon strikes at both sites. The 2–3 m drop in sea-level increased relative elevation of the sites and increased their distance from the coastline. Other factors, such as depositional progradation of the coastline, vertical growth of barrier crests and closure of tidal inlets, may also have contributed to lower sensitivity at these sites. However, it seems unlikely that decreased sensitivity alone explains the reduction in the number of typhoon-deposited sand layers post-3900 cal. yr. BP. Despite falling sea-level, both sites remain at a relatively low elevation (below ~2 m a.m.s.l.) and are within a few hundred meters of the coastline. At Cha-am, Typhoon Vae, which was only tropical storm strength at landfall, was presumably able to transport sand over 800 m into the marsh. A higher-intensity storm, such as Typhoon Gay, which reportedly had 11-m-high swells and 185 km/h winds at landfall, would very likely be capable of transporting sediment into both sites and forming preserved geologic records.

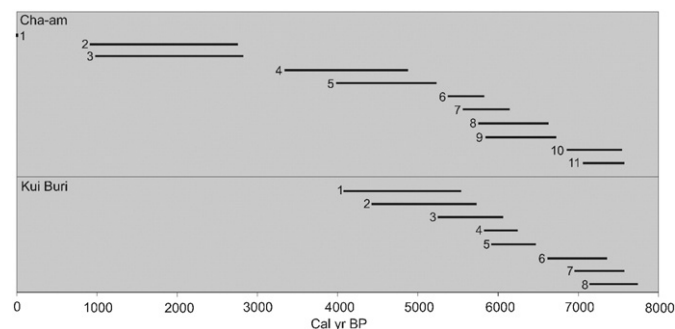


Fig. 9. Bayesian age–depth model derived 95% probability ranges of ages of typhoon strikes recorded at Cha-am and Kui Buri. Some of sand beds 4–11 at Cha-am may be coeval (result of the same typhoon strike) with sand beds at Kui Buri, but the precise number cannot be determined because of the large uncertainties in ages.

Over the last few decades tropical cyclone climatology research has focused on linking evidence of millennial-scale tropical cyclone variability to climatic changes within the Holocene. The underlying premise of these studies is that changing climatic conditions, such as sea surface temperatures or the position of high and low pressure centers, can change the location and frequency of tropical cyclogenesis, increase the intensity of tropical cyclones, or affect atmospheric steering mechanisms, preferentially guiding more tropical cyclones into a particular region (Bove et al., 1998; Donnelly, 2005; Donnelly and Woodruff, 2007; Elsner and Liu, 2003; Elsner et al., 2004, 2008; Emanuel, 2005; Emanuel and Nolan, 2004; Emanuel et al., 2004; Fan and Liu, 2008; Frappier et al., 2007; Liu, 2004; Knutson et al., 2010; Liu and Fearn, 2000a, 2000b; McCloskey et al., 2013; Nott, 2003; Nott and Hayne, 2001; Nott et al., 2007; Pielke et al., 2005; Toomey et al., 2013; Trenberth, 2005; Webster et al., 2005; Walsh, 2004; Woodruff et al., 2008, 2009, 2015; Wu and Wang, 2004).

In the western North Pacific, increased Northern Hemisphere solar forcing in the early- to mid-Holocene resulted in the Mid Holocene Warm Period, characterized by warmer and wetter conditions (Braconnot et al., 2007a, 2007b; Kerwin et al., 1999; Wanner et al., 2008, 2014). ENSO activity was reduced during this period, creating La Nina-like conditions. Increased Northern Hemisphere summer insolation also created higher summer temperatures and a stronger summer monsoon. These climatic changes may have resulted in more frequent and/or more intense tropical cyclones in Southeast Asia, including the Gulf of Thailand – a similar mechanism (depressed ENSO activity and a stronger West Africa monsoon) has been invoked to explain a 5000-year record of intense hurricane variability from Puerto Rico (Donnelly and Woodruff, 2007).

Paleotempestological studies conducted in Japan and southern China have provided insights into possible linkages between climate change and basin-wide patterns of tropical cyclone variability. Woodruff et al. (2009) used sediment coarseness and strontium (Sr) content in lagoonal sediments at Kamikoshiki, Japan, to identify periods of increased tropical cyclone activity over the last 6400 years. Their results suggest a correlation between periods of increased El Niño (ENSO) occurrence and periods of more typhoon-induced deposition (Fig. 10 a, b).

Although in the western North Atlantic there is a general suppression of cyclogenesis during ENSO years (Bove et al., 1998; Gray, 1984; Fig. 10 c), the frequency of tropical cyclones is less affected by ENSO variability in the western North Pacific. There is, however, an eastward shift in tropical cyclone genesis location during enhanced ENSO periods. As a result, tropical cyclones are more likely to follow northward recurving

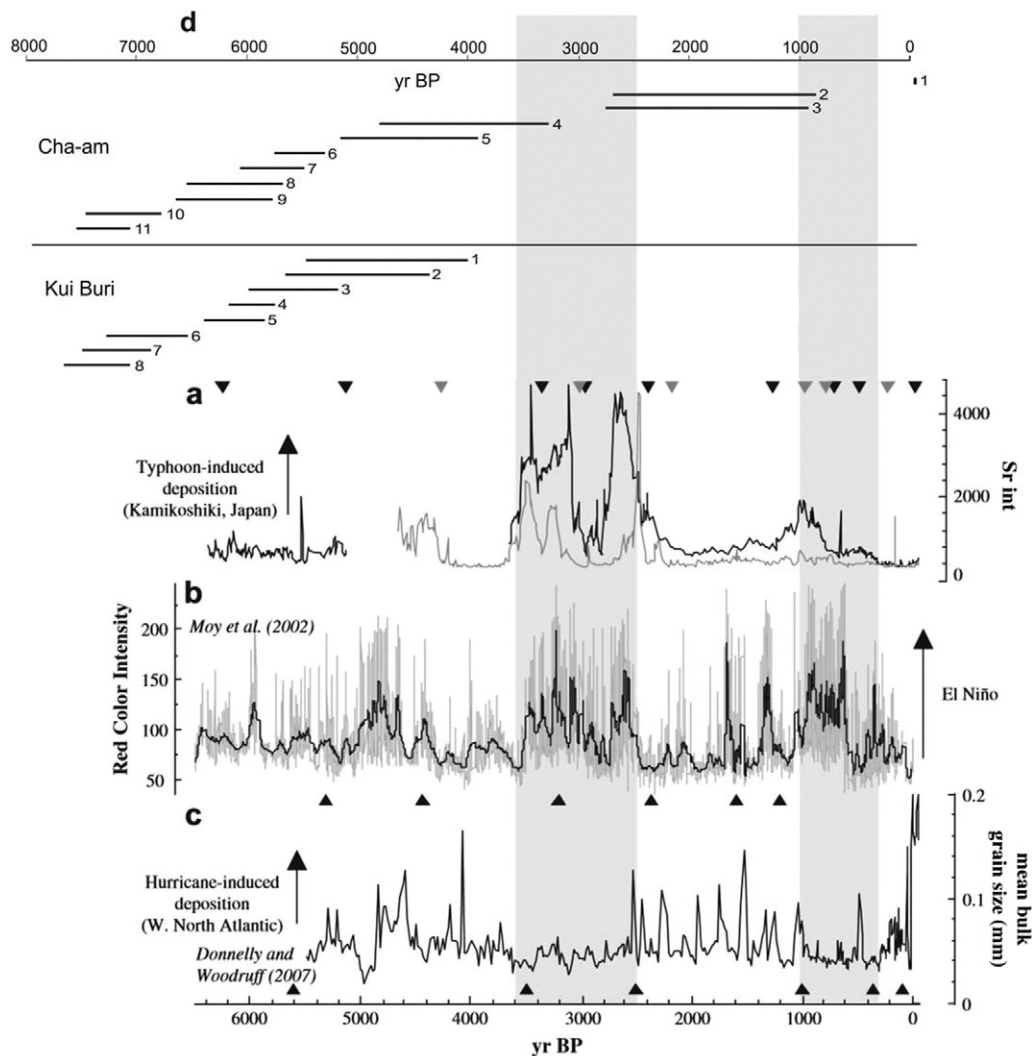


Fig. 10. a. Sr time-series for inferred typhoon-induced deposition at Kamikoshiki, Japan; b. ENSO reconstructions from Laguna Pallcocha, Ecuador (Moy et al., 2002); c. hurricane-induced sedimentation from the western North Atlantic (Donnelly and Woodruff, 2007); d. estimated age ranges of typhoon strikes on the Gulf of Thailand coast. Vertical shaded bars in plots represent periods of increased ENSO activity (modified from Woodruff et al., 2009).

trajectories, leading to greater likelihood of tropical cyclone strikes on Japan (Elsner and Liu, 2003). A ca. 1000-year record of typhoon landfalls from southern China, shows increased typhoon activity during reduced ENSO activity over the last ca. 400 years, reflecting a westward shift in tropical cyclone genesis location and more southerly storm trajectories (Liu et al., 2001). Historical observations also support an ENSO-driven seesaw pattern in typhoon activity in the western North Pacific (Chan, 1985).

Preliminary study results from Thailand appear to support this model of an oscillating pattern in tropical cyclone activity between the northern and southern western North Pacific (Fig. 10 d). Between two and five times as many typhoons are recorded on the Gulf of Thailand coast in the mid-Holocene compared to the late-Holocene; this higher-activity period corresponds to an apparently long period of generally suppressed ENSO activity in the mid-Holocene (to at least 6400 cal. yr. BP – the end of the ENSO record of Moy et al., 2002). A maximum of three out of 11–19 typhoons recorded in Thailand occurred during periods of enhanced ENSO activity ca. 2500–3600 cal. yr. BP and ca. 300–1000 cal. yr. BP (the vertical shaded bars in Fig. 10). This is an intriguing finding and supports the need for additional work on the typhoon record from Thailand to improve record chronology and better control for site sensitivity effects.

6. Conclusions

Anomalous sand layers in low-energy, fine-grained coastal environments form a record of Holocene typhoon strikes on a section of the Gulf of Thailand coast. The record has pronounced variability; typhoons are two to five times more frequently recorded in the mid-Holocene, compared to the late-Holocene. Although this variability may in part reflect greater site sensitivity resulting from the mid-Holocene sea-level highstand on the Thai–Malay Peninsula, it is unlikely that site sensitivity changes alone explain this record. It is also possible that the record reflects climatic changes associated with the Mid-Holocene Warm Period that favored the development of more frequent and/or intense typhoons in Southeast Asia. The apparent millennial-scale variability in typhoon activity from Thailand supports an emerging model of an ENSO-driven oscillation in tropical cyclone activity between the northern and southern western North Pacific. This preliminary finding of a link between climatic controls and typhoon activity in Southeast Asia warrants further investigation. Long-term typhoon records should be obtained from other sites to confirm a mid-Holocene tropical cyclone hyper-active period within the region. If confirmed, this finding could have important implications for future typhoon activity in Southeast Asia, given projected consequences of ongoing global warming.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant No 1305787, the Thailand Research Fund (TRF:BRG5780008), Chulalongkorn University (CU57-058-CC), a UNT Charn Uswachoke International Development Fund award and a grant from the UNT Small Grants Program. The manuscript was improved by comments of two anonymous reviewers.

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Paleogeographic Reconstruction and History of the Sea Level Change at Sam Roi Yot National Park, Gulf of Thailand

PEERASIT SURAKIATCHAI¹, MONTRI CHOOWONG^{1*}, PUNYA CHARUSIRI¹,
THASINEE CHAROENTITIRAT¹, SAKONVAN CHAWCHAI¹, SANTI
PAILOPLEE¹, AKKANEEWUT CHABANGBORN¹, SUMET PHANTUWONGRAJ¹,
VICHAI CHUTAKOSITKANON¹, STAPANA KONGSEN¹, PARISA NIMNATE^{1,3}
AND RAPHAEL BISSEN²

¹ Morphology of Earth Surface and Advanced Geohazards Research Unit (MESA RU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, THAILAND

² Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, THAILAND

³ Division of Geoscience, Mahidol University, Kanchanaburi Campus, Kanchanaburi 71150, THAILAND

* Corresponding author. Montri Choowong (monkeng@hotmail.com)

Received: 12 February 2018; Accepted: 4 September 2018

ABSTRACT.— In this study, the paleogeography and the natural history of sea level change was reconstructed for the Sam Roi Yot National Park, Prachuap Khiri Khan, Gulf of Thailand, one of the tropical natural conservation areas. Beach ridge sand and marine shells attached to sea notches were dated by Optically Stimulated Luminescence and conventional C¹⁴ radiocarbon techniques. The paleo-landform features recognized in the inland region of the national park were a coastal bay, beach ridge plain and tombolos. The semi-circle paleo-coastal bay possibly developed at the same time as the upper sea notch, some 6,500–6,000 y ago. These inland landforms have subsequently become a tidal flat after tombolos connected the limestone islands to the mainland. This process coincided with the formation of the middle sea notch, 3,000–1,000 y ago. A total of 163 shells were collected from 10 locations with different environments, including the beach ridge, swale, tidal flat and former tidal flat. They were classified into 57 species (12 Gastropoda and 45 Bivalvia species). *Anadara inaequalis*, *Anadara pilula*, *Saccostrea cucullata*, *Anomalocardia squamosa*, *Meretrix meretrix* and *Dosinia cretacea* were found extensively in most areas. All these species indicated a mangrove environment to the intertidal zone.

KEY WORDS: Paleo-coastal bay, Holocene sea level change, beach ridge plain, progradation, Gulf of Thailand

INTRODUCTION

Coastal zones are dynamic and their evolution is related to climate change (global warming) and sea level history. Global warming has been considered to be a key factor for local-scale sea level changes, which have led to the loss of coastal equilibrium, including along Thailand's coast (e.g., Sinsakul, 1992; Choowong et al., 2004; Choowong, 2011; Phantuwongraj and Choowong, 2012; Phantuwongraj et al., 2013; Williams et al., 2016). Climate changes can pose a threat to coastal lowland areas, including the coastal plain along the

Gulf of Thailand (GoT) in Thailand. Basically, to better understand the evolution of each low-lying coastal area, a combination of geomorphology, sedimentology, paleontology and isotope dating are needed. Geological records of marine transgression and regression are preserved more or less in the form of ancient landforms and their deposits. These geological records have led to frequent discussions about the paleoenvironment and paleogeography, and have become the key background information for inferring the history of sea level changes.

Most previous geological studies regarding coastal evolution in Thailand have set their focus on the Lower Central Plain of the upper GoT (e.g., Takaya, 1971; Thiramongkol, 1983; Choowong, 2011) and excluded the other coastal zones. This is because the Central Plain is a low-lying plain at 1–4 m elevation above the present mean sea level (MSL), and so is sensitive to the effect of rising sea level in the future. Although the study of coastal evolution has been extended to the other coastal regions, for example, peninsular Thailand (Horton et al., 2005) and the Chumphon coast at the southwest coast of the GoT (Nimnate et al., 2015), the evolution of the Sam Roi Yot (SRY) coastal plain has never been analyzed in detail.

Among the literature on coastal evolution research in Thailand, the coastal changes along the Andaman Sea have been reconstructed by episodic evolution of a beach ridge at Phrathong Island (Lansai, 2004; Brill et al., 2014), as well as sea notches and caves in the limestone bedrock from Phang Nga to Satun (Scheffers et al., 2012). Outside of the Lower Central Plain of the Chao Phraya and Tha Chin Rivers (Takaya, 1971; Thiramongkol, 1983; Choowong, 2011), the history of sea level change with respect to paleogeography is limited because their landforms have been changed tremendously by rapid urbanization (Supajanya, 1983; Choowong et al., 2004; Nimnate et al., 2015). In this study, we present new geomorphological and geological evidence of the GoT coastal evolution from the conservation area of the SRY National Park (NP), Prachuap Khiri Khan, on the northwestern coast of the GoT. The reconstruction of the paleogeography is also presented.

The SRYNP was established in 1996 as Thailand's first coastal NP and covers an

area of 98.8 km² (Fig. 1), extending from 12° 04' to 12° 21'N and 99° 51' to 100° 02'E. This conservation area has a significant ecological value as it is home to a large variety of animals, including several hundred bird species, both common and migratory, which use it as breeding and resting areas.

Based on the Köppen climate classification, SRY is located in a tropical monsoon climate (Köppen, 1918). The amount of rainfall is higher than 100 mm between May and November and decreases to about 20 mm between December and February (Manisarn, 1995). From October to May, the temperature is approximately 23–32 °C and from June to September it is 20–30 °C (Manisarn, 1995). In Thailand, coastal processes are generally controlled by waves and tides. At Cha-am (Upper west-coast of the GoT), the mean tidal range is 1.26 m and mean sea level is 1.76 m. At Kui Buri, about 100 km south of Cha-am, the mean sea level is 1.61 m at the mean lowest low water and the mean tidal range is 1.03 m (Williams et al., 2016). Wave action is mainly influenced by the seasonally reversing wind of the northeast and southwest monsoons from May to October and from November to April, respectively. The southwest monsoon generates the surface waves along the Andaman coast. The waves along the GoT coast, however, are mainly influenced by the northeast monsoon (Manisarn, 1995).

MATERIALS AND METHODS

Aerial photographs

Aerial photographs taken in 1955, 1967 and 1970, a topographic map compiled in 1964 and satellite images taken in 2014 were used to classify the coastal landforms (Table 1). Ancient and present day coastal

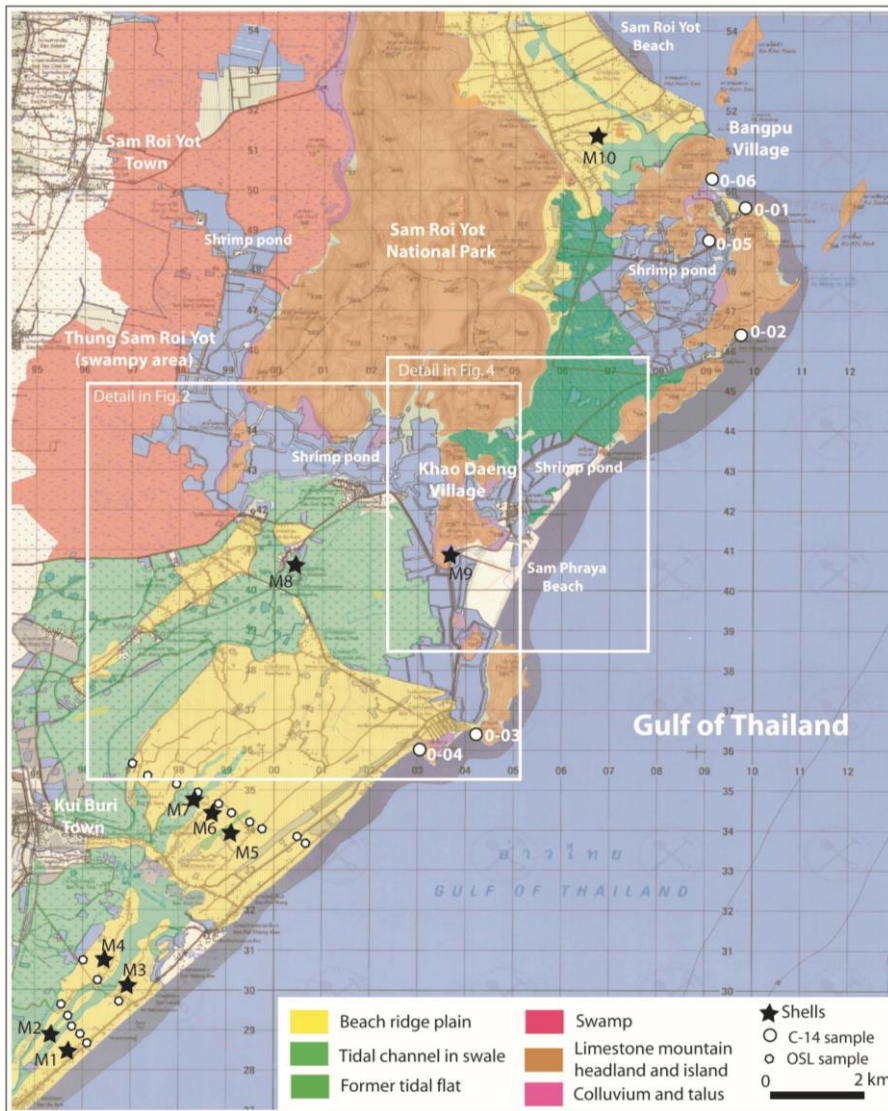


FIGURE 1. Coastal landforms overlying a topographical map (Royal Thai Survey Department and Department of Mineral Resources of Thailand). Sample locations for ^{14}C and optically stimulated luminescence (OSL) datings, and the index map of Figs. 2 and 5, were included.

landforms were identified using stereo-pair aerial photos and a mirror stereoscope. Oblique air-photographs and video records were performed using a drone (Phantom 3 standard type).

Field survey

Field investigations were used to search for the evidence of sea-level changes, possibly preserved along the coast of the SRYNP. Classification of shells deposited within each landform from 11 locations was

TABLE 1. Series of topographic maps and aerial-photographs used in this study.

Material used	Detail (year of air-photo taken; map sheet; series)	Compiled and published year	Publisher
Topographic map	Interpreted from air-photos taken in 1954 (ID 49472) with hydrographic charts I produced in 1941 Map sheet 4947 II, L708 Sathani Kui Buri	1961	RTSD
	Map sheet 4933 II; L7018 Amphoe Kui Buri	2000	RTSD
Aerial photographs	1955 (ID 23962)	1955	RTSD
	1968 (ID 0002)	1970	RTSD
	1994 (ID 0012)	1994	RTSD
Satellite image	2015	2015	Google Earth

RTSD = Royal Thai Survey Department

comparatively based on the previous published catalogues (Surakiatchai, 2006; Robba et al., 1993, 2002, 2004, 2007). Oyster fossils from several levels of sea notch walls, both far inland and from limestone headlands, were collected. The height at which the fossils were attached to the notch wall was measured and related to the astronomical tides. The astronomical tide level records from the Ko Lak tide gauge data at Prachuap Khiri Khan Bay were used as reference datum. The level of mean high tide was measured from additional significant biomarkers. An example of such a biomarker is the small oyster, *Saccostrea cucullata*. Its uppermost horizontal level of occurrence was assumed to represent the Mean High Water level (MHW) with a fluctuation of ± 10 cm (Scheffers et al., 2012). Both, the level of oysters attached to the sea notch wall as well as the horizontal line of the recent biomarker, were used to determine the height of the biological sea level indicators and contributed to improving the accuracy of the ancient sea level curve. A theodolite, SOKKIA total station series 10, was applied for topographical leveling. Direct vertical distances of biomarkers and oysters in sea notches, located close to the present

shoreline, were measured. A digital handheld GPS (Garmin) was used to get the position of the inland ridge and swale along with the topographic survey.

Dating methods

The age of the fossils was determined by ^{14}C radiocarbon dating, performed at the Office of Atomic Nuclear for Peace of Thailand (OANP). The ^{14}C data was calibrated with the Calib 7.0 online program, using the northern hemisphere terrestrial calibration curve (Reimer et al., 2009; Southon et al., 2002).

Beach ridge sands were dated by Optically Stimulated Luminescence (OSL) (Roberts and Plater, 2006). In the sample preparation process, each sample was divided into two portions and used for evaluating the (i) equivalent dose (ED) and (ii) annual dose (AD) including the water content measurement. The portion used to evaluate the ED was performed in subdued red light whereas that for the AD, including the water content, was prepared with light exposure. Dried samples were sieved and treated with hydrochloric acid, hydrogen peroxide and sodium oxalate to remove carbonate, organic material and clay. After density separation, the pure quartz was etched with concentrated hydrofluoric acid.

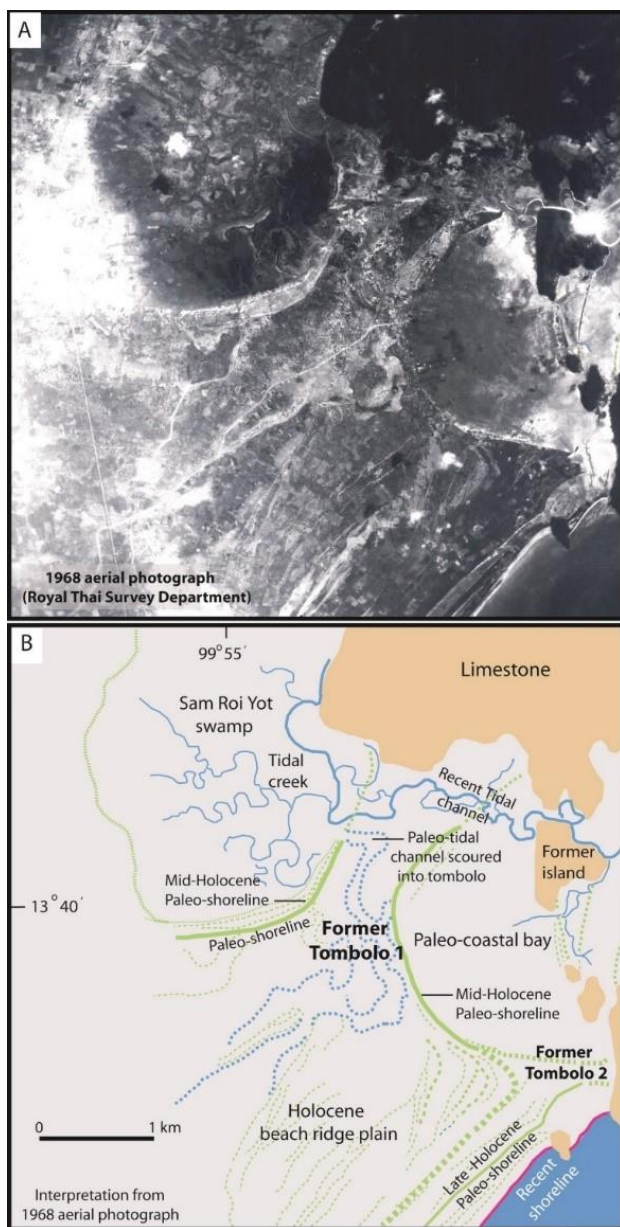


FIGURE 2. Aerial photograph interpretation showing the classification of ancient landforms and their paleogeography. Former tombolo 1 was recognized in the middle part leading to the formation of brackish swamp in the west and the semi-circle paleo-coastal bay. The inner part of the beach ridge plain found in the south formed at the same time as tombolo 1. The outer ridges set formed at the same time as tombolo 2 (Aerial-photo taken in 1968; Royal Thai Survey Department).

The Risø TL/OSL DA 20 instrument with a $^{90}\text{Sr}/^{90}\text{Y}$ beta source was operated at the Department of Geology, Chulalongkorn

University. Luminescence signals were detected through a Hoya U340 filter (7.5 mm) after blue LED stimulation, performed

TABLE 2. OSL dating results from the beach ridge plain (Locations in Fig. 1)

Sample no.	Distance from shoreline (m)	U (ppm)	Th (ppm)	K (%)	Water (%)	De (Gy)	Age (y)	Age (BP)
K4-1	170	1.91±0.10	0.35±0.14	2.40	0.58±0.05	0.55±0.01	950±80	884±80
K4-2	430	2.48±0.12	0.53±0.14	12.36	0.67±0.05	1.58±0.03	2350±220	2284±220
K4-3	1180	2.62±0.12	0.53±0.16	3.20	0.84±0.06	2.08±0.06	2463±250	2397±250
K4-4	1500	2.63±0.04	0.57±0.27	0.34	0.85±0.06	3.37±0.12	3980±200	3914±200
K4-5	1900	2.53±0.10	0.55±0.16	1.43	0.80±0.05	6.54±0.19	8186±700	8120±700
K4-6	2200	2.80±0.01	0.65±0.06	4.00	0.88±0.03	6.41±0.31	7270±450	7204±450
K4-7	2480	2.70±0.03	0.72±0.04	1.69	0.96±0.03	6.18±0.15	6410±260	6344±260
K4-8	3100	4.05±0.03	0.73±0.06	1.98	1.10±0.04	6.94±0.23	6282±340	6216±340
K4-9	3500	5.13±0.05	0.85±0.08	1.77	1.34±0.05	9.08±0.31	6756±390	6690±390
K4-10	3800	4.73±0.07	1.01±0.08	2.02	1.41±0.05	10.34±0.30	7339±390	7273±390

at 125 °C for 50s. The equivalent doses were measured by the SAR protocol of Murray and Wintle (2000, 2003). Mean equivalent doses were calculated from the concentrations of the ⁴⁰K, ²³²Th and ²³⁸U radionuclides.

RESULTS

Recent and paleo-coastal landforms

The central part of the SRYNP area is dominated by high limestone mountains with cliffs and bounded in the east by a coastal plain, including marshy swale, tidal flat, beach and swampy areas. The limestone is grey to bluish-grey with fossils indicating reef limestone interbedded with light brown feldspathic and calcareous sandstone. A Permian age was derived for the sequence (DMR, 1999). The Quaternary unconsolidated sediment lies beneath the low-lying coastal zone. This led to a subdivision of the study sites according to geomorphological units, such as beach ridge plain, alluvial, colluvial and high-relief units

(Fig. 1). The area in the west part of the NP is composed of a swampy environment, including tidal creeks, inlets and outlets (Klong Khao Daeng). In the southern part of the swampy area, a semi-circle shape was interpreted as a paleo-bay, connected to the headland by a tombolo (see Fig. 2). A beach ridge plain was also dominant in the southern part of the area. The inner part of the beach ridge consisted of narrow ridges intervened with shallow swales. The orientation of the ridges conformed to the direction of the former tombolo 1 formation. Between the inner and outer beach ridge sets, a large swale with traces of a tidal channel, developed in swale, was recognized. The orientation of the outer set of ridges started with a cusped sand cape and conformed to the direction of the former tombolo 2. The OSL dating derived from the sand ridges (sample locations are shown in Fig. 1) are shown in Table 2. Progradation of the beach ridge plain also unveiled the gradual regression until reaching the MSL at the present day coastline.

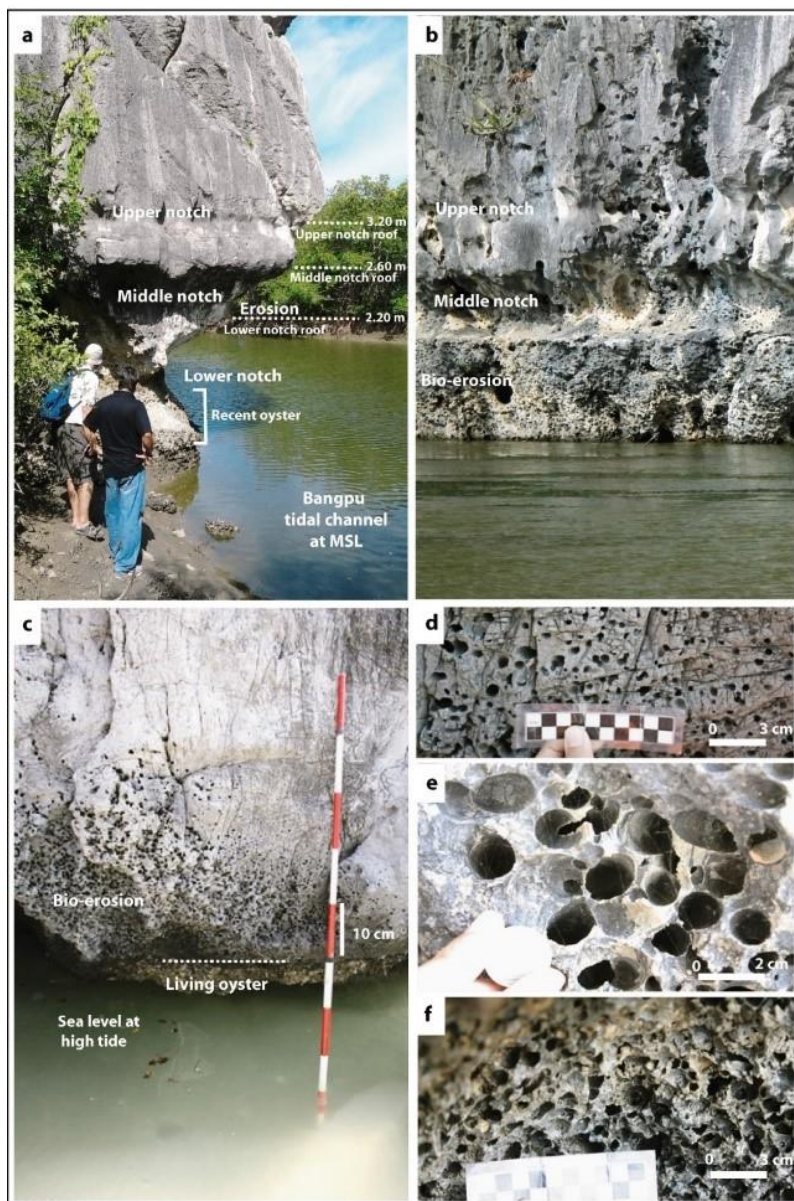


FIGURE 3. Photographs of different levels of sea notches as well as bio-construction and erosions in notches. (a and b) Three levels of notches at Bangpu tidal channel. Middle notch was scoured by the lower one, (c) limestone headland with bio-erosion (*Lithophaga* boreholes) and bio-construction (living oyster), (d, e and f) close-up of *Lithophaga* boreholes.

Geological and biological indicators of sea level change

Sea notch

Permian limestone terrain dominated, as a karst mountainous area, the middle part of

the SRYNP and at the headlands in the eastern part. Tidal notches, which are formed when the sea level remains relatively stable, have been used as a sea level indicator in microtidal marine areas,

TABLE 3. Radiocarbon (^{14}C) dating of oysters attached to the notch walls.

Sample no.	Notch level	Altitude (m a MHW)	Material	Conventional age (y BP)	Cal. age (a BP) (2SD)	Mean cal. age (a BP)
Khao Thian						
O-01	Middle	2.0	Oyster	3400±170	2789–3610	3216
Ban Khung Tanot						
O-02	Lower	1.0	Oyster	2480±150	1714–2477	2100
Ban Thung Noi						
O-03-1	Middle	1.4	Oyster	5160±160	5062–5854	5476
O-03-2	Middle	1.2	Oyster	2140±210	1255–2202	1702
O-03-3	Lower	1.0	Oyster	1380±150	641–1216	902
Khao Khwang						
O-04	Middle	2.0	Oyster	2680±200	1858–2806	2352
Khao Luk Klom						
O-05	Middle	2.5	Oyster	3090±110	2596–3159	2851
Ban Bang Pu						
O-06-1	Middle	2.6	Oyster	780±180	45–633	366
O-06-2	Middle	2.3	Oyster	1060±180	288–940	617
O-06-3	Middle	2.0	Oyster	2420±120	1741–2314	2028

for example, in the Mediterranean (Pirazzoli, 2005; Pirazzoli and Evelpidou, 2013) and along the GoT coast (Choowong, 2002, 2011; Choowong et al., 2004). At least three distinctive levels of sea notches are common at the base of the limestone cliffs in the SRY area (Fig. 3a). The highest notch, generally less incised than the lower one, was located as far as 3 km inland and had no bio-construction features. The distance between the roof and base is about 45 cm, with 10 cm vertex (Fig. 3b). The highest sea notch level is on average 2.67 m above the present mean tide level (Dusitapirom et al., 2008). Bio-construction, especially oysters, was recognized in the middle and lowest sea notch level (Fig. 3c). Results of ^{14}C dating from the oysters attached to the sea notch wall are shown in Table 3. At the shore and in places where tidal channels are located, only the lowermost notch is actively formed.

Bio-erosion

At the base of the limestone headland, bio-erosion (borings) was recognized (Fig. 3c). Bio-erosion in sea notches, formed by organisms living in the wave zone, can be used to infer the maximum tidal range (Kelletat, 1997). Evidence of bio-erosion (bio-corrosion and bio-abrasion), including the grazing traces of chitons and bivalves (*Lithophaga*), was found at SRY, and was similar to the fauna found at the Andaman coast (Kázmér and Taboroši, 2012; Scheffers et al., 2012). Chiton grazing trails and *Lithophaga* boreholes were recognized above the roof of an active notch (Fig. 3d–f).

Taxonomic identification of shell fauna

A total of 57 molluscan species (12 Gastropoda and 45 Bivalvia) belonging to 45 genera and 31 families (Figs. 4 and 5), were classified from the 10 sampled localities (M1–10; Fig. 1). *Anadara inaequalvis*, *Anadara pilula*, *Saccostrea*

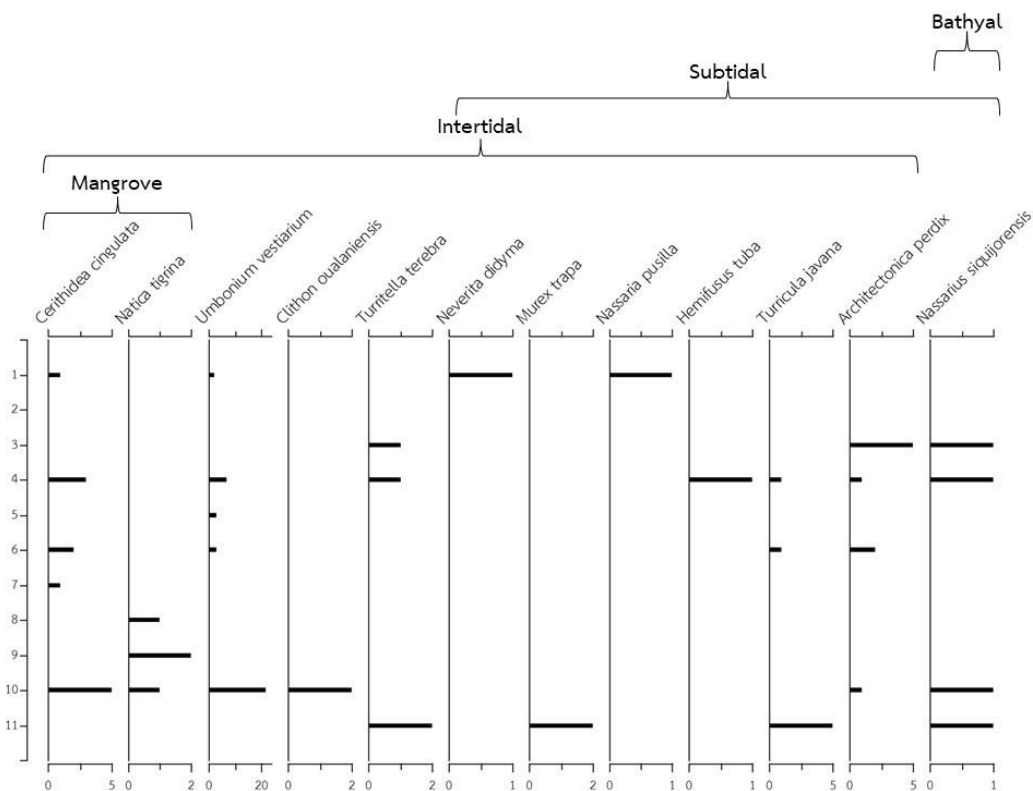


FIGURE 4. Chart of Gastropoda sorted by habitat (number). X-axis is the species of Mollusca and the Y-axis is the sample location.

cucullata, *Anomalocardia squamosa*, *Meretrix meretrix* and *Dosinia cretacea* were found in most areas, indicating a mangrove environment to the intertidal zone (Tables 4–6). All of these species are marine mollusks that lived in the Holocene (Surakiatchai, 2006; Robba et al., 2002, 2004, 2007) (Plates 1–5, in Appendix). The occurrence of fauna from location M8 indicated that the paleo-shoreline was located about 4 km inland from the recent shoreline.

DISCUSSION AND CONCLUSION

Middle to late Holocene paleogeography

Paleogeographic reconstructions of the inland coastal zone of the GoT, from the Central Plains of Thailand, have rarely been published (Umitsu et al., 2002). Coastal landforms around the GoT are somewhat different from those recognized along the west coast of Thailand (Andaman Sea coast). The GoT is classified as a depositional coast with a distinct sequence of beach ridges, lagoons with broad marsh plains and tidal flats (Choowong, 2011). Along the coast of GoT, a few paleo-shoreline delineations have been reported,

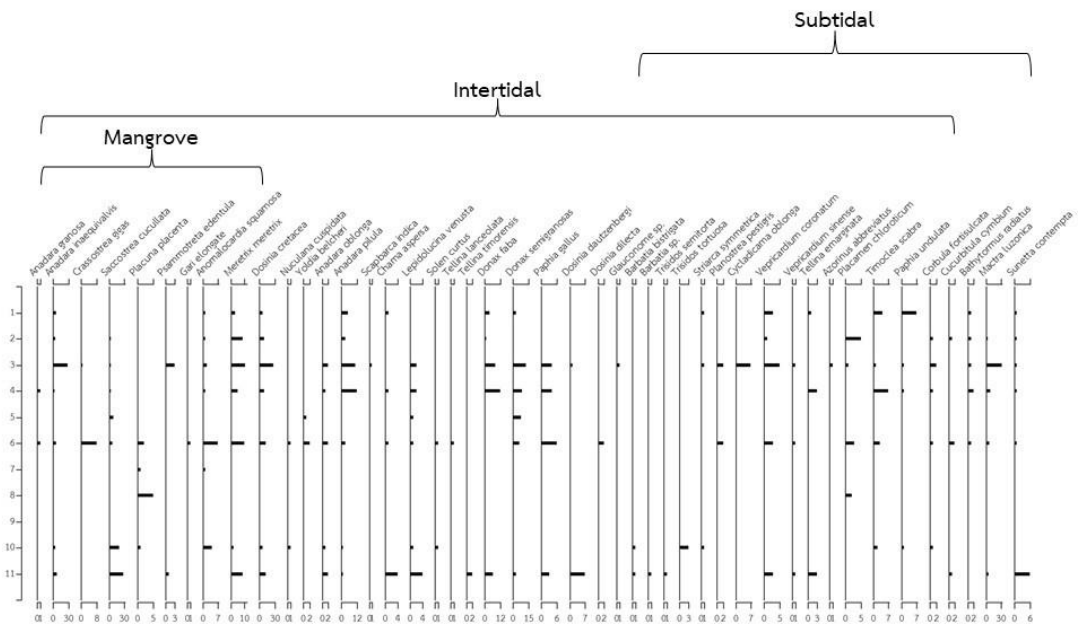


FIGURE 5. Chart of Bivalvia sorted by habitat (number). X-axis is the species of Mollusca.

such as at SRY (Chalermlarp, 1996) and Chumphon (Phantu Wongraj et al., 2010; Nimnate et al., 2015). The most extensive invasion by the sea occurred in the central plain of Thailand, where the Holocene transgression reached as far as 70 km north of Bangkok (Natalaya and Rau, 1981). Within peninsula Thailand, the furthest landward transgression occurred at the east coast at Nakon Srithammarat, and reached

about 40 km inland from the present shoreline (Choowong, 2011).

In this paper, we approximately determined the boundary of paleo-coastal landforms in relation to the gradual regression of sea level from the middle to late Holocene (Fig. 6). Considering the aerial photograph taken in 1968 (Fig. 2), the land has been modified (Fig. 6A–D). Khao Daeng canal has supplied sediment to the

TABLE 4. Summary of mollusks and their environment in the study area.

Area	Species (Gastropoda/Bivalvia)	Depositional environment
M1	20 (4/16)	Intertidal to subtidal
M2	14 (0/14)	Intertidal (mangrove)
M3	32 (3/29)	Intertidal to subtidal
M4	27 (7/20)	Intertidal
M5	5 (1/4)	Intertidal
M6	34 (4/30)	Intertidal
M7	3 (1/2)	Intertidal (mangrove)
M8	4 (1/3)	Intertidal (mangrove)
M9	1 (1/0)	Intertidal (mangrove)
M10	23 (6/17)	Intertidal

TABLE 5. Number of Gastropoda found in the 10 study sites.

Species	Area									
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
<i>Architectonica perdix</i>	0	0	5	1	0	2	0	0	0	1
<i>Cerithidea cingulata</i>	1	0	0	3	0	2	1	0	0	5
<i>Clithon oualaniensis</i>	0	0	0	0	0	0	0	0	0	2
<i>Hemifusus tuba</i>	0	0	0	1	0	0	0	0	0	0
<i>Murex trapa</i>	0	0	0	0	0	0	0	0	0	2
<i>Nassaria pusilla</i>	1	0	0	0	0	0	0	0	0	0
<i>Nassarius siquijorensis</i>	0	0	1	1	0	0	0	0	0	2
<i>Natica tigrina</i>	0	0	0	0	0	0	0	1	2	1
<i>Neverita didyma</i>	1	0	0	0	0	0	0	0	0	0
<i>Turricula javana</i>	0	0	0	1	0	1	0	0	0	5
<i>Turritella terebra</i>	0	0	1	1	0	0	0	0	0	2
<i>Umbonium vestiarium</i>	2	0	0	7	3	3	0	0	0	22

coast (Fig. 6A), where traces of the subaqueous sand bar at the mouth of Khao Daeng canal were also observed (Fig. 6B). The inlet/outlet of the SRY swamp is located far inland between limestone hills (Fig. 6C), and was used to help to delineate the boundary of the paleo-shorelines, where the paleo-coastal bay and tombolo 1 were located far inland, as shown in Figure 2. Figure 6D shows the trace of wash-over sediment and submerging and emerging sand bars in transition at the shore.

The mollusks (Figs. 4 and 5) also provided evidence of the paleo-environment found inland, including bathyal, subtidal, intertidal and mangrove. They are extant species and their frequency and distribution helped to confirm the paleo-landforms of the area. The recognition of the paleo-bay and former tombolo highlights the better understanding of the paleo-geographical evolution of the area in relation to the records of sea level changes in Thailand.

History of sea level changes

Episodic coastal plain evolution in relation to sea level changes has been reported from many parts of the Thai-Malay peninsula (Geyh et al., 1979; Tjia, 1996; Hesp et al., 1998; Mallinson et al., 2014; Culver et al., 2015). Sedimentological, paleontological and geomorphological evidence helped to define the Holocene coastal evolution of the Setiu wetland region, part of the lower Thai-Malay peninsula, in the last 7 millennia (Mallinson et al., 2014), where a rapid sea level rise is suggested to have occurred between 5,700 and 3,000 y ago. Along the limestone and granite coasts of the Phang-nga Bay and Phuket (Andaman Sea), bio-erosive notches, benches of rock oysters, belts of boring bivalves and boring sea-urchins, as well as coral colonies have been recognized. Since they occur in recent as well as dead or inactive formations, they were used to precisely determine the past sea levels (Scheffers et al., 2012).

TABLE 6. Number of Bivalvia found in the 10 study sites.

Species	Area									
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
<i>Anadara granosa</i>	0	0	0	1	0	1	0	0	0	0
<i>Anadara inaequalis</i>	6	4	28	3	0	7	0	0	0	13
<i>Anadara oblonga</i>	0	0	2	1	0	2	0	0	0	3
<i>Anadara pilula</i>	5	3	11	12	0	3	0	0	0	2
<i>Anomalocardia squamosa</i>	1	1	2	1	0	7	1	0	0	4
<i>Azorinus abbreviatus</i>	0	0	1	0	0	0	0	0	0	0
<i>Barbatia bistrigata</i>	0	0	0	0	0	0	0	0	0	2
<i>Barbatia</i> sp.	0	0	0	0	0	0	0	0	0	1
<i>Bathytormus radiatus</i>	1	1	1	2	0	1	0	0	0	0
<i>Chama aspersa</i>	1	0	0	1	0	1	0	0	0	4
<i>Corbula fortisulcata</i>	0	1	2	1	0	1	0	0	0	1
<i>Crassostrea gigas</i>	0	0	1	0	0	8	0	0	0	0
<i>Cucurbitula cymbium</i>	0	1	0	0	0	2	0	0	0	1
<i>Cycladicama oblonga</i>	0	0	7	0	0	0	0	0	0	0
<i>Donax faba</i>	4	1	8	12	0	0	0	0	0	6
<i>Donax semigranosa</i>	3	0	13	9	8	6	0	0	0	3
<i>Dosinia cretacea</i>	6	9	27	10	0	13	0	0	0	20
<i>Dosinia dautzenbergi</i>	0	0	1	0	0	0	0	0	0	7
<i>Dosinia dilecta</i>	0	0	0	0	0	2	0	0	0	0
<i>Gari elongate</i>	0	0	0	0	0	1	0	0	0	0
<i>Glauconome</i> sp.	0	0	1	0	0	0	0	0	0	0
<i>Lepidolucina venusta</i>	0	0	2	2	1	1	0	0	0	5
<i>Macra luzonica</i>	2	3	32	8	0	6	0	0	0	5
<i>Meretrix meretrix</i>	3	9	11	5	0	10	0	0	0	11
<i>Nuculana cuspidata</i>	0	0	0	0	0	1	0	0	0	1
<i>Paphia gallus</i>	0	0	4	4	0	6	0	0	0	3
<i>Paphia undulata</i>	7	0	1	1	0	0	0	0	0	1
<i>Placamen chloroticum</i>	0	5	1	0	0	3	0	2	0	0
<i>Placuna placenta</i>	0	0	0	0	0	2	1	5	0	1
<i>Planostrea pestigris</i>	0	0	2	0	0	2	0	0	0	0
<i>Psammotreta edentula</i>	0	0	3	0	0	0	0	0	0	1
<i>Saccostrea cucullata</i>	0	4	4	4	9	7	0	1	0	49
<i>Scapharca indica</i>	0	0	1	0	0	0	0	0	0	0
<i>Solen curtus</i>	0	0	0	0	0	1	0	0	0	1
<i>Striarca symmetrica</i>	1	0	1	0	0	0	0	0	0	1
<i>Sunetta contempta</i>	1	1	1	1	0	1	0	0	0	6
<i>Tellina emarginata</i>	1	0	0	3	0	0	0	0	0	3
<i>Tellina lanceolata</i>	0	0	0	0	0	1	0	0	0	0
<i>Tellina timorensis</i>	0	0	0	0	0	0	0	0	0	2
<i>Timoclea scabra</i>	4	0	1	7	0	3	0	0	0	2
<i>Trisidos semitorta</i>	0	0	0	0	0	0	0	0	0	1
<i>Trisidos tortuosa</i>	0	0	0	0	0	0	0	0	0	3
<i>Vepricardium coronatum</i>	3	1	5	0	0	3	0	0	0	3
<i>Vepricardium sinense</i>	0	0	1	0	0	1	0	0	0	1
<i>Yoldia belcheri</i>	0	0	0	0	1	2	0	0	0	0

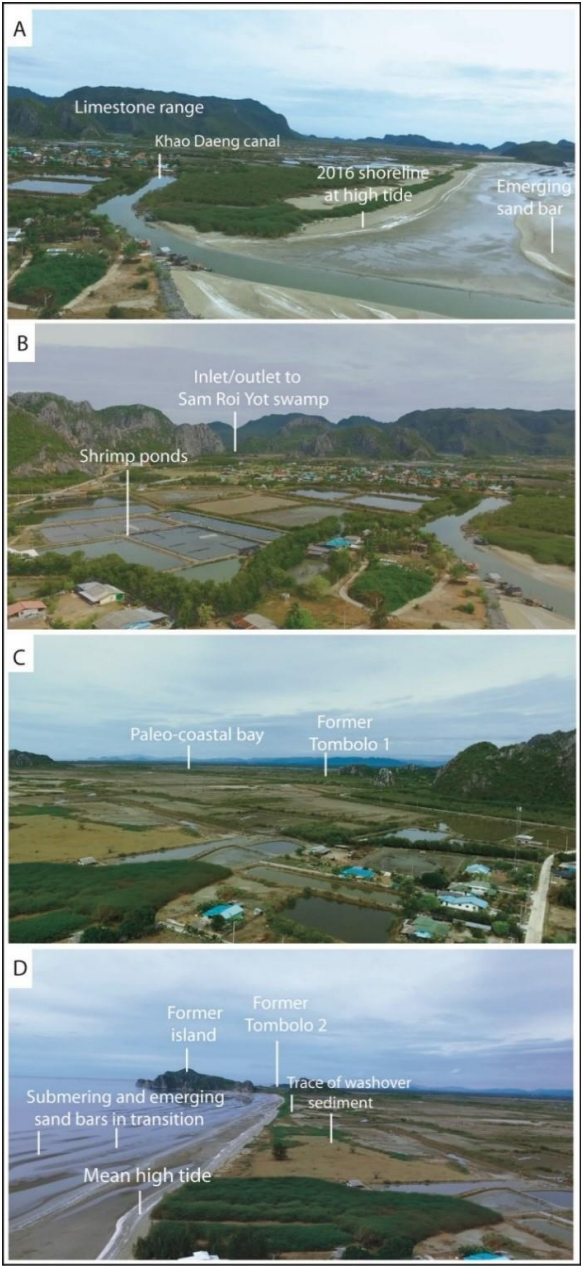


FIGURE 6. Oblique view of the recent morphology of the barrier system. (A) Khao Daeng canal is the main transport route supplying land sediment to the coast. Trace of present normal high tide in 2016 and subaqueous sand bar were also observed (looking northwest). (B) Inlet/outlet to SRY swamp is located far inland between limestone hills (looking northwest). (C) Locations of paleo-coastal bay and tombolo 1 are located far inland (looking southwest). (D) Trace of wash-over sediment and submerging and emerging sand bars in transition at the shore (looking south).

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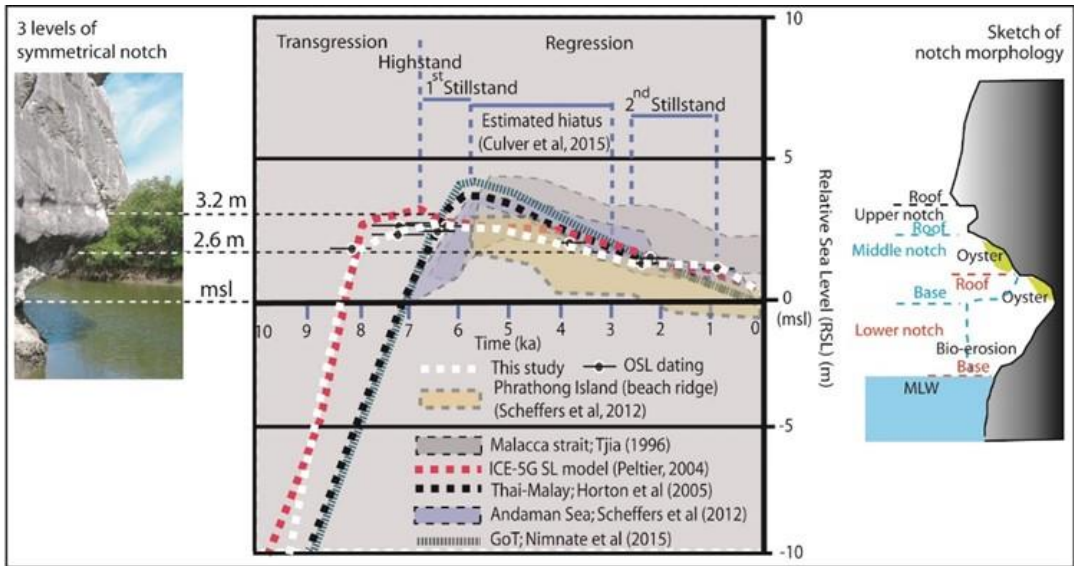


FIGURE 7. Compilation of sea level curves from Southeast Asia and South China Sea. Three levels of sea notch (left) and sketch of notch morphology (right) showed correlation with sea level curve. Proposed sea level curve derived from this study shows in white dash-line.

Sedimentological and palynological investigations from the Great Songkhla Lake (middle peninsula) revealed that the area was one of the earliest mangrove environments in Southeast Asia (8,420–8,190 cal. y BP), which was subsequently replaced by a freshwater swamp at 7,880–7,680 cal. y BP, owing to the decline of marine influence (Horton et al., 2005). Sea level observations from the Great Songkhla Lake and the other areas of the Malay-Thai Peninsula also revealed an upward trend in the Holocene relative sea level from a minimum of -22 m at 9,700–9,250 cal. y BP to a mid-Holocene high stand of 4,850–4,450 cal. y BP, which equates to a rise of c. 5.5 mm/y (Horton et al., 2005). In the Chumphon estuary, located in the upper part of the Thai peninsula, a series of beach ridge plains, which formed as a spit, were recognized as far as 10 km inland from the present shoreline. Progradation of beach ridge plains started after the sea had reached

a highstand at around 6,500 cal. y BP (Nimnate et al., 2015).

In this paper, the relative sea level curves from the Thai-Malay peninsula were compiled (Fig. 7). We also propose a revised relative sea level curve from SRY based on ^{14}C radiocarbon and OSL dating (Fig. 7). We used the plotted OSL ages (y in BP) of beach ridge sands to reconstruct the sea level curve. The OSL errors were acceptable (less than 10%) and the elevation of dated sands was measured by precise survey camera. The obtained curve corresponded well with the ICE-5GSL model proposed by Peltier (2004). The ^{14}C dating results of fossils from the innermost to the outer parts of the former tidal flat within the former tombolo 1 (Fig. 1) provided ages of $7,360 \pm 420$, $2,200 \pm 270$ and $1,520 \pm 250$ y BP, respectively, (Surakiatchai, 2006). The ^{14}C radiocarbon dating results from this study of oysters from the sea notch walls provided at least

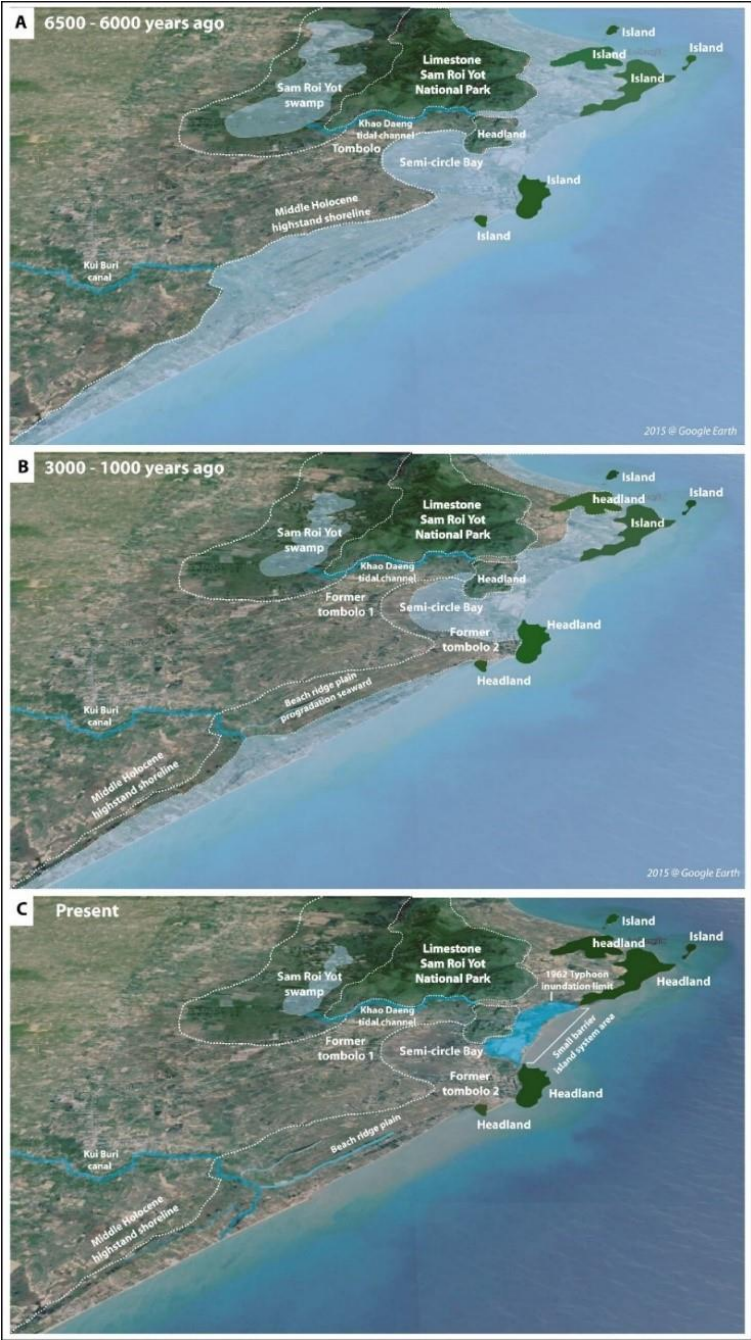


FIGURE 8. Reconstruction of paleogeography from the SRYNP. Background satellite image was taken from Google Earth.

the period of time the oysters lived in and tentatively reflected two breaks in the

gradual regression, times when the sea level had been stable or come to a standstill. The

sea level reached a highstand about 6,500 y ago (Fig. 8A) and presumably stagnated for 500–1,000 y, leading to the formation of the upper notch. The highstand was at 3–4 m height above the present MSL, as evidenced from the small uppermost sea notch. The lack of oysters in the upper notch is probably due to the small curvature of the notch, which was an unsuitable environment for the oysters to live in. The upper notches found inland (Fig. 2a and b) were possibly formed at the limestone base during the highstand.

The OSL dating data also unveiled the initiation of an extensive progradation of beach ridge plain around 6,000 y ago. A series of continuous beach ridges reflect the start of a continuously falling sea level from 6,000 until 3,000 y ago, leading to the extensive progradation of the beach ridge plain. The sea level seems to have remained stable once again from 3,000 to 900 y ago (Fig. 8B). Middle notches, with living oysters, and large swale, between beach ridges, were formed during this second stable sea level period. The OSL-dated beach ridge sand contained shells, which indicated the gradual progradation of the beach during the marine regression. The ^{14}C ages of the oyster fossils also indicated the time of gradual regression, and agreed with the results from dating shells in the beach ridge (Choowong et al., 2004).

This study aimed to reconstruct the paleogeography and history of sea level change during the Holocene from the east coast of the GoT. At SRYNP, evidence of sea level change was deduced from paleo- and recent landforms. A series of aerial photographs from different periods of time provided clues of the paleo-landforms and led us to a better understanding of the paleogeography of this well-preserved coastal environment. Overall, the physical

and biological evidence coupled with a good chronology from this area unveiled the history of the sea level change, both transgressive and regressive formations. The set of innermost beach ridges is a significant transgressive formation, reported for the first time in this study. The OSL dating showed the progradation of beach ridges landwards after the sea reached a highstand around 6,500 years ago. The formation of solution sea notches, bio-erosion at the base of limestone and ^{14}C dating of oyster fossils, attached to sea notch walls, are all physical and biological clues to confirm the sea level at different periods of time. All the geological, geomorphological and biological evidence guided us to a successful reconstruction of the paleogeography, in close relation to the history of sea level change.

ACKNOWLEDGEMENTS

The 90th Anniversary of Chulalongkorn University provided Ph.D funding and JASSO student exchange support program at University of Tsukuba to the first author. Part of the work was supported by the Thailand Research Fund (TRF: BRG5780008) and Ratchadapisek Somphot Endowment, Chulalongkorn University (CU57-058-CC). Thanks to Prof. Miklos Kázmér for discussion on bio-erosion and constructive advises during fieldwork. We thank the officers at Thailand Institute of Nuclear Technology for Radiocarbon Dating. Editor and anonymous reviewers are thanked for the significant improvement of the manuscript.

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APPENDIX

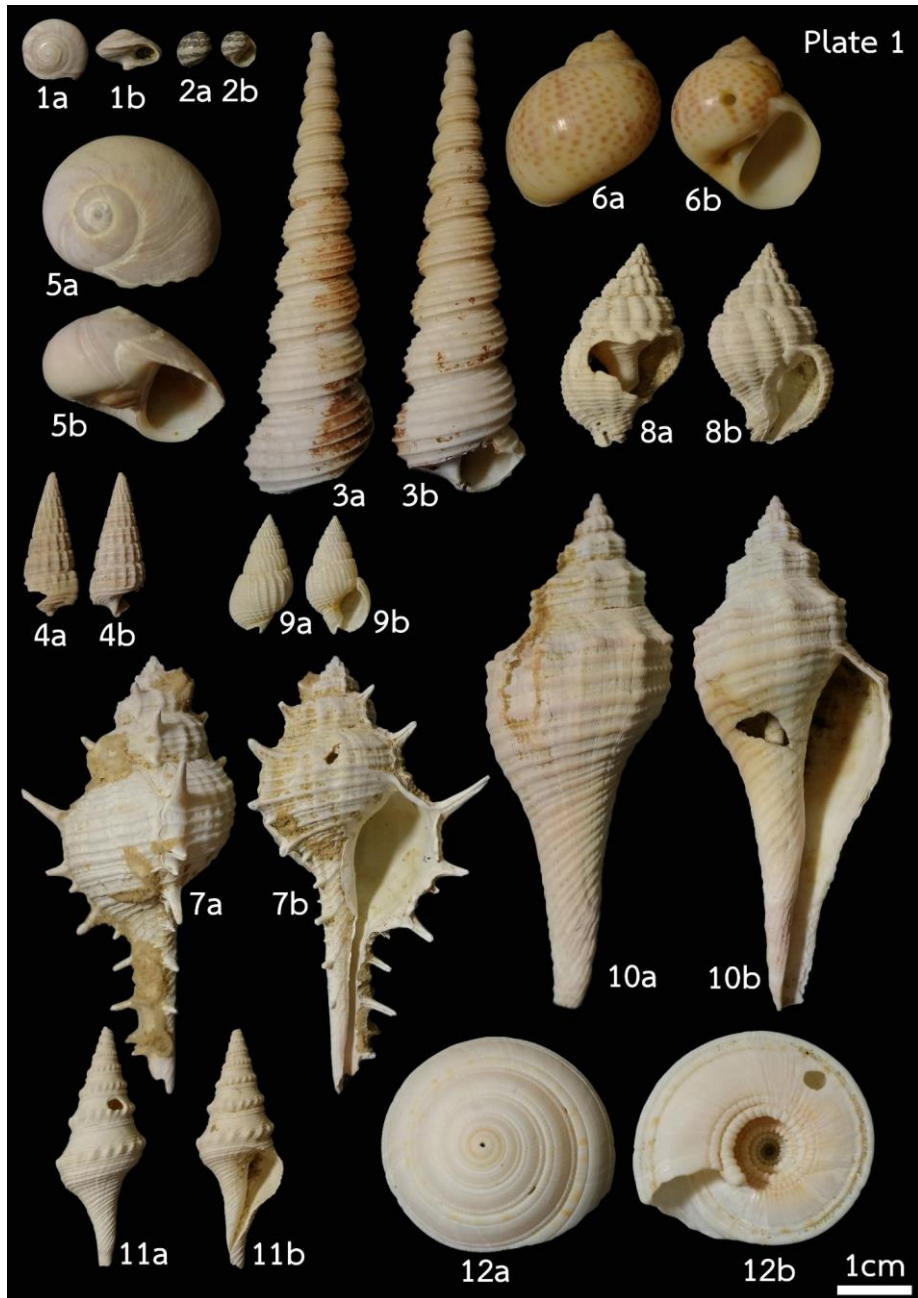


PLATE 1. Mollusca collected from the study areas 1) *Umbonium vestiarium*, 2) *Clithon oualaniensis*, 3) *Turritella terebra*, 4) *Cerithidea cingulate*, 5) *Neverita didyma*, 6) *Natica tigrina*, 7) *Murex trapa*, 8) *Nassaria pusilla*, 9) *Nassarius siquijorensis*, 10) *Hemifusus tuba*, 11) *Turricula javana* and 12) *Architectonica perdix*.

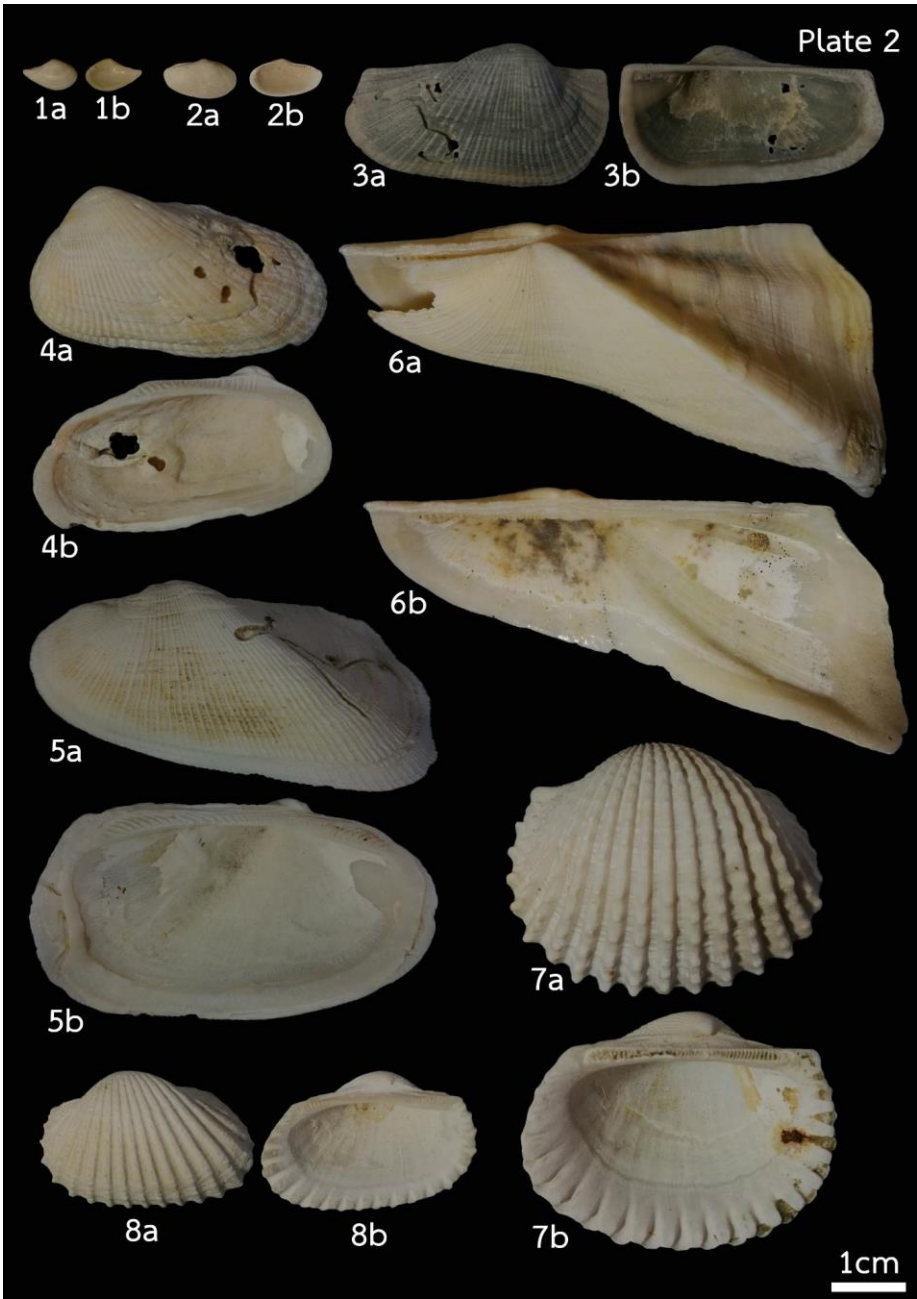


PLATE 2. Mollusca collected from the study areas 1) *Nuculana cuspidata*, 2) *Yoldia belcheri*, 3) *Barbatia bistrigata*, 4) *Barbatia* sp., 5) *Trisidos semitorta*, 6) *Trisidos tortuosa*, 7) *Anadara granosa* and 8) *Anadara oblonga*.

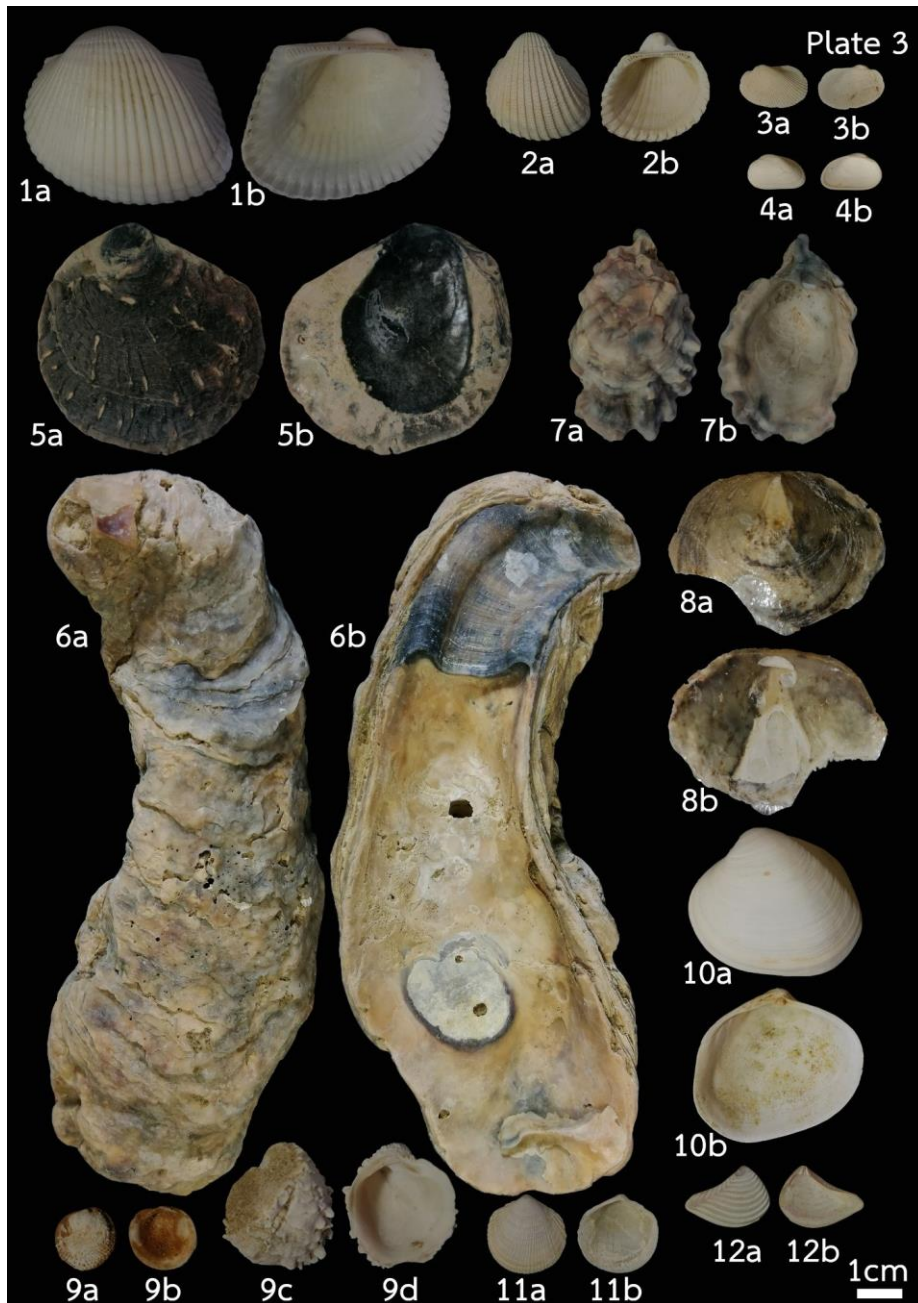


PLATE 3. Mollusca collected from the study areas 1) *Anadara inaequalis*, 2) *Anadara pilula*, 3) *Scapharca indica*, 4) *Striarca symmetrica*, 5) *Planostrea pestigris*, 6) *Crassostrea gigas*, 7) *Saccostrea cucullata*, 8) *Placuna placenta*, 9) *Chama aspersa*, 10) *Cycladicama oblonga*, 11) *Lepidolucina venusta* and 12) *Bathytormus radiates*.

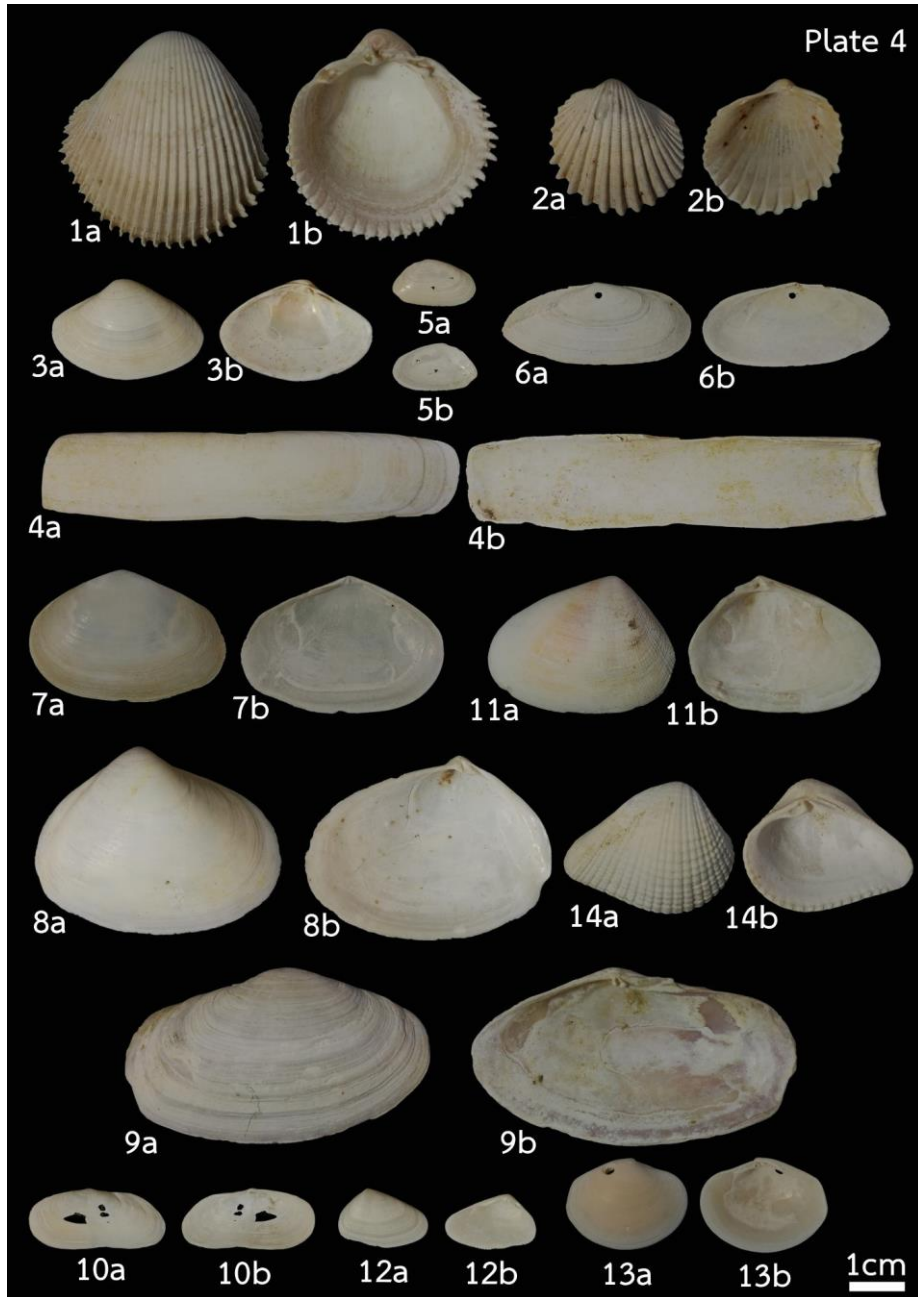


PLATE 4. Mollusca collected from the study areas 1) *Vepricardium coronatum*, 2) *Vepricardium sinense*, 3) *Mactra luzonica*, 4) *Solen curtus*, 5) *Tellina emarginata*, 6) *Tellina lanceolata*, 7) *Tellina timorensis*, 8) *Psammotreta edentula*, 9) *Gari elongate*, 10) *Azorinus abbreviatus*, 11) *Donax faba*, 12) *Donax semigranosas*, 13) *Sunetta contempta* and 14) *Anomalocardia squamosa*.

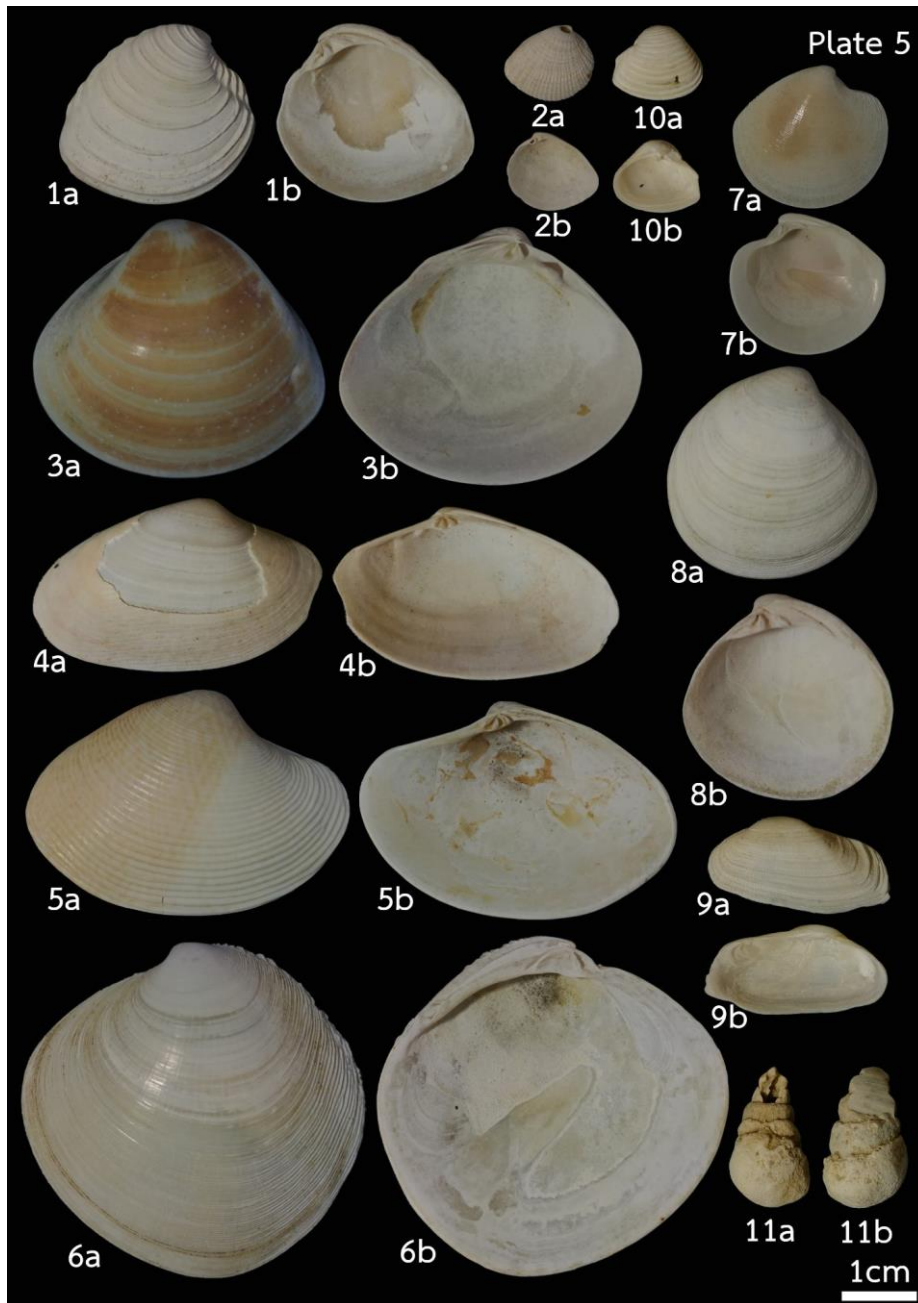


PLATE 5. Mollusca collected from the study areas 1) *Placamen chloroticum*, 2) *Timoclea scabra*, 3) *Meretrix meretrix*, 4) *Paphia undulata*, 5) *Paphia gallus*, 6) *Dosinia cretacea*, 7) *Dosinia dautzenbergi*, 8) *Dosinia dilecta*, 9) *Glaucanome* sp., 10) *Corbula fortisulcata* and 11) *Cucurbitula cymbium*.



Optically stimulated luminescence dating reveals rate of beach ridge and sand spit depositions from the upper Gulf of Thailand

Journal:	<i>Songklanakarin Journal of Science and Technology</i>
Manuscript ID	SJST-2017-0264.R6
Manuscript Type:	Original Article
Date Submitted by the Author:	07-Jun-2018
Complete List of Authors:	Surakiatchai, Peerasit; Chulalongkorn University, Geology Songsangworn, Ekkachai; Chulalongkorn University, Geology Pailoplee, Santi; Chulalongkorn University, Geology Choowong, Montri; Chulalongkorn University, Geology Phantu Wongraj, Sumet; Chulalongkorn University, Geology Chabangborn, Akkaneewut; Chulalongkorn University, Geology Charusiri, Punya; Chulalongkorn University, Geology
Keyword:	Optically stimulated luminescence (OSL) dating, sand spit, sea level change, beach ridge plain, Gulf of Thailand

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Submitted to

“Songklanakarin Journal of Science and Technology (SJST)”

TITLE

**Optically stimulated luminescence dating reveals rate of beach
ridge and sand spit depositions from the upper Gulf of Thailand**

Peerasit Surakiatchai, Ekkachai Songsangworn, Santi Pailoplee, Montri Choowong*, Sumet

Phantuwongraj, Akkaneeewut Chabangbon and Punya Charusiri

*Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit
(MESA RU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok,
Thailand*

* Corresponding author

Montri Choowong, Ph.D.

Email: monkeng@hotmail.com

Tel.: (66) 2218-5445; Fax: (66) 2218-5464

Abstract [140 words]

In order to increase the understand in history of late Quaternary coastal evolution, optically stimulated luminescence (OSL) dates of 12 quartz-rich samples collected from Chanthaburi paleo-sand spit and 37 samples from beach ridges at Sam Roi Yot (SRY) national park, the upper Gulf of Thailand were analyzed. Single-aliquot regenerative (SAR) technique was employed after OSL sample treatment. As a result, both equivalent dose and annual dose provide OSL signals internally consistent. Derived OSL ages are in good agreement with stratigraphic evolution of spit and beach ridge progradation. OSL dating of paleo-sand spit reveals the age ranging from 17,210 to 1,370 years. An average lateral migration rate of sand spit varies from 0.2 to 1.8 m/year. OSL age of beach ridge plain from SRY started from 10,200 to 880 years. Beach ridge plain has an average eastward progradation of 0.4-22 m/year.

Keywords: Optically stimulated luminescence (OSL) dating; sand spit; sea level change, beach ridge plain, Gulf of Thailand

41 **Body text** [4,525 words]

42 **1. Introduction**

43 Among various types of coastal landforms, the orientation of sand spit and series of
 44 beach ridges is of significant clue to refer the progradation, evolution of the coast and their
 45 paleo-current direction. Systematic dating of spit and beach ridge collected perpendicular to
 46 the shoreline is, therefore, useful for illustrating shoreline development in any sites of
 47 interest. The precise altitude of each spit and beach ridge coupled with reliable result of
 48 dating can be remarkably revealed the migration rate of beach ridge progradation as well as
 49 provided as one of geological proxies of sea level change (Karpytchev, 1993; Tribe, 2008;
 50 Szkornik, Gehrels, & Murray, 2008). At present, it is widely accepted that the AMS
 51 radiocarbon dating is the most reliable scientific dating method, in particular for the
 52 Quaternary period (Hajdas, 2008). However, in practice, radiocarbon dating requires specific
 53 organic sample which was rarely preserved in beach sand or spit, likewise, it may
 54 contaminate by modern roots (Kilian, Geel, & Plicht, 2000). Thus, in this study, we applied
 55 optically stimulated luminescence (OSL) datings of sand grain to estimate rate of deposition
 56 of sand spit and beach ridge. In contrast to the other scientific dating methods, OSL dating is
 57 able to date quartz-rich sediments representing the last exposure to daylight during the
 58 transportation process. Mathematically, the date can be presented as expressed in equation (1)
 59 (Aitken, 1985) below.

$$\text{OSL date} = \frac{\text{Equivalent dose (ED)}}{\text{Annual dose (AD)}} \quad (1)$$

61
 62 where the equivalent dose (ED) (in the unit of Gy) is the luminescence intensities emitted
 63 during the sample was stimulated by optical (i.e., light) source. Whereas, the annual dose
 64 (AD) (in the unit of Gy/yr) is the annual dose determined from the concentration of natural

radioisotopes, i.e., uranium (U), thorium (Th) and potassium (K), surrounding the sample recognized.

OSL dating is beneficial for late Quaternary dating with the reliability of age ranging from about months to 150,000 years old with an error ranged around 5-10% (Murray & Wintle, 2000; Murray & Olley, 2002). In addition, based on literature reviews, a number of OSL dating with coastal sand were demonstrated successfully, i.e., beach dune sequence in Australia (Banerjee et al., 2003), marine terrace sediments in Korea (Choi, Murray, Jain, Cheong, & Chang, 2003), beach ridge plain in Denmark (Nielsen, Murray, Pejrupa, & Elberling, 2006), paleo-shorelines in Tibet (Lee, Li, & Aitchison, 2009), and coastal barrier spit in Germany (Reimann, Naumann, Tsukamoto, & Frechen, 2010). In order to establish the evolution of the coastal area in this study, paleo-sand spit observed along the eastern part of the Gulf of Thailand and from SRY beach ridge plain were dated. The dates obtained here are useful to estimate average local and lateral migration rate and/or the regional evolution of sea level change in the period of spit and beach ridge development.

2. Study Area and Sample Location

Paleo-sand spit recognized in this study area is located about 15 km landward from the present-day shoreline of Chanthaburi Province, eastern part of Thailand (Figures 1A and 1B). According to coastal geomorphologic map (DMR, 2001), at least 9 units of different geomorphologic landforms were classified including subtidal flat, intertidal flat, young sandy beach, young lagoon, marsh, old lagoon, old tidal flat, old sandy beach (defined as paleo-sand spit in this study), and disturbed areas (Figure 1A). Based on detailed remote sensing interpretation, paleo-sand spit at Chanthaburi is composed of 12 ridges generally lying in northwest-southeast and slightly concaves toward the land to northeast direction at the end of spit (Figure 1B). Spit ridge is about 0.4-1.14 km wide. At present, spit ridges are covered in

some parts by bushes and trees and were disturbed mainly by human communities in particular for shrimp farm. The northwestern part of spit is limited at old lagoon; whereas, the southwestern and the southern parts are blanketed by tidal flat (Figure 1A). Based on field investigations, each spit has a very low gradient.

Beach ridge plains of SRY are located at Pran Buri and Kui Buri Districts of Prachuap Khiri Khan Province (Figure 2). Choowong et al. (2004) classified the coastal landforms at Pran Buri and SRY coasts that consisted of tidal flat, beach ridge plains, tidal channel and paleo-coastal bay. At SRY beach ridge plain, long and parallel ridge along the coastline were described. Shallow swales were also found in between ridges making irregular and undulating terrain of beach ridge plain.

3. Material and Method

We interpreted several series of aerial photographs and satellite images taken in different period of times. At Chanthaburi, aerial photograph taken in 1954 was interpreted to locate site specific sample collection of OSL dating. At Pran Buri and Kui Buri taken in 1955 (ID 23962), aerial photograph taken in 1954 (ID 49472) with hydrographic charts I produced in 1941 were used to map geomorphological units, especially beach ridge plain. Satellite images from Google Earth were also employed to locate OSL sampling points on beach ridge.

A total of 12 samples of sands were collected from spit ridge at Chanthaburi and 37 samples from Prachuap Khiri Khan. All samples were collected from manually dug soil pits, below soil development (i.e., in the C-horizons). Sample collection was carried out one times, therefore, no comparison in water content in different seasons has been done. In order to measure OSL intensities representing the ED, samples were taken in plastic tubes and sealed immediately to retain moisture and stored in lightproof plastic bags. Thereafter, some parts of

116 sand were collected additionally surrounding the ED sampling location. This part is used for
117 AD evaluation.

118 Beach ridge plains at Pran Buri consist of three set of ridges with erosional lines
119 recognized clearly as indicated by dash lines in Figure 2. Because beach ridge plains are
120 narrow, only a transect line was designed for OSL sampling. At Bangpu village of SRY, two
121 transect lines were assigned almost in west-east direction. At the south of SRY, large beach
122 ridge plain at Kui Buri was selected. Set of beach ridges intervening with swales are
123 common. We collected OSL at depth 30-50 cm from surface to avoid land surface
124 modification (Figure 3D).

125 In sample preparation process, 2 portions of samples were divided including 1) ED
126 measurement, and 2) AD including water content measurement. The portion of ED was
127 carried out in the subdued red light whereas the portions of AD, including water contents
128 were prepared with light exposed. Methodology for measuring ED, AD and example of each
129 sample analysis were summarized and described below. A similar method was applied to all
130 samples collected from Chanthaburi and Sam Roi Yot coasts.

131

132 **3.1 Equivalent Dose (ED) Measurement**

133 For ED portions, wet sieve was employed to recover grains 74–250 µm in diameter
134 (Takashima & Honda, 1989). Then, this fraction was etched with HCl for carbonate-fragment
135 elimination. In addition, in order to avoid the effect of alpha dose rate, the HF was utilized to
136 remove the quartz skin (Takashima & Honda, 1989). Thereafter, the ferro-minerals were
137 eliminated using an iso-dynamic magnetic separator. In order to check the homogeneous of
138 samples, all treated quartz samples were tested by X-ray diffraction (XRD), the result reveals
139 the purification of alpha quartz. In addition, it is constrained by samples that have significant
140 infrared (IR)-stimulated signal compared to blue light signal.

The ED measurements were carried out using a Risø TL/OSL reader (TL/OSL-DA-15), Department of Geology, Faculty of Science, Chulalongkorn University, Thailand. Each measurement was equipped with a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ beta radiation source and a blue (470–720 nm) light source (Bøtter-Jensen, 1997; Bøtter-Jensen, Bulur, Duller, & Murray, 2000). In this OSL measurement, we used the detection filter of 7.5 mm Hoya U-340 and preheated temperature at 220 °C with the rate 5 °C/second. Prepared quartz grains were attached to a 9.8 mm diameter stainless steel disc, using silicone oil. A single-aliquot regenerative (SAR) technique (Murray, Marten, Johnston, & Martin, 1987; Murray & Wintle, 2000; 2003) was used for assessing all ED, with test doses around 10% of the estimated natural dose (N). The fixed test dose (usually 10–20% of the natural dose) was applied to correct for any sensitivity changes. The example of OSL measurement of the sample number SP-2 is given in Figure 3.

From Figure 3A, blue lines correspond to OSL decay curve of natural dose (N); meanwhile, the other color lines correspond to the additional doses (R_1 – R_3). As an integral part of SAR protocol, behavior of samples is tested by examining recuperation (measurement of zero dose) and recycling ratio (ratio between the first and last regenerated signals; Murray & Wintle, 2000). Of six iterative tests, most results had T_x/T_n graph within the range 0.9–1.1 (Figure 3C).

In order to perform OSL growth curve and ED estimation, OSL signals were calculated by integration of the first 2 seconds of data and subtracting the background (30–40 seconds). As demonstrated in Figure 3B, for example, black squares represent OSL signal (L_x/T_x) of R_1 – R_3 which show general trend in thin blue line. According to OSL signal of N (open square) corresponding to the trend line, the ED of this aliquot of sample number SP-2 was estimated around 30 second or 4.23 Gy (1 second = 0.141 Gy). In terms of growth curve, some samples show slightly exponential trend, but not clear. All seem to show linear trend. We, however, calculated age results and compare between linear and exponential trends. Calculated ages are somewhat different (not exceed 300 years). In term of beach evolution,

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we can accept this difference in age because we consider age in millennium scale. As mentioned above, SAR technique was employed, the result of one disc represents a single-aliquot ED. In this study, 10 discs of aliquots per sample were measured. The series of obtaining ED results is shown. For instance, sample number SP-2, the ED obtained in this measurement is in the range of 3.50-9.67 Gy. Among 7 available ED, most values are in 3.81-5.04 Gy. There is only one ED value of 9.36 Gy that can be measured from sample number SP-2. In contrast, sample no. SP-10 reveals sparsely distribution of the obtained ED ranged between 9.09-9.43. According to Duller (2008), four different age models that can be applied in the analysis of ED datasets are the (i) central or average age model, (ii) common age model, (iii) minimum age model and (iv) finite mixture model. It is noted that each model depends on its own specific assumption that has a valid, but different value and unique meaning. For instance, the central model is commonly used when the population of the ED distribution exists. Meanwhile the minimum age model assumes that only part of the sample was bleached or heated. Based on the distribution of ED, the minimum age models were utilized in this study and the results are shown in Table 1.

3.2 Annual Dose (AD) Measurement

In this study, AD of each sample was also derived from natural radioisotopes concentrations, i.e., U (ppm), Th (ppm), and K (%), measured by high-resolution gamma spectrometry (Table 1). Based on the obtained concentration of these three radionuclides, AD values of each sample were evaluated according to standard table proposed by Bell (1979) including the calculated cosmic ray dose rate (Prescott & Hutton, 1994). Thereafter according to Aitken (1985), AD obtained above was reduced by attenuation factors based on both grain-size distribution and water content. AD of each sample and error calculation was calculated according to Singh et al (2017) (Table 1). Comparing between AD of all samples, it reveals that AD of sample no. SP-10 (AD = 0.33±0.03 Gy/ka) is less than the other samples. This is

193 according to low concentration of U (0.28 ± 0.04 ppm), Th (0.68 ± 0.16 ppm), and K
194 ($0.03 \pm 0.06\%$) whereas high of water content (3.6%; Table 1). Regarding sample number SP-
195 2 which defined as the maximum AD, the most prominently high of the radionuclides
196 concentration is according to the %K (up to 2.16 ± 0.12) whereas %K of the other samples are
197 less than 1.0 (Table 1).

198 In this preliminary work, AD errors are low, while ED errors are quite high. However,
199 we inferred our result of OSL datings for the explanation of beach ridge evolution in a
200 millennium scale, so that the 10 percent error of dating is acceptable. However, for further
201 study, it should be calculated through advanced statistics (e.g. Galbraith & Roberts, 2012).

202 203 **4. Results and Discussions**

204 **4.1 OSL ages and rate of paleo-sand spit deposition from Chanthaburi**

205 Based on both ED and AD obtained from the above-mentioned method, OSL dates of
206 each sample were evaluated according to equation (1). As shown in Table 1, OSL ages
207 indicate that paleo-sand spit at Chanthaburi began to form at $17,210 \pm 1280$ years ago (SP12)
208 and stopped forming around $1,370 \pm 200$ years ago (SP2). In general trend, all 12 units of
209 sand spit ages display a decreasing trend as expected for the migration of spit in
210 southeastward direction. However, sand spits no. SP3-4 and SP7-9 are of very similar age
211 and essentially contemporaneous because of the overlapping error ranges. Very close OSL
212 ages were also obtained from sand spits numbers SP-9-10.

213 In addition, according to the distance between each unit of sand spit with the
214 implement by OSL dates evaluated in this study, rate of sand spit deposition and migration
215 can be contributed. According to progradation rates estimated from this study, the rate of
216 sand spit can be divided into three phases. Firstly, the initial phase when sands spread
217 moderately around 0.25- 0.45 m/year at around 6,300 years (from sand spit number SP2-6).
218 Secondly, during the formation of spit number SP7 to SP8 own OSL date as short and similar

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as 410 years (cal. 8390-7980 year). The calculated rate of sand spit is more rapidly spread up to around 1.80 m/year. Finally, during the formation of spit number SP10 to SP12, spit migration rate decreased down to 0.2-0.50 m/year. In summary, the average rate of paleo-sand spit deposition from Chanthaburi is estimated around 60 cm/year considering throughout 16,800 years during $1,370 \pm 200$ to $17,210 \pm 1280$ years. However, we interpreted two OSL age results (SP11 and SP12) that might be reworked and preserved the age of original alluvial sources because the paleo-shoreline around 12,000-17,000 years was located at several meters below the present mean sea level.

4.2 OSL ages of beach ridge plain from SRY

At the south of Pran Buri area, two transect lines were designed (also see Figure 2). The OSL date from the first transect provided the age of innermost beach ridge up to 10,200 years where the sample was collected from 300 m away from recent shoreline. The maximum age of beach ridge in the second transect was 9,610 years in place where sample was picked up from 470 m away from the present shoreline. At the north of Pran Buri area, the age of beach ridge from the first transect is 7,650 years from ridge located at 750 m away from recent shoreline. The age of beach ridge from second transect is 6,510 years from ridge located at 940 m inland from recent shoreline (Table 2).

At SRY area, OSL samples were collected from 4 transects. First transect is located northernmost part. OSL date provided the age of beach ridge 6,260 years located at 1,450 m away from recent shoreline. At the second transect, the age of 4,650 years was detected from ridge located at 1,900 m from recent shoreline. Beach ridge at the third transect owns the age up to 5,290 years at 1,800 m away from recent shoreline. At the southernmost final transect, the age of ridge is 5,140 years where it is located at 1,670 m away from recent shoreline (Table 3). However, two OSL age results from Pran Buri (P1-2 and P2-3) were not taken into

244 account for sea level discussion because they were probably reworked and preserved the
245 older age from original sources of sand.

246 At Kui Buri, OSL dating was carried out from 3 transects. At the first transect, the age
247 is 7,860 years dated from ridge locating at 1,070 m away from recent shoreline. Beach ridge
248 at the second transect provides the age of 7,810 years at 1,350 m from recent shoreline. The
249 third transect provides the age of 6,890 years from ridge located at 1,700 m away from recent
250 shoreline (Table 4).

251 Based on the above-mentioned OSL age dating coupled with aerial photograph
252 interpretation from Pran Buri, the paleo-environment was the open sea at from 10,000-2,000
253 years ago. Ridge and swale (former beach ridge plain) have been formed since 2,000 to 1,000
254 years ago. At SRY area, the paleo-environment was a semi-enclosed bay at 6,500-2,000 years
255 ago. Likewise, Pran Buri and SRY, ridge and swale from Kui Buri have been formed since
256 2,000 to 1,000 years ago. The coastal plain at Kui Buri formed as bay shape connecting to the
257 open sea at 8,000-2,000 years ago. Tidal flat formed extensively at 2,000 to 1,000 years ago
258 and then, the former and recent beach ridge and swale were formed thereafter.

259

260 **4.3 Implication for sea level history**

261 The evolution of SRY, Pran Buri and Kui Buri coastal plain at the western part of
262 GoT is comparatively equivalent with the evolution of paleo-sand spit from the eastern side
263 of GoT in term of temporal progradation. Results of OSL datings confirmed that the paleo-
264 environment from both sides of GoT was once the open sea during the late Pleistocene.
265 However, the age of coastal plain development was somewhat different from place to place.
266 At Chanthaburi, sand spit shows series of continuous curved ridge formation from the late
267 Pleistocene to late Holocene, whereas the west coast of GoT mostly preserved the record of
268 the middle Holocene highstand. Only maximum age of beach ridge at Pran Buri provided the
269 age of 10,200 year comparatively corresponds with the age of late Pleistocene marine

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transgression. It suggested very rare preservation of transgressive beach ridge. Mostly, beach ridge at SRY given the maximum age of 6,260 year suggests the age of highstand. Similarly, beach ridge at Kui Buri provides the age of 7,860 year to which it can be related to highstand as well. All these OSL datings were plotted into sea level curve and results show the ages seem likely equivalent well with sea level curve from ICE 5G SL model (Peltier, 2004). However, the altitude of highstand level during the middle Holocene from this study is somewhat different from beach ridge plain and paleo-sand pit at Chumphon estuary and Thai-Malay peninsula where Nimnate, Chutakositkanon, Choowong, Pailoplee, & Phantu Wongraj, (2015) and Horton et al. (2005) reported the age of highstand of about 6,500 years with about 4 m of highstand above the present sea level, respectively.

Interestingly, OSL results show that the late Pleistocene beach ridges were observed at Chanthaburi where beach ridges were likely formed as strandline in very limited environment for strandplain to be developed. This strandline is, therefore, likely to be the only evidence of Pleistocene beach ridge in the upper GoT. The absence of the late Pleistocene beach ridges somewhere else along the coast of upper GoT was probably because during that time, the open sea environment provided inappropriate accommodation space for preserving rapid beach ridge transgression. The late Holocene development of small scale barrier system around SRY coastal plain (Surakiatchai, 2005) was the additional reason to confirm the environment of this coastal plain. However, anomalously flooding by typhoons or storms in the past also led to an overwash of the low-lying areas along the coastline (Williams et al., 2016). Traces of washover sediment were recognized on top of baymouth spit. Baymouth bar was eroded and left behind the healed storm surge channel. These multiple layers of washover deposits suggested the frequency of storm events in this coastal plain to which these storms modified and influenced the preservation potential of the late Pleistocene beach ridge transgression.

296 5. Conclusion

297 This study has shown that OSL chronology can be used for calculating rate of spit and
298 beach ridge deposition and further apply to discuss the history of sea level change and coastal
299 evolution history from the upper GoT. This OSL age dating technique is suitable for beach
300 ridge where organic materials (peat, charcoal) were rare or not available. In this study, the
301 uncertainty of OSL dating is approximately less than 10 percent which is acceptable for
302 beach ridge plain. Although, the method is acceptable, but the discussion on age result from
303 OSL may contain the complication because samples may not preserve the real age of the
304 latest deposition or they were reworked.

305 We recognized paleo-sand spit locating about 15 km far inland from the present
306 shoreline at Chanthaburi, eastern part of GoT. OSL dating from this spit provided the age
307 ranged from late Pleistocene to late Holocene. Spit itself is of significant evidence of paleo-
308 shoreline and the continuous formation through the Holocene can tell us the episodic
309 evolution quite clear. Results of OSL dating from spit in the eastern part and beach ridge
310 plain in the western part of the GoT shows that paleo-shoreline used to locate far inland from
311 the present-day shoreline during late Pleistocene and early Holocene.

312 At Chanthaburi paleo-sand spit, the dates reveal that they were developed from
313 $17,210 \pm 1280$ to $1,370 \pm 200$ years. Combining the OSL ages with the number of sand spit
314 and the distance from each dated spitting ridge, we derive an average lateral migration rate of
315 0.6 m/year (sand spit number SP2-12). OSL age of beach ridge plain from SRY started from
316 10,200 to 880 years providing the rate of eastward progradation of 0.4-22 m/year. The OSL
317 dating can be applied as one step in developing the better understanding of coastal evolution
318 particularly in place where beach ridges were formed as spit and the beach ridge plain. The
319 further work to constrain is dates by the other scientific methods if the samples are available.

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Acknowledgements

Part of data is extracted from Ph.D thesis of first author under the scholarship from 90th Anniversary of Chulalongkorn University. This work was partly sponsored to MC by Thailand Research Fund (BRG5780008) and Ratchadapisek Somphot Endowment (CU59-060-CC). Special thanks are extended to MESA RU, Department of Geology, Faculty of Science, Chulalongkorn University, for logistic supports during fieldwork. Mr. Non Prapasanobon is credited as the first person to make detail survey and map the paleo-sand spit at Chanthaburi. We acknowledge thoughtful comments and suggestions by editor and anonymous reviewers, which enhanced the quality of this manuscript significantly.

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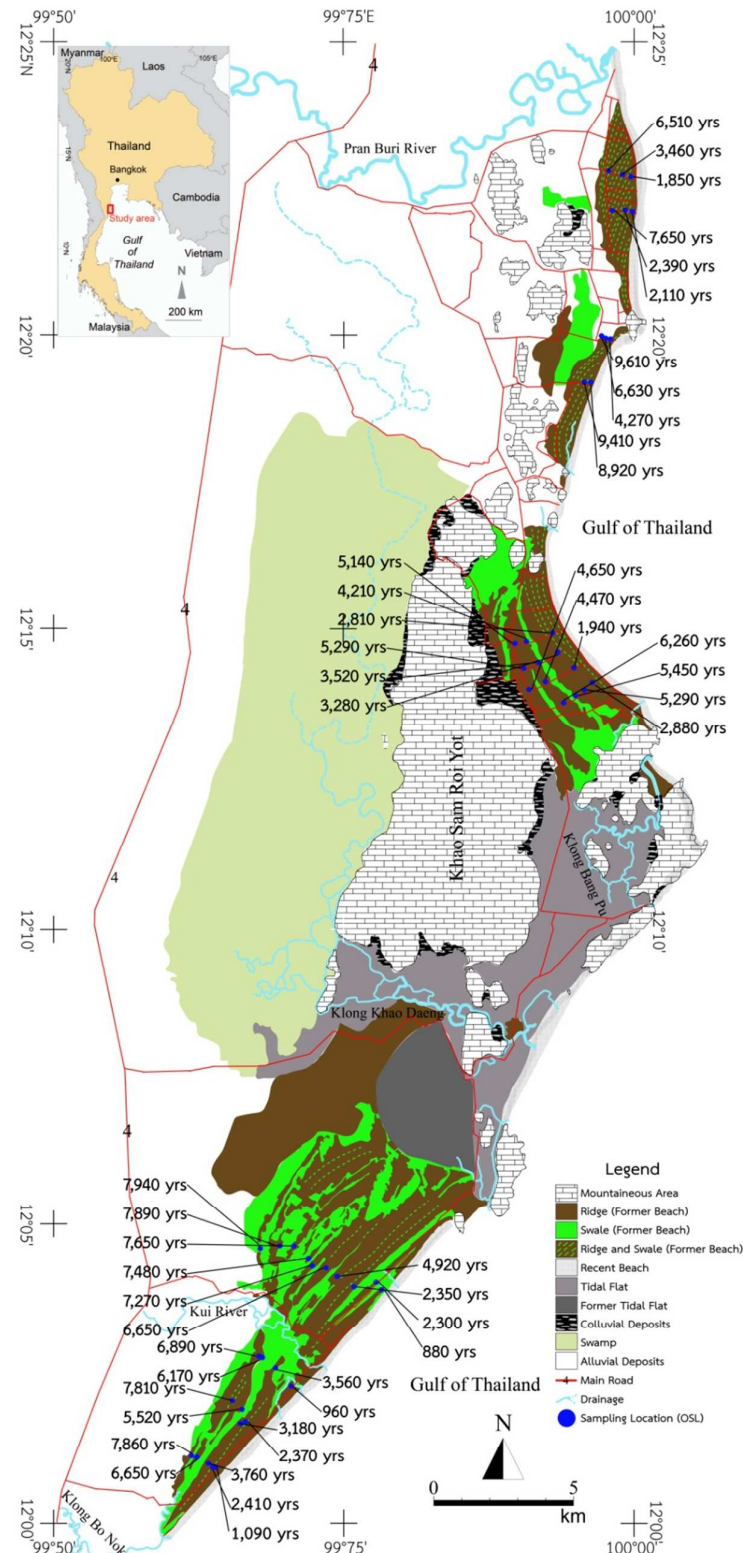


Figure 2. Geomorphological map of Pran Buri, SRY and Kui Buri with OSL ages of beach ridge. Location of OSL samples are listed along each transect for each location in Tables 2 to 4.

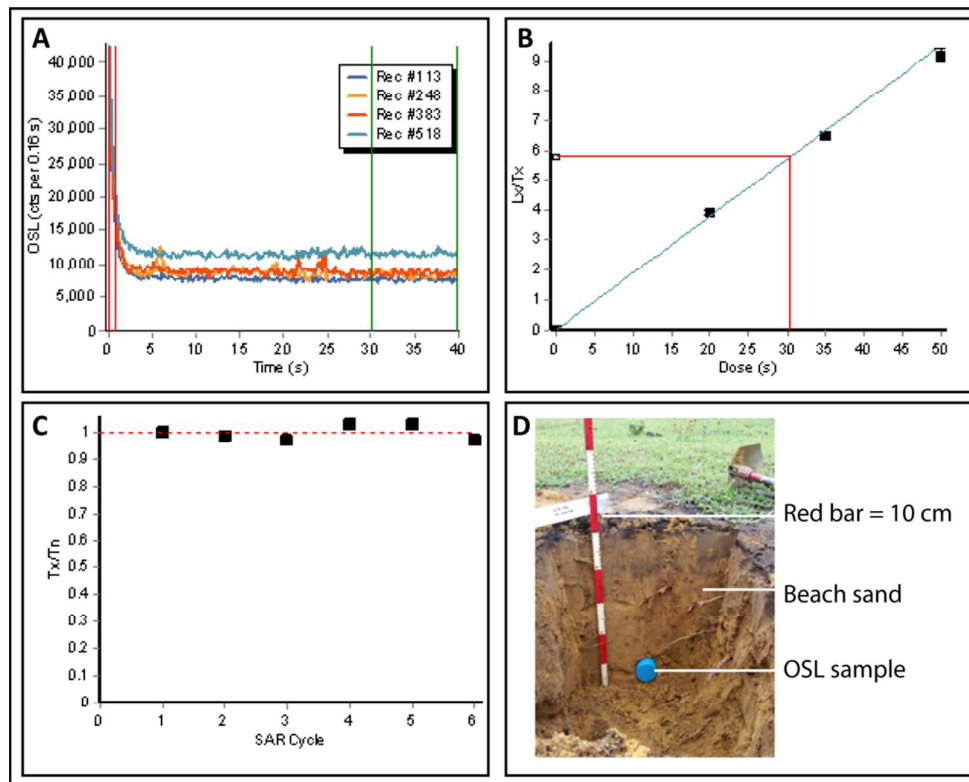


Figure 3. Example of graphs of ED measurement (sample number SP-2) showing (A) OSL decay curve (B) recycling ratio, (C) OSL growth curve and (D) field picture showing excavation and depth of sample collection.

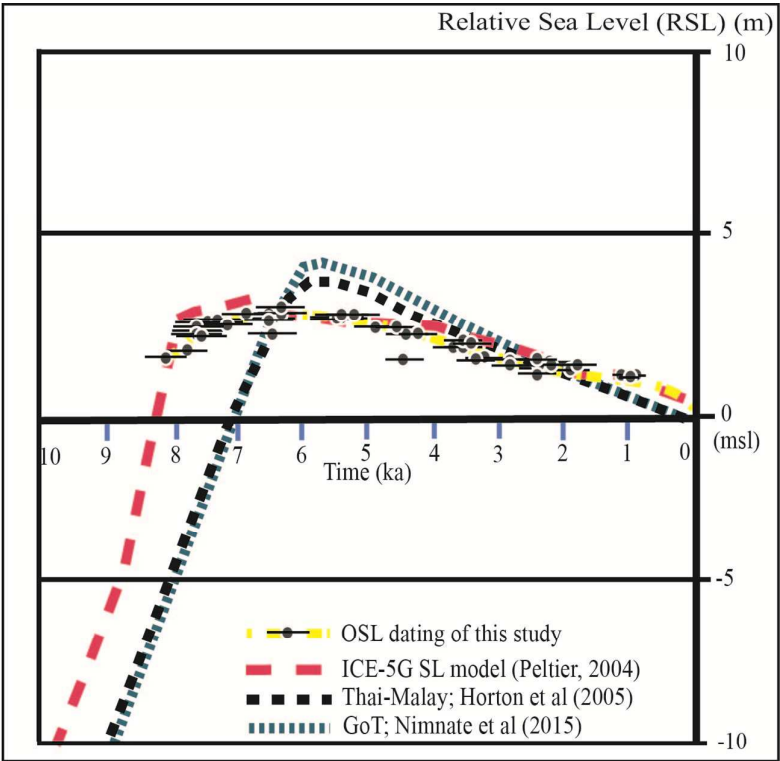


Figure 4. Plot of OSL datings in comparison with sea level curve from Chumphon, GoT beach ridge plains and paleo-sand spit (Nimnate et al., 2015), Thai-Malay peninsula (Horton et al., 2005) and ICE-5G sea level model (Peltier, 2004).

Table 1. OSL dating Result of 12 sand samples collected from the paleo-sand spit, eastern Thailand.

No.	Sample	U (ppm)	Th (ppm)	K (%)	W (%)	AD (Gy/ka)	ED _{min} (Gy)	OSL Age (Yr)	Distance (m)	Accretion Rate (m/Yr)	Spitting Rate (cm)
1.	SP-1	0.19±0.03	0.85±0.12	0.7±0.15	3.3	1.01±0.07	0.47±0.24	460±230*	-	-	-
2.	SP-2	0.28±0.03	0.92±0.14	2.16±0.12	2.7	2.54±0.16	3.50±0.73	1,370±300	400	2.3	44
3.	SP-3	0.35±0.04	1.17±0.15	0.22±0.02	2.8	0.58±0.03	2.34±0.37	4,050±670	640	-	-
4.	SP-4	0.45±0.03	1.24±0.14	0.48±0.12	2.7	0.87±0.05	2.14±0.10	2,450±180	400	-	75
5.	SP-5	0.61±0.03	1.29±0.74	0.62±0.15	2.6	1.06±0.11	5.61±0.23	5,290±560	700	4	25
6.	SP-6	0.65±0.04	1.33±0.19	0.16±0.02	2.8	0.60±0.04	4.07±0.11	6,800±440	460	3	30
7.	SP-7	0.49±0.04	1.18±0.19	0.07±0.05	0.1	0.46±0.03	3.86±0.76	8,390±170	1140	1	72
8.	SP-8	0.51±0.03	0.98±0.15	0.07±0.04	3.8	0.45±0.03	3.55±0.85	7,980±1760	340	-	83
9.	SP-9	0.42±0.04	0.53±0.23	0.11±0.03	3.0	0.43±0.03	3.57±0.54	8,240±1370	460	0.5	177
10.	SP-10	0.28±0.04	0.68±0.16	0.03±0.06	3.6	0.33±0.03	3.09±0.16	9,420±1010	610	2	52
11.	SP-11	0.35±0.04	0.78±0.15	0.13±0.02	2.4	0.46±0.03	5.80±0.32	12,710±1120	650	5	20
12.	SP-12	0.56±0.03	0.89±0.15	0.07±0.03	3.3	0.45±0.03	7.77±0.20	17,210±1280	1040	4	23

*Note: SP-1 cannot be used for interpretation due to large number of error possibly from incomplete (break down) selected quartz grain.

Table 2 OSL dating results from beach ridge plain (Pran Buri)

No.	Sample	U (ppm)	Th (ppm)	K (%)	W (%)	AD (Gy/ka)	ED _{min} (Gy)	OSL Age (Yr)	Distance (m)	Accretion Rate (m/Yr)
Transect 1										
1.	P1-1	1.32±0.1	9.34±0.1	1.06±0.1	0.85	1.63±0.1	15.35±0.61	8,920±550	-	-
2.	P1-2	1.05±0.1	4.06±0.1	1.33±0.1	1.07	1.86±0.1	16.60±0.77	9,410±780	160	3
Transect 2										
3.	P2-1	1.05±0.1	4.50±0.1	1.14±0.1	0.85	1.51±0.1	6.45±0.23	4,270±320	-	-
4.	P2-2	1.11±0.1	4.62±0.1	1.03±0.1	2.15	1.42±0.1	9.39±0.61	6,630±630	200	12
5.	P2-3	1.66±0.1	6.52±0.1	0.76±0.1	1.34	1.48±0.1	14.20±0.62	9,610±770	160	19
Transect 3										
6.	P3-1	0.89±0.1	2.98±0.1	0.55±0.1	0.68	0.88±0.1	1.86±0.07	2,110±250	-	-
7.	P3-2	0.64±0.1	2.12±0.1	0.60±0.1	0.29	0.80±0.1	1.91±0.12	2,390±330	210	1
8.	P3-3	1.24±0.1	4.21±0.1	0.82±0.1	0.56	1.27±0.1	9.73±0.44	7,650±690	350	15
Transect 4										
9.	P4-1	0.71±0.1	2.75±0.1	0.79±0.1	0.79	1.02±0.1	1.88±0.16	1,850±230	-	-
10.	P4-2	1.31±0.1	6.88±0.1	0.75±0.1	0.39	1.42±0.1	4.94±0.25	3,460±290	230	7
11.	P4-3	1.15±0.1	3.44±0.1	0.88±0.1	0.84	1.24±0.1	8.10±0.65	6,510±730	450	7

Table 3 OSL dating results from beach ridge plain (Sam Roi Yot)

No.	Sample	U (ppm)	Th (ppm)	K (%)	W (%)	AD (Gy/ka)	ED _{min} (Gy)	OSL Age (Yr)	Distance (m)	Accretion Rate (m/Yr)
Transect 1										
1.	S1-1	1.03±0.1	3.31±0.1	0.62±0.1	0.51	0.99±0.1	2.86±0.18	2,880±340	-	-
2.	S1-2	0.98±0.1	3.53±0.1	0.80±0.1	0.90	1.14±0.1	6.02±0.27	5,290±520	430	6
3.	S1-3	0.91±0.1	3.79±0.1	1.03±0.1	0.90	1.33±0.1	7.24±0.41	5,450±510	340	0.5
4.	S1-4	0.99±0.1	4.10±0.1	1.06±0.1	0.87	1.40±0.1	8.75±0.46	6,260±550	410	2
Transect 2										
5.	S2-1	1.18±0.1	4.90±0.1	0.72±0.1	0.36	1.35±0.1	2.63±0.11	1,940±160	-	-
6.	S2-2	1.00±0.1	3.88±0.1	0.92±0.1	0.53	1.32±0.1	5.91±0.30	4,470±400	870	3
7.	S2-3	0.78±0.1	3.43±0.1	1.00±0.1	0.73	1.27±0.1	5.89±0.33	4,650±440	480	0.5
Transect 3										
8.	S3-1	0.81±0.1	2.98±0.1	0.67±0.1	1.83	0.94±0.1	3.09±0.19	3,280±400	-	-
9.	S3-2	1.03±0.1	4.47±0.1	0.95±0.1	4.18	1.29±0.1	4.54±0.20	3,520±310	580	0.4
10.	S3-3	0.89±0.1	2.91±0.1	0.84±0.1	1.06	1.11±0.1	5.85±0.24	5,290±520	470	4
Transect 4										
11.	S4-1	1.15±0.1	4.83±0.1	0.70±0.1	0.58	1.20±0.1	3.37±0.11	2,810±250	-	-
12.	S4-2	0.80±0.1	3.15±0.1	0.80±0.1	1.22	1.06±0.1	4.48±0.16	4,210±420	780	2
13.	S4-3	0.86±0.1	3.48±0.1	0.85±0.1	0.68	1.16±0.1	5.95±0.41	5,140±560	420	1.5

Table 4 OSL dating results from beach ridge plain (Kui Buri)

No.	Sample	U (ppm)	Th (ppm)	K (%)	W (%)	AD (Gy/ka)	ED _{min} (Gy)	OSL Age (Yr)	Distance (m)	Accretion Rate (m/Yr)
Transect 1										
1.	K1-1	0.77±0.1	2.14±0.1	0.39±0.1	5.36	0.62±0.1	0.68±0.02	1,090±180	-	-
2.	K1-2	0.74±0.1	2.29±0.1	0.45±0.1	22.14	0.53±0.1	1.29±0.04	2,410±450	60	22
3.	K1-3	0.84±0.1	2.76±0.1	0.34±0.1	2.15	0.66±0.1	2.49±0.16	3,760±610	160	8
4.	K1-4	0.73±0.1	2.40±0.1	0.34±0.1	1.17	0.62±0.1	4.11±0.16	6,650±1,100	360	8
5.	K1-5	0.82±0.1	1.71±0.1	0.32±0.1	4.92	0.62±0.1	4.31±0.20	7,860±1,480	190	6
Transect 2										
6.	K2-1	0.77±0.1	2.49±0.1	0.35±0.1	2.07	0.63±0.1	1.50±0.07	2,370±380	-	-
7.	K2-2	0.75±0.1	2.31±0.1	0.35±0.1	7.29	0.58±0.1	1.85±0.10	3,180±570	150	5
8.	K2-3	0.71±0.1	2.07±0.1	0.31±0.1	1.05	0.56±0.1	3.12±0.17	5,520±1,020	400	6
9.	K2-4	0.68±0.1	2.11±0.1	0.41±0.1	4.06	0.62±0.1	4.88±0.30	7,810±1,340	390	6
Transect 3										
10.	K3-1	0.65±0.1	1.81±0.1	0.41±0.1	9.34	0.56±0.1	0.54±0.02	960±170	-	-
11.	K3-2	0.82±0.1	3.51±0.1	0.44±0.1	1.98	0.80±0.1	2.84±0.10	3,560±460	810	3
12.	K3-3	0.77±0.1	2.09±0.1	0.43±0.1	1.85	0.68±0.1	4.19±0.43	6,170±1,100	510	5
13.	K3-4	0.84±0.1	2.64±0.1	0.56±0.1	2.83	0.82±0.1	5.67±0.39	6,890±960	100	7

Natural Hazards

Characteristics of ancient storm surge deposit from southern peninsular, Gulf of Thailand based on sedimentological evidences and OSL-based chronology --Manuscript Draft--

Manuscript Number:	NHAZ-D-18-01376	
Full Title:	Characteristics of ancient storm surge deposit from southern peninsular, Gulf of Thailand based on sedimentological evidences and OSL-based chronology	
Article Type:	Manuscript	
Keywords:	Storm surge; coastal hazard; sedimentary structure; OSL dating; coastal erosion; southern Thailand	
Corresponding Author:	Montri Choowong, Ph.D Chulalongkorn University Faculty of Science Bangkok, <None> THAILAND	
Corresponding Author Secondary Information:		
Corresponding Author's Institution:	Chulalongkorn University Faculty of Science	
Corresponding Author's Secondary Institution:		
First Author:	Stapana Kongsen, M.Sc	
First Author Secondary Information:		
Order of Authors:	Stapana Kongsen, M.Sc	
	Sumet Phantu Wongraj, Ph.D	
	Peerasit Surakiatchai, Ph.D	
	Parisa Nimnate, Ph.D	
	Montri Choowong, Ph.D	
Order of Authors Secondary Information:		
Funding Information:	Chulalongkorn University (90 Anniversary Ratchadapisek Endowment Fund)	Mr Stapana Kongsen
	Thailand Research Fund (BRG5780008)	Dr Montri Choowong
Abstract:	Grain size analysis coupled with detailed description of sedimentary structures unveil sediment sources and transport process from the ancient coastal storm events recorded in beach ridge plain, wet swale and muddy environments at Kui Buri, Prachuap Khiri Khan, Southern Peninsular, Thailand. In this study, a total of 141 sand samples collected from the process of shore-normal beach and layers of candidate storm sediments were analyzed by laser granulometric method. As a result, at least 21 events of candidate coastal storms were described. In general, grain size distribution of beach sediments shows unimodal, whereas candidate storm sediments reveal the combination of multimodal, bimodal and unimodal distributions. Plots of statistical parameters are also capable of differentiating the coastal storm deposits from shore-normal beach sediments, especially the plot of mean grain size against skewness, mean grain size against kurtosis and skewness against kurtosis. Sedimentary structures preserved in ancient coastal storm deposits include parallel and inclined landward lamination, mud rip-up clasts, layer of shell fragments, pebble grain, normal and reverse grading, sharp lower and upper contacts. Candidate storm layers overlain on dry beach ridge and intervened with mud in swale show finer and thinner landward deposit. Marine shell fragments, smaller foraminifers, ostracod and scaphopod (tusk shell) were also preserved well. According to ten samples of OSL dating and a correlated AMS age, multiple layers of coastal storm-induced sand derived from different frequency of coastal storm activity are likely to confirm sea level oscillatory	

	during the middle to late Holocene.
Suggested Reviewers:	Santi Pailoplee, PhD Professor, Chulalongkorn University Faculty of Science pailoplee.s@gmail.com Prof. Santi is well-known geoscientist working on geological hazards in Thailand and Southeast Asia for a long time. He is one of suitable reviewers.
	Krit Won-in, PhD Professor, Kasetsart University kritwonin@gmail.com Prof. Krit Won-in is an expert in OSL dating and Quaternary coastal research in Thailand and Japan. He is one of suitable reviewers.
	Ken-ichiro Hisada, PhD Professor, University of Tsukuba hisada.k@arsia.geol.tsukuba.ac.jp Prof. Hisada has long experiences of coastal hazard research in Japan and Southeast Asia. He can help reviewing this manuscript significantly and provide constructive comments.
	Akkaneewut Chabangborn, PhD Senior lecturer, Chulalongkorn University Akkaneewut.c@hotmail.com Dr Akkaneewut owns his expertise in Quaternary and coastal researches in Thailand. He published a lot of work on coastal hazards, climate change that based quite well with the context of this manuscript. He can review this manuscript constructively.
	Punya Charusiri, PhD Professor, Chulalongkorn University punya.c@chula.ac.th Professor Punya is well-known and very famous geoscientist in Thailand and Southeast Asia. His expert is on geology of Thailand, chronological datings and so on. He will provide constructive review for this work definitely.
Opposed Reviewers:	

Dear Editor,

I, on behalf of all authors, would like to submit our manuscript titled “Characteristics of ancient storm surge deposit from southern peninsular Thailand based on sedimentological evidences and OSL-based chronology” for considering to be published in Natural Hazards. The work involves field investigation of storm surge deposit in the coastal beach ridge plain of the peninsular Thailand. Coastal geomorphological and sedimentological analyses coupled with OSL chronology have been carried out. We believe our result will provide as local-scale analog of storm surge depositional characteristics in order to better the understanding in behavior of storm in the tropical zone.

I certify here that this work has never been submitted elsewhere and contains no conflict of interest.

Yours sincerely,

Professor Montri Choowong, Ph.D

Corresponding author

Characteristics of ancient storm surge deposit from southern peninsular, Gulf of Thailand based on sedimentological evidences and OSL-based chronology

Stapana Kongsen¹, Sumet Phantuwongraj¹, Peerasit Surakiatchai¹, Parisa Nimnate^{1,2} and Montri Choowong^{1,*}

¹ Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit (MESA RU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

² Division of Geosciences, Mahidol University, Kanchanaburi Campus, Kanchanaburi 75110, Thailand

* Correspondence: Montri.c@chula.ac.th; Tel.: +66-819-200-758

Received: date; Accepted: date; Published: date

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Keywords: Storm surge; coastal hazard; sedimentary structure; OSL dating; coastal erosion; southern Thailand

Introduction

Along the world coastlines, it becomes very necessary for coastal community to prepare for the inevitable effects of such an extreme coastal natural disaster as typhoon or hurricane which is one of the direct results from present day global climate variations. The appropriate coastal management, defensive measure, warning system and emergency evacuation should be taken into account seriously to order to prevent from these extreme events. At present, sedimentary record is one of the geological evidences which can indicate environmental changes resulted from such high energy events as tsunami and extreme coastal storm. In addition, high energy events causing abrupt flooding of sea water can leave the distinct signature of anomalous sand deposits inland (commonly known as washover deposits, varying in shape, thickness and preservation potential of sedimentary structures (Donnelly 2005). The existence of washover deposits both on surface and subsurface can be used as a significant antecedent evidence to confirm the assumption that those of the areas were affected by coastal storm events. Therefore, searching for geological records of coastal storm in the past is still scientific challenges amongst many geoscientists and remains necessary for the social community.

In Thailand, candidate sand sheets of extreme coastal storm events were recognized (Phantuwongraj et al 2008, 2010; Phantuwongraj and Choowong 2012; Kongsen et al 2016; Williams et al 2016). Sedimentary structures of storm overwash process and their characteristics mainly include laminated sand layer, normal and reverse grading, washover fan, mud rip-up clast, sharp top and basal contacts, wedge-like shape, marine shell assemblage, marine microfossils, diatom (Donnelly 2005, 2001; Elsner 2007; Horton et al 2009; Lane et al 2011; Liu and Fearn 1993; 2000a, b; Liu 2004, 2007; Phantuwongraj et al 2013; Williams 2010; Williams et al 2016). Furthermore, they are often associated with paleotempestological science directly. Basically, paleotempestology is relevant to the buried offshore and/or beach sediments that were transported inland by prehistorical storm surge wave on low-lying areas located abruptly behind the sea and preserved well by muddy sedimentation in the low energy condition, forming a sand layer as a key indicator of coastal storm event in the past (Liu and Fearn 1993, 2000a, b; Liu 2004, 2007).

It is a fact that recognizing an anomalous sand layer buried in the subsurface of various coastal environments from an extreme coastal disaster (high energy event) sometimes comes along with a number of difficulties. The way to distinguish coastal storm and tsunami deposits is still needed, although the various

diagnostic keys used to define these events were reported and developed (Choowong et al 2008; Goff 2004; Goto 2015; Jankaew et al 2008 Kortekaas and Dawson 2007; Morton 2007; Nanayama et al 2000; Nott 2007; Komatsubara et al 2008; Phantuwoongraj and Choowong 2012; Tuttle et al 2004). Moreover, the depositional process of these events depends on several controlling factors from place to place such as the intensity of the event, duration, surge height, types of vegetation, beach morphology, elevation, micro-topography, sediment supply, sediment composition, mineralogy (Jagodziński et al 2012; ; Morton and Sallenger 2003; Phantuwoongraj and Choowong 2012; Turtle et al 2004).

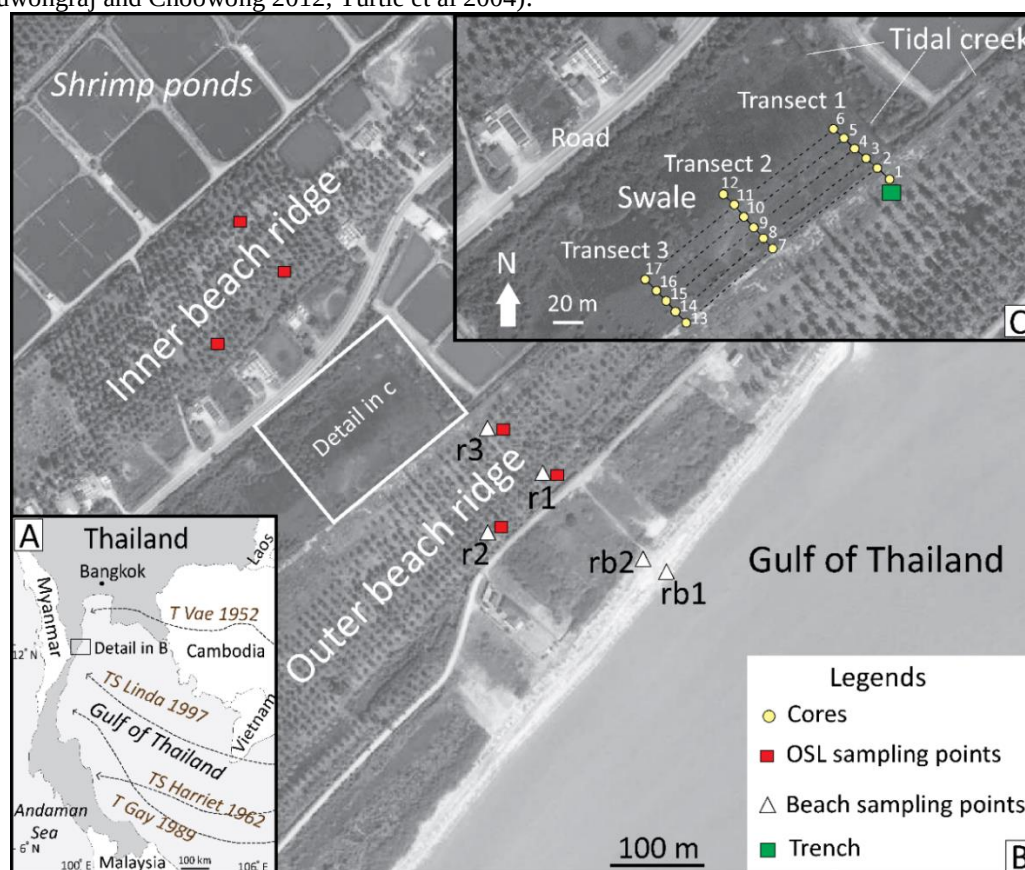


Fig. 1 Location of study site at Kui Buri, Prachuap Khiri Khan Province, southern peninsular Thailand showing (A) index map of Thailand with paths of tropical storm (TS) and typhoon (T) hit the coastal area, (B) orthophotograph of beach ridges, swale and locations of sampling points, r; ridge sediment and rb; recent beach sediment, and (C) transect lines and sample locations of cores.

Consequently, with several attempts to improve our understanding in terms of geological records of historic and prehistoric coastal storm events in Thailand, the major objectives of this paper aimed (i) to describe and discuss the resulting discovery of this study, (ii) to present the sedimentological approach for discriminating storm and beach deposit based on using sedimentological criteria of grain size analysis as a locally-valid indicator for the sediment source and the transport process of ancient coastal storm deposits and (iii) to expand the previous work published by Williams et al (2016) on the issue of the regional cyclone frequency according to the results of optically stimulated luminescence (OSL) dating and a correlated age that provide chronological representative ages of storm event.

2. Materials and Methods

2.1 Kui Buri area and impact of modern coastal storm

We continued and extended our searching for potential ancient storm deposits in the same swale on the north where Williams et al (2016) discovered them from Kui Buri, Prachuap Khiri Khan Province, southern peninsular, Thailand. The hypothesis is made on the reason that the distinctive feature of geomorphological setting here provides the potential sites appropriate to preserve the prehistoric coastal storm events. Particularly, a low-lying swale situated behind a beach ridge instantly is the targeted area (Fig. 1B). The targeted swale of this paper here is located at 12° 03' 46.00" N and 99° 55' 24.00" E and between two beach ridges where we named each beach ridges as outer and inner beach ridges (Fig. 1B). The outer beach ridge is located 650 m long

perpendicular and 300 m long parallel to shoreline. Although, the north and the south parts of swale have been modified by shrimp pond farming (Fig. 2), however, this study site has not been disturbed by the anthropogenic activity (Kongsen et al 2016).

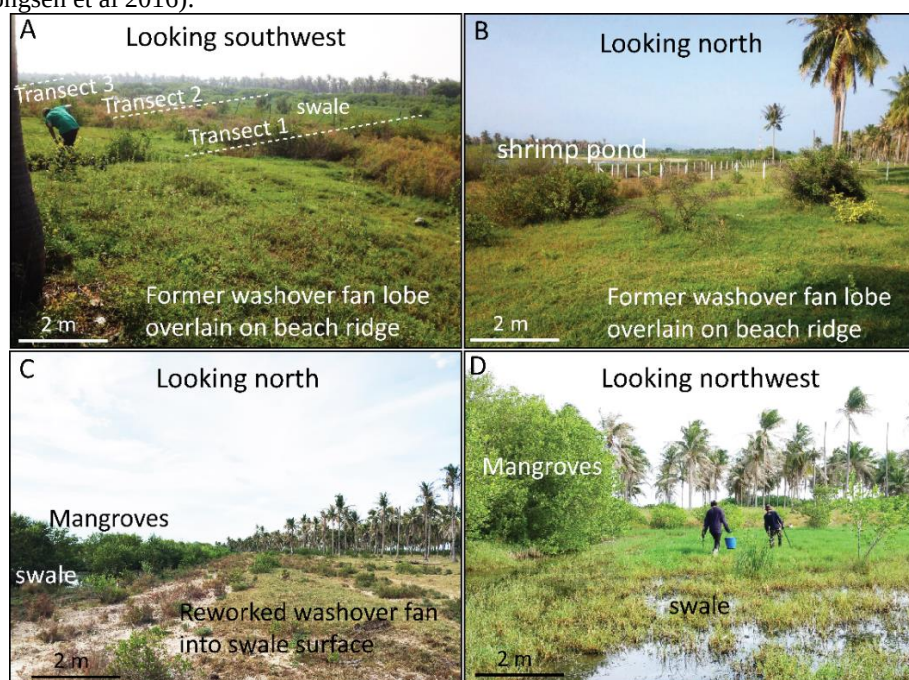


Fig. 2 Photographs of study site showing (A) three transect lines across beach ridge where former washover fan lobe overlain on shore-normal beach ridge, (B) swale modified into shrimp ponds in the north of area, (C) traces of reworked sand from washover deposits on swale surface and (D) the condition of wet swale.

The floor of swale is elevated at 0.6 m above mean tide level (MTL). Fine-grained particles (silt and clay) were found and existed on the surface of swale which was presumably transported during heavy rainfall and/or flooding from tidal channel during high tide condition (Fig. 2). Thus, it can be assumed that the normal sedimentation of swale environment here is relatively constant and has a low energy condition. In swale, water level varies from 10 to 50 cm, depending on local topography (Fig. 2D). Also, tidal creeks, sedge and mangrove (*Rhizophora apiculata*) were commonly observed. During site reconnaissance, the amount of sand compounded with broken shell debris was observed dominantly on the latter of outer beach ridge surface. This is one additional reason to infer this process of sedimentation as washover debris rather than shore normal wave deposits.

The Gulf of Thailand coast has been suffered from four extreme coastal storms two typhoons and two tropical storms in the past century including Typhoon Vae in 1952, Tropical storm Harriet in 1962, Typhoon Gay in 1989 and Tropical storm Linda in 1997 (Fig. 1A). Typhoon Gay in 1989 was attributed to one of the worst case of deadly extreme coastal storm events hit the Gulf of Thailand (Phantu Wongraj et al 2008). This event led catastrophic damages to country at least eleven-thousand Billion baht and caused the death approximately 900 fatalities. And top of that, Thailand has just started officially recording storm data in 1951, therefore, the presence of data in the decadal scale is relatively difficult to estimate and predict the future storm activity correctly. The problems on the lack of such prehistoric and historic records as the number of storm, the storm intensity and frequency should be developed apparently.

In case of the impact by modern coastal storm events, when considering the storm tracks (Fig. 1A), it seems that the sedimentary traces of these coastal storms would be preserved somewhere in the area where the coastal storms approached or traversed across. However, sedimentological analysis of these modern coastal deposits in this site has not been carried out. In Thailand, there have been a few reports and researches regarding coastal storm-induced deposits or paleotempestology. In fact, the coastal storm deposits were coincidentally discovered from the report of mineral exploration (Roy 1990). Roy (1990) reported the remain of sedimentary clues from Typhoon Gay hit Thailand coast in December 1989 at a small beach of Khao Huai Khrok area, Prachuap Khiri Khan, southern peninsular, the Gulf of Thailand where the 40 cm thick washover sand mixed with heavy minerals was found. Also, floating debris (storm marker) was observed at an elevation of approximately 1.6 m above high tide level. Almost two decades later, Phantu Wongraj et al (2008) described sand sheets, varying between 4 to 60 cm in thickness, in a muddy environment near Chaiya, Tha Chana and Leam Talumpuk, southern peninsular, the Gulf of Thailand. The detailed sedimentary structures were described by Phantu Wongraj et al (2008) including sharp upper and lower contacts with muddy layers which was suggested that these unusual sand layers seemed likely to be the potential sedimentary traces of tropical storm

Harriet in 1962, typhoon Gay in 1989 and tropical storm Linda in 1997. Phantuwongraj et al (2010), subsequently, described multiple layers of paleo-storm sand sheets found in a swale located 1 km inland from the present shoreline near Panang Tak area, Chumphon, southern peninsular, the Gulf of Thailand. However, candidate storm sand sheets found at these two places where Phantuwongraj et al (2008), (2010) discovered have not been documented in terms of the depositional ages.

Similarly, at Kui Buri area, the track way of tropical storm Linda strike in 1997 was not only made landfall close to this study area, but also ran across Prachuap Khiri Khan area to the west coast at the Andaman Sea. However, no sedimentary trace of tropical storm Linda was found and reported. Therefore, we infer that the missing sediments of tropical storm Linda may be caused either by the interventions of the anthropogenic activity along the coastal area such as the recreational construction (resorts and hotels), fishery (shrimp and fish pond farming), and coastal agriculture or spontaneous reworking, and erosional processes.

2.2. Remote sensing and topographic survey

Initially, data on aerial photographs and satellite imagery of Kui Buri area were interpreted for recognizing coastal geomorphologic features and also used to locate the best preservation potential site of ancient storm deposits - that is swale or other low-lying area. To confirm the data interpreted from aerial photographs and satellite image, field checking was carried out subsequently after finishing coastal geomorphologic interpretation.

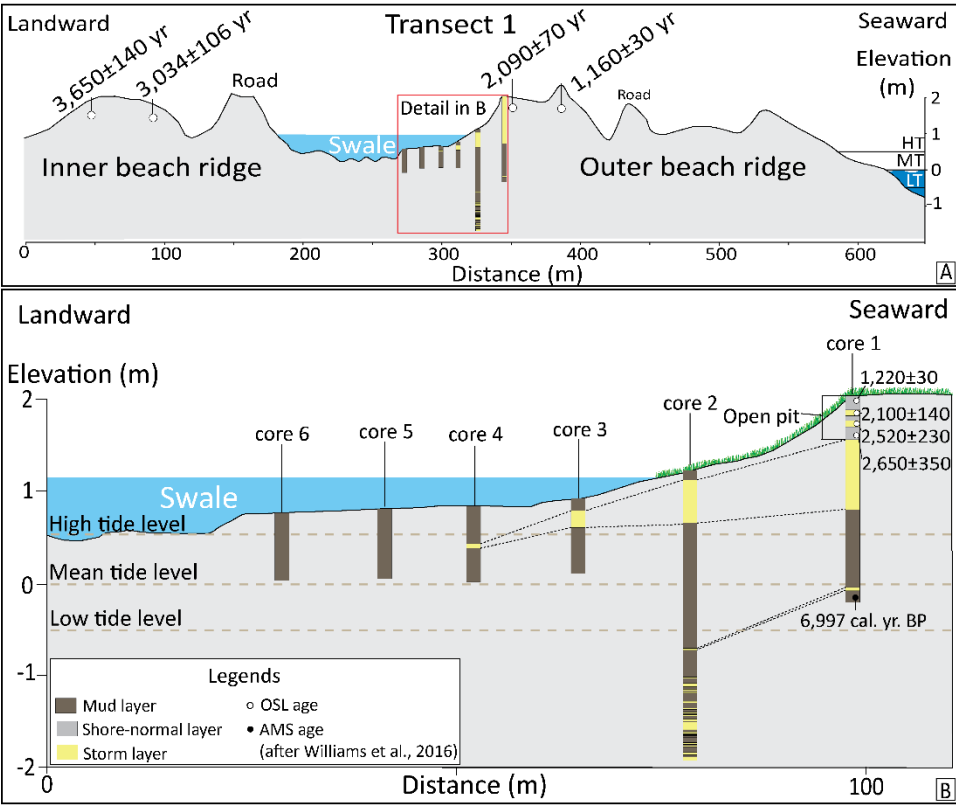


Fig. 3 Cross-section with irregular topography of outer beach ridge, swale and inner beach ridge measure with a total station survey camera showing (A) OSL ages of beach ridge formation and (B) close up of swale where locations of aluminum tubes and gauge cores were collected, and wedge-shape extension of storm sand sheet with landward thinning. OSL dating of washover fan lobe sediment also provided the depositional ages between 1,200 to 2,600 years.

Beach profile (Fig. 3A) was surveyed by using a SOKKIA total station survey camera along the east-west cross-shore transects. The starting point of surveying was performed at the sea level during the time of measuring westward across outer beach ridge, swale and inner beach ridge respectively (Fig. 3A, B) and all stations were also referenced by a hand-held GPS. Moreover, topographic profiles were referenced to sea level at the time of survey for establishing mean tide level (MTL), high tide level (HTL) and low tide level (LTL) by calculating the predicted tide level obtained from the nearest tide gauge (Ko Lak station) At study site, three beach profiles were measured and mean tidal is in the range of approximately 1 m. Later, mean tide levels of three beach profiles are set at zero point and high tide and low tide levels are in the range of 0.5 m from the top and the bottom lines of zero point (Fig. 3).

2.3. Stratigraphy, grain size analysis and Optically Stimulated Luminescence

During site reconnaissance, investigating stratigraphy was primarily conducted by using a gouge core in order to estimate the depth of potential ancient storm layer under subsurface around 2 m depth. After examining subsurface sediments and finding anomalous sand layers, coring was applied to retrieve stratigraphy. Stratigraphy was made along three east-west transects in swale perpendicular to the shoreline with distance 350 to 450 m inland (see locations of cores in Fig. 1C). 3-inch-diameter and 2 mm thick aluminum tubes were used to retain the details of sedimentary structure inside. A total of seventeen core samples were obtained (cores 1 to 17) in the length 1-3 m depth from the ground surface. All locations of coring were also referenced by a hand-held GPS. The spaces between each core were about 7-8 m. All sample cores retrieved from swale were sealed by duct tape. Then, all of the cores were transported to the Sedimentology lab at Department of Geology, Faculty of Science, Chulalongkorn University for analyzing and sampling. Sample cores were cut lengthwise and sediment samples within cores were separated into two sides crosswise. Then, logging and photographing of each core were carried out. Nearly all of the core samples retrieved show the continuity of candidate storm-induced washover deposits except for some core in the part of central swale such as cores 5, 6, 11, 12, 16 and 17 (see location of cores in Fig. 1C). However, core samples of transect 1 were solely described in this paper because they fully contain important sedimentological and stratigraphic features and the rest of cores also yields the similar characteristics of candidate washover deposits.

In transect 1, candidate storm layers were only recognized in cores 1, 2, 3 and 4. Samples of candidate storm sediments were picked at every 0.5 cm especially in the place where sedimentary structures (lamination) were observed. Unstructured candidate storm layers were collected every 1 cm. Additionally, we collected samples of beach sediments originated from shore normal process for comparatively analyzing. We named the sampling points of beach sediment sample as recent beach 1 (rb1), recent beach 2 (rb2), ridge sediment 1 (r1), ridge sediment 2 (r2) and ridge sediment 3 (r3) (see Fig. 1B). The number of 136 samples picked up from candidate layers of ancient storm and 5 samples of beach sediments were analyzed by using laser granulometric method. All data obtained from the aforementioned analysis were subsequently computed by the moment method (McBride 1971). In addition to grain size analysis, all selected sediments were also discriminated into sub-samples for detecting physical properties including composition (Fritz and Moore 1988), roundness and sphericity (Powers 1953) under a microscope. Sub-samples were dried in the oven at the temperature of 70 °C for 24 hours, and then dry-sieved through a 63 µm sieve (mesh 230) to gain sand fraction without finer particles. By doing this, the clear visualization of sand assemblages under a microscope for identifying each mineral composition can be conducted without finer-grain adhesion.

Furthermore, in the fieldwork along the lines of the outer and inner beach ridges, we excavated small pits at approximately 40 cm depth from the beach ridge surface for collecting quartz-rich materials used in OSL dating technique. A total of six OSL samples were collected for establishing lateral age control of beach ridge formation (see locations of OSL samples in Fig. 1B). Additionally, four OSL samples were vertically collected at the latter of outer beach ridge. It is a trench where the length from ground surface to the bottom is 85 cm depth and this also is the same point of collecting core 1. The trench profile itself contains two candidate storm layers at 50-58 cm and 65-72 cm depth which intercalated with shore-normal process (beach ridge) (Fig. 2). The characterization of sand-over-sand pattern at this trench is relatively difficult to recognize. Nonetheless, we differentiated them by using the different color of sand layers and the presence of marine shell fragments as a major key to define the candidate storm layers in the field. Subsequently, this is confirmed by using a microscope to detect the different composition of candidate storm and shore-normal sediments. Also, a number of marine microorganisms including foraminifera, ostracod and scaphopod (tusk shell) were found in candidate storm sediments, while almost 99 percent of quartz is the main composition of shore-normal layers. All stations of OSL samples were also referenced by a hand-held GPS and the number of ten OSL samples were designated as K1 to K10, correspondingly (Table 1 and Fig. 1).

The steps of collecting OSL samples were divided into two parts including (i) equivalent dose samples (ED) and (ii) annual dose samples (AD). In case of ED samples, at approximately 40 cm depth from ground surface, we applied 0.5 cm thick PVC tubes to collect sand used for ED samples in order to avoid the exposure of sunlight. Because ED quartz sands trapped original ages for long time would be started resetting to zero year at once, when they are first exposed to the present sunlight. Next, sand surrounding ED samples were collected for AD samples in the lightproof plastic bag and can be exposed to the sunlight.

At laboratory, OSL samples were analyzed in Quaternary Dating laboratory, Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok, Thailand. A small portion of each AD samples was separated for measuring water content. The rest of AD samples was dried at the temperature of 40 °C in the oven. AD sample sands were dry-sieved through an 841 µm (mesh 20) sieve and a pan. Sand fractions of pan (290 g) were kept for measuring natural radioisotopes concentration including Uranium (ppm), Thorium (ppm) and Potassium (%) by using high-resolution gamma spectrometry. Then, these concentrations were evaluated by using the standard table (Bell 1979) and the calculated cosmic ray dose rate (Prescott and Hutton 1994).

On the issue of ED samples, the samples of equivalent dose or paleodose were operated in the night room with the subdued red light. The samples of ED sands were wet-sieved through a 74 and a 250 µm sieve (mesh

60 and 200), then 74-250 μm sand fractions in diameter were etched by HF 24% for 20 minutes and washed with distilled water. Later, those of sand grains were cleaned with HCL 35% for 20 minutes to gain the purified quartz. Distilled water was used to wash sand fractions again and dried at the temperature of 40 °C for 48 hours. Next, the ferro-minerals in the dried-aliquot-sized samples (74-250 μm) were separated by using an iso-dynamic magnetic separator to provide the homogeneity of ED samples. ED measurements were carried out on Risø OSL/TL readers which equipped with a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ beta radiation source and a blue ($470\pm 20\text{ nm}$) light source (Bøtter-Jensen et al 2000; Bøtter-Jensen 1997). Aliquot-sized grains were attached to a 9.8 mm diameter stainless steel disc in the form of monolayer by using silicone oil. The number of five aliquots was mainly used for each age. Also, a single-aliquot regenerative (SAR) technique was employed to assess all ED samples with the test doses around 10% of the estimated natural dose (N) (Murray et al 1987; Murray and Wintle 2000). Based on ED distribution, in general the minimum age model was applied in this study (Duller 2008). OSL decay curve, growth curve, dose recovery, recycling ratio, and recuperation of each ED sample and each age are presented in online supplementary materials.

3. Results

3.1. Stratigraphy and sedimentary structures

Core 1 was situated in the most seaward location of transect 1 which far from the present shoreline around 275 m. This core was collected in the same location of trench (Fig. 1E) where the trench profile at 0-85 cm depth composed of two candidate storm layers interbedded with two layers of shore normal sand deposits. As mentioned above, we started collecting core 1 at the bottom floor of trench (at 85 cm depth). Core 1 is 140 cm long. Within core 1, two additional candidate storm layers were also observed at 10-36 cm and 127-128.5 cm depth (Fig. 5). Between 36 cm and 127 cm, a pale reddish mud layer was also observed which likely indicated iron oxidation and quiescent period. Thus, we counted the numbers of four candidate storm layers within the trench and core 1 as appeared in stratigraphy (Fig. 5). Sedimentary structures of candidate storm layers in this core consist mainly of parallel lamination (Fig. 4A), shell fragment layer (Fig. 4B), sharp lower and upper contacts with mud layers (Fig. 4C).

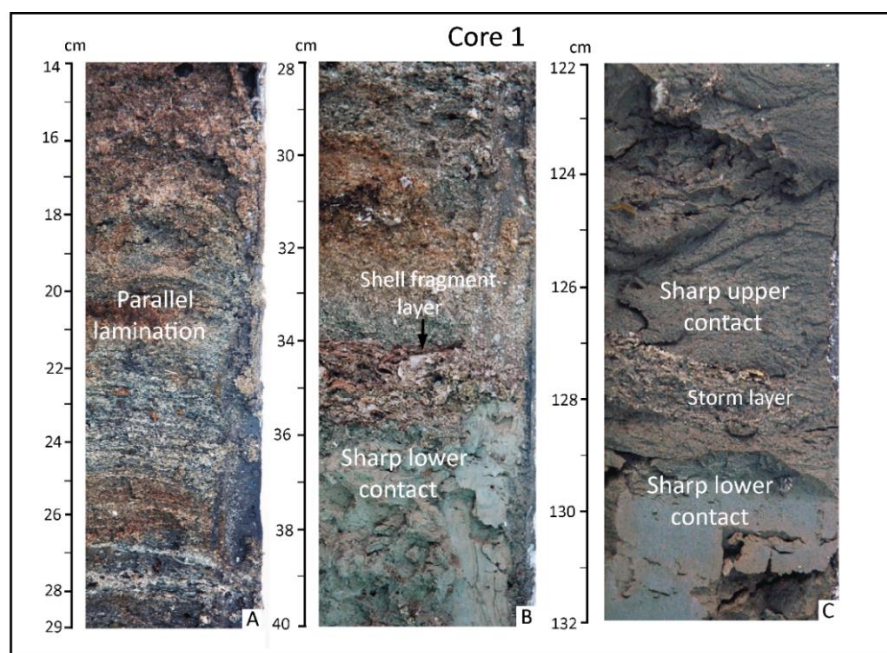


Fig. 4 Close up of internal sedimentary structures of storm-induced sand sheets within core 1 showing (A) parallel lamination, (B) layer of shell fragments and sharp contact with mud underneath and (C) a storm-induced sand sheet between upper and lower muddy layer.

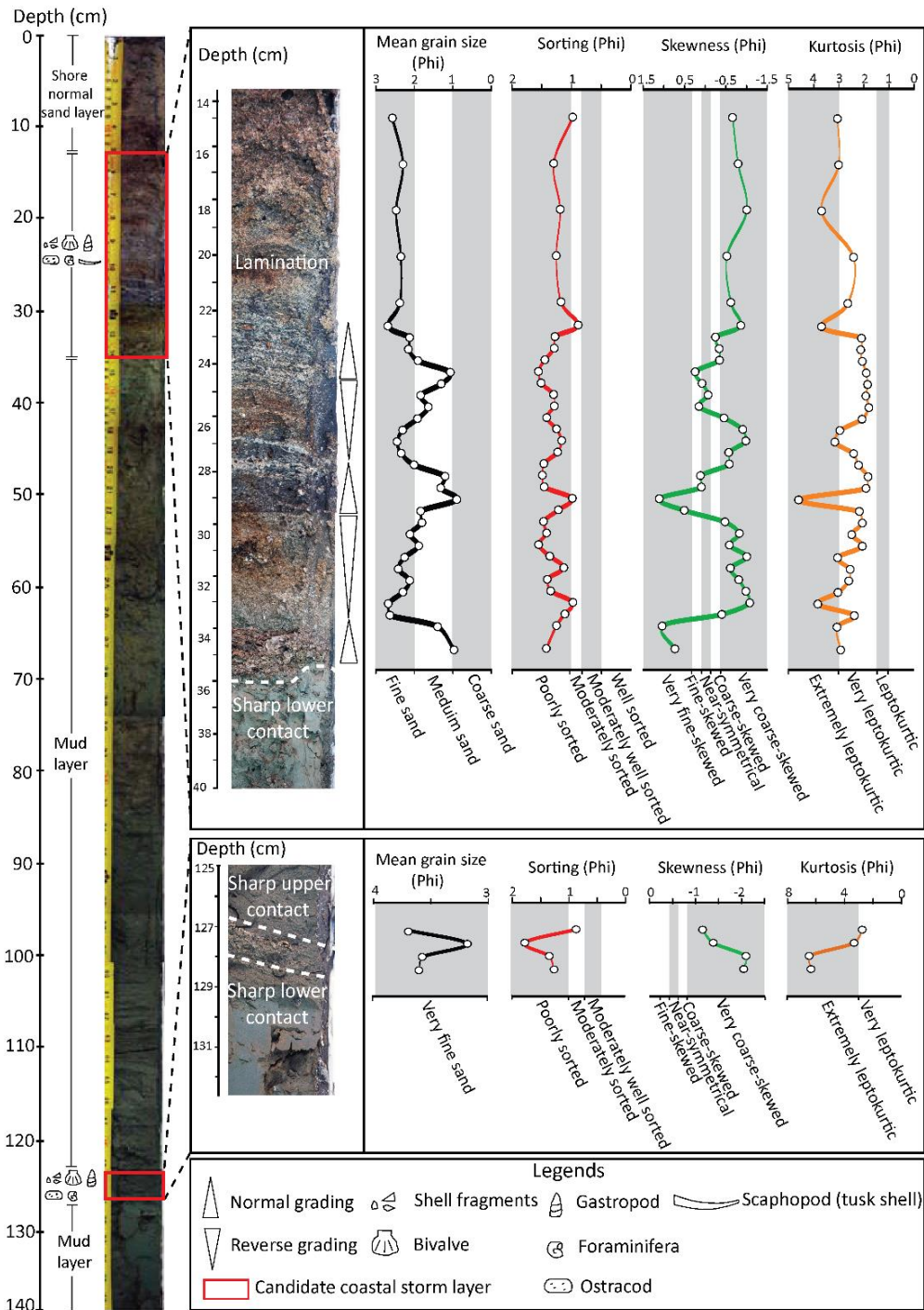


Fig. 5 Stratigraphy of core 1 showing the position of sedimentary structures observed inside together with the distribution of statistical parameter derived from grain size analysis (mean grain size, sorting, skewness and kurtosis) throughout the vertical profile.

Core 2 is the longest core of transect 1 (300 cm long). The location of core 2 is far inland from core 1 around 7 m (see location in Fig. 1C). A total of 21 candidate storm layers were found in this core. The first candidate storm was found at 20-55 cm depth, containing gradational upper contact with a black silty sand layer and sharp basal contact with an oxidized mud layer (Fig. 7). Pebble and shell fragments were also observed in this layer. Between 55 cm and 180 cm, pale reddish mud layer similar to core 1 is also observed. Below 180 cm, 20 dark grey sand layers of candidate storm events compounded with shell fragments were observed throughout the depth from 180 to 300 cm that interbedded with dark muddy layers, showing sharp top and lower contacts (Fig. 8). Mostly sedimentary structures of candidate storm layers in this core are quite similar to core 1 such as sharp upper and lower contacts interbedded with dark muddy layers. However, we found additional information of sedimentary structures in this core that included mud rip-up clasts (Fig. 6A), inclined landward laminated sand (Fig. 6B), shell fragment layer

(Fig. 6C). Nevertheless, inclined landward lamination generated from coring is unlikely because the location of core 2 is in the distal part of storm deposits (Fig. 2).

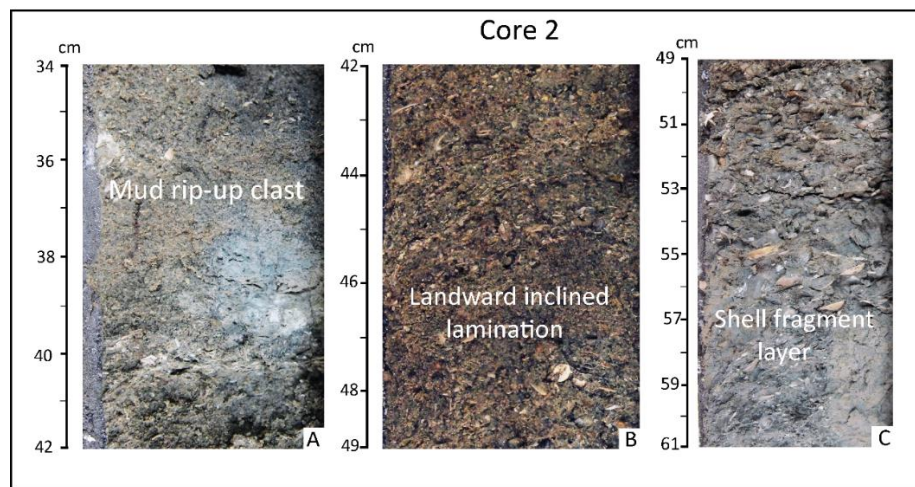


Fig. 6 Close up of internal sedimentary structures of storm-induced sand sheets within core 2 showing (A) mud rip-up clasts, (B) landward inclined lamination and (C) complete shape of marine shell fragments.

Core 3 was collected in the wet swale. It is approximately 80 cm long. The location of core 3 is far from core 2 around 7 m inland. One unstructured candidate storm layer compounded with shell fragments was observed at 10-29 cm depth (Fig. 7). Its sedimentary structures compose of sharp upper and lower contacts with upper and lower pale reddish muddy layer which similar to core 1 and core 2. Notably, pebble was also observed at depth 28 cm, indicating unusual wave intensity. Bioturbation activity such as rootlets appeared on the top of core was also observed.

Core 4 is also 80 cm long. It was collected in wet swale similar to Core 3. One thin layer of inclined landward candidate storm sand compounded with shell fragments were observed at 41-45 cm depth (4 cm). The sedimentary structures of this candidate storm layer show mainly sharp upper and lower contacts with oxidized mud layers. No lamination or ichnofabric (structures formed by organism activity) was found in this sand sheet.

Cores 5 and 6 were also collected in the wet swale (62 cm and 67 cm long, respectively) and no candidate storm sand layer was found. But reddish pale mud layer was observed in both cores. The characteristics of mud layers are similar as described in core 1, 2, 3 and 4, with an exception of core 2 in the deeper part (180-300 cm). The absence of candidate storm sand layer of these cores may associate with the intensity of coastal storm event that wave run-up of storm surges is probable to run out of energy.

At transect 1, according to the thickness of candidate coastal storm layers appeared in stratigraphy of core 1 to core 4, the first candidate storm layers of each core were correlated by using sharp contacts, color of sand layer, composition, marine fossil and microfossil. It is found that the characterization of thinner landward deposits or wedge-like shape was observed distinctly which clearly represents the transportation of marine source (Fig. 3B).

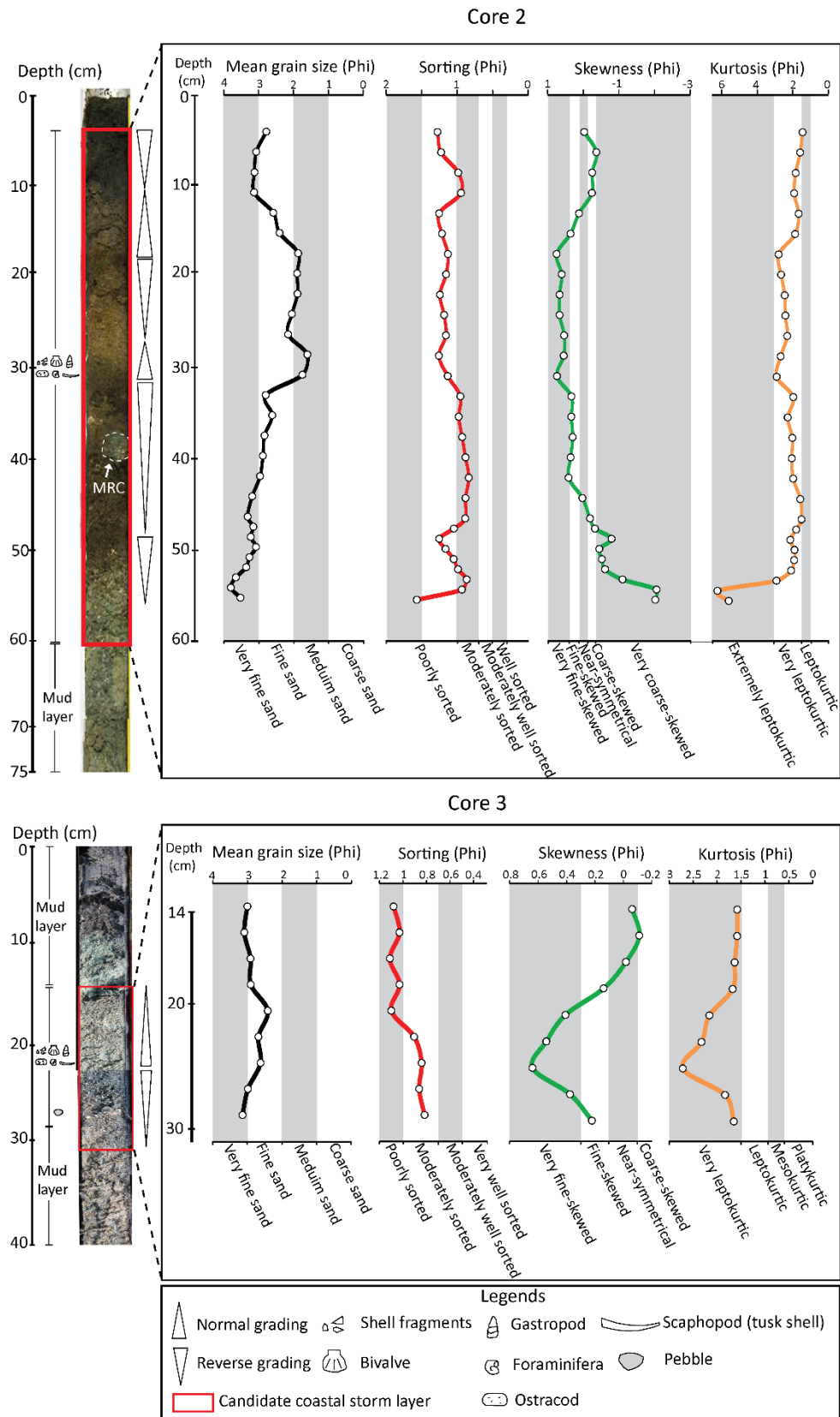


Fig. 7 Stratigraphy of core 2 and core 3 showing the position of sedimentary structures observed inside together with the distribution of statistical parameter derived from grain size analysis (mean grain size, sorting, skewness and kurtosis) throughout the vertical profile.

Additionally, the longest core of transect 1 to transect 3 (Cores 2, 7 and 13) parallel in the same line were stratigraphically linked for establishing the correlation (Fig. 8). As mentioned above, the major keys used to correlate the candidate storm layers were the existence of marine macrofossil and microfossil,

sharp contact, color of sand layer, thickness, and composition. As a consequence, it is found that the candidate storm layers in each core are different in the number of depositional events. The maximum and minimum of candidate coastal storm layers are 21 layers and 12 layers which were recognized in core 2 and core 7, respectively. Core 13 is merely composed of 13 layers of candidate storm. It is likely that the pre-existing surface of irregular topography before the depositional event of coastal storm may cause those storm layers to deposit unequally or vegetation community that covered the area in the prehistorical period on both large- and small-scales also influenced directly inland storm depositional processes. Because each type of vegetation itself that varies in height and density of population can directly alter flow conditions during overwash event and/or can act as a buffer against the detrimental effect of storms (Costanza et al 2008), causing the different thickness of coastal storm deposits, dissipation of wave energy and/or even no deposition in the area.

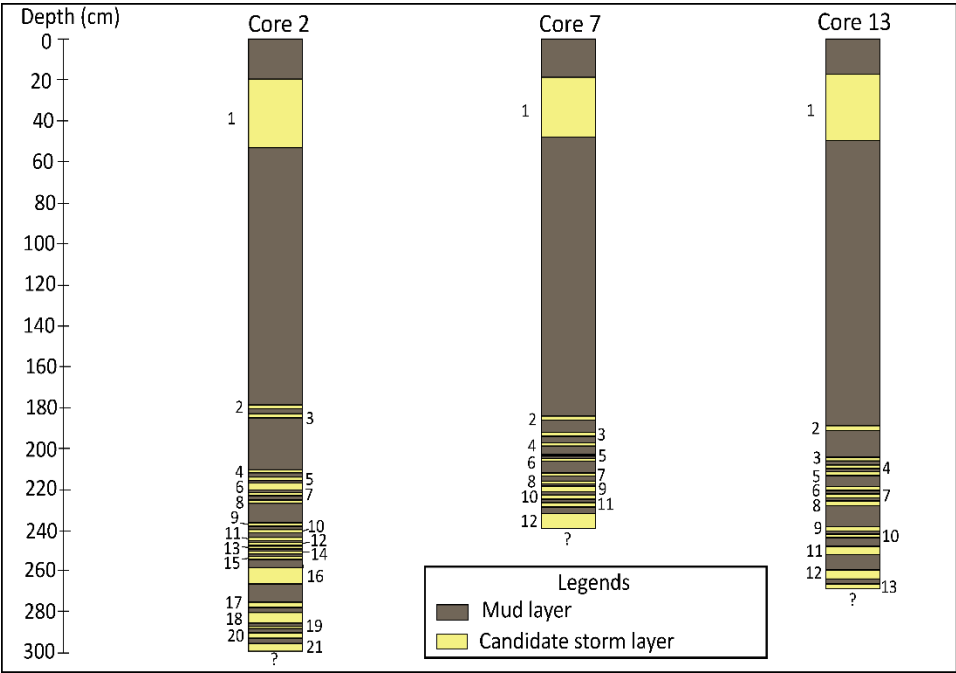


Fig. 8 Stratigraphic correlation of cores 2, 7 and 13 belong to transects 1, 2 and 3, respectively showing multiple layers of candidate storm sand sheet at depth between 180 and 280 cm which were drilled at the margin of washover fan lobe and probably were formed during middle Holocene according to correlating AMS dating from wood of Williams et al (2016) at depth 110 cm.

3.2. Sedimentological analysis

3.2.1 Composition

Detecting composition under a microscope was conducted to derive the physical differences between shore-normal beach and storm deposits. It is important to note here that in this study most of the compositions of candidate storm samples in the swale environment and samples of recent beach 1 and 2 are closely relatively similar such as quartz, feldspar, heavy mineral, shell fragment debris, marine macrofossil (bivalve and gastropod) and microfossil (foraminifera, ostracod and scaphopod (tusk shell)), these samples are located differently (see locations of sampling points in Fig. 1B) which varies between 60-70% of quartz sand and 20-30% in bioclast grains. The rest of composition contains feldspar and heavy mineral in very low content (1-3%). This similarity in composition also includes two samples of candidate storm in the trench profile, but the concentration of them seems to be lower in bioclast grains (10-15%) due to possible weathering. In contrast to samples of ridge sediment 1, 2 and 3, almost 100 percent quartz sand without any bioclast grain surrounding was examined which recognize these two deposits clearly. Interestingly, between 21 cm and 36 cm in core 1, samples of candidate storm contain high percentage of bioclast grains up to 70% distinctively. Moreover, all of the individual samples of candidate storm, the existence of marine microfossils, especially foraminifera and ostracod were found clearly. Further, the variety of sphericity and roundness found in candidate storm samples varies from low to high sphericity with very angular to sub-rounded sand. On the other hand, shore-normal beach samples in general show only high sphericity with sub-angular to sub-rounded sand, except for sample of ridge sediment 3 which was classified as low sphericity with very angular to sub-angular sand. In terms of such other physical properties as quartz shapes, surface features and microfossil, it is found that samples of candidate storm and recent beach 1 and 2 are highly similar.

3.2.2 Mean grain size

The difference in mean grain size between samples of storm and shore-normal beach deposit was used to indicate primary source of sediment supply, energy conditions of depositional environment and transport process. Mean grain sizes in samples of recent beach 1, 2 and ridge sediment 3 are classified as fine sand varying between 2.33 and 2.41 phi, while samples of ridge sediment 1 and 2 appear to be medium sand, ranging between 1.90 and 1.50 phi. Nevertheless, candidate storm samples reveal considerable difference in mean grain size varying from very fine to coarse sand (3.99-0.98 phi), without any size of very coarse sand. In addition, when vertically plotted mean grain sizes of candidate storm, the fluctuation in values can be observed in core 1. It is assumed that during storm event these sediments were deposits under the extreme condition as a consequence of flow behavior and depositional mechanism because three sets of normal grading and two sets of reverse grading were detected within laminated sand layer of core 1 from top to bottom (Fig. 5).

In core 2, mean grain sizes of candidate storm consists mainly of very fine to fine sand. There are only five samples which show medium sand. Further, the vertical distribution of mean grain sizes is similar to of core 1 when plotted and also sets of normal and reverse grading (from top to bottom) are also observed (Fig. 7). Notably, mean grain sizes of candidate storm samples slightly decrease when compared with core 1.

Mean grain size of core 3 consist primarily of fine to very fine sand. Single pebble was also observed within this core. The vertical variation in this core tends to show both fining and coarsening upward (top to bottom) (Fig. 7). Candidate storm samples of core 4 contain only very fine sand in mean grain size in which the uppermost sample is coarse silt. Based on the results of mean grain sizes, it is clear that the deposits of candidate storm sediments found in this transect show the characterization of finer landward deposits associated with marine origin.

3.2.3 Standard deviation

Standard deviation indicates sediment sorting and fluctuation in kinetic energy or velocity condition of depositional mechanism (Sahu 1964). Sorting values of beach sediments range between 0.62 and 1.02 phi which represent moderately to moderately well sorted sand, except for the sample of recent beach 1 which was collected close to the present sea level shows poorly sorted nature. Sorting values of candidate storm samples (core 1-4) range between 1.94 and 0.42 phi showing moderately, moderately well and poorly and well sorted nature. However, between 236 cm and 238 cm, only three samples of candidate storm sediments contain well sorted found within core 2. Vertical variations of sorting values are also similar to mean grain size (Fig. 5, 7). In other words, there are the fluctuations of sorting that alter in four ranges of core 1. Vertical changes of sorting values from moderately to poorly sorted sand in core 1 can be observed at depth of 1 to 21, 22 to 29, 29.5 to 33.5 and 34 to 36 cm (Fig. 5). Sorting values of core 2 also show three vertically opposite pattern (top to bottom) from poorly to moderately sorted nature at depth of 9 to 15 cm, 16 to 46 cm and 47 to 55 cm (Fig. 7). Sorting values of core 3 candidate storm sediments display poorly to moderately sorted nature, whereas sorting from top to bottom of core 4 shows poorly to moderately sorted nature.

3.2.4 Skewness

Skewness indicates the asymmetry of frequency distribution. Skewness values of shore-normal beach samples from this area range between -0.74 and 0.02 phi. Samples of recent beach 1, 2 and ridge sediment 3 are classified as very coarse skewed nature, while samples of ridge sediment 1 and 2 are classified as near-symmetrical nature. Skewness of candidate storm samples appears to show in all ranges (hereinafter referred to very fine-skewed, fine-skewed, near-symmetrical, coarse-skewed and very coarse-skewed nature) which range between -3.76 and 1.11 phi. However, the skewness values associated with candidate storm sediments in each core are relatively complicated (Fig. 5, 7). For example, in general skewness values of candidate storm samples of core 1 tend to show very coarse-skewed nature, yet nine samples of very fine-skewed and fine-skewed nature are present (Fig. 5). The main skewness values of candidate storm sediments of core 2 become very coarse-skewed nature. Only a few samples of core 2 show values in near-symmetrical and very-fine skewed nature (Fig. 7). The variation in skewness values was also found in candidate storm sediments of core 3. Between 15 cm and 20 cm, they consist of coarse-skewed and very coarse-skewed nature, while fine skewed and very fine-skewed natures were found at 20-30 cm depth (Fig. 7). Skewness values of candidate storm samples of core 4 show only very coarse-skewed.

3.2.5 Kurtosis

Kurtosis values of both candidate storm and beach sediments appear to be the same nature of distribution, ranging between 1.44 and 12.33 phi. Kurtosis values fall under leptokurtic, very leptokurtic and extremely leptokurtic nature of distribution (Fig. 5, 7). However, only candidate storm sediment of core 3 display very leptokurtic nature.

3.2.6 Grain size distribution

Grain size distribution curves of both candidate storm and shore-normal beach samples were plotted in order to compare their discrepancies (Fig. 6). Samples of shore-normal beach curves show merely the characteristic of unimodal distribution which fall under the range of fine and medium sand. On contrary, curves of candidate storm distribution appear three types of characteristics, i.e. unimodal, bimodal and multimodal distributions which fall under all ranges of sediment sizes, varying from clay to pebble. This indicates the sediments which were imported into this swale by storm have the different derivation of sediment source. Curves of grain size distribution of all samples also display the similar existence of one mode which fall under the sand-sized modes. This possibly suggests the depositional process of coastal storm event in the past that remobilized the pre-existing sediments of each coastal zone landward by storm surges.

Table 1 Results of OSL dating from inner, outer beach ridges and trench

Sample no.	Depth below surface (cm)	U (ppm)	Th (ppm)	K (%)	Water (%)	AD (Gy/ka)	ED (Gy)	Age (yr)
K1	40	0.78±0.01	2.04±0.01	0.37±0.002	2.48	0.614±0.01	0.718±0.01	1,160±30
K2	40	0.53±0.01	1.92±0.01	0.31±0.002	1.37	0.517±0.01	1.083±0.03	2,090±70
K3	40	0.69±0.01	2.26±0.01	0.36±0.002	2.44	0.605±0.01	0.744±0.02	1,220±40
K4	40	0.68±0.01	1.87±0.01	0.26±0.002	2.26	0.497±0.01	1.51±0.28	3,034±106
K5	40	0.49±0.01	1.53±0.01	0.32±0.002	1.81	0.481±0.01	1.758±0.05	3,650±140
K6	40	0.66±0.01	2.28±0.01	0.32±0.002	1.76	0.743±0.01	1.832±0.01	3,190±100
K7	20	0.73±0.01	3.38±0.01	0.77±0.002	6.89	0.970±0.01	1.186±0.04	1,220±30
K8*	50	0.71±0.01	0.45±0.01	0.84±0.002	29.74	0.738±0.01	1.55±0.1	2,100±140
K9*	65	1.01±0.01	4.74±0.01	0.93±0.002	23.40	0.993±0.01	2.51±0.23	2,520±230
K10	85	1.10±0.01	5.52±0.01	1.09±0.002	25.82	1.106±0.01	2.931±0.39	2,650±350

* The results of OSL dating in the candidate storm layers

3.3. Optical Stimulated Luminescence dating

OSL-based chronology obtained from ten samples of two beach ridges are presented in Table 1. OSL dating results provide the ages of inner beach ridge in the period between 3,650±140 and 3,034±106 years ago (sample no. K5 and K4), while the ages of outer beach ridge span the period between 2,090±70 and 1,160±30 years ago (sample no. K2 and K1). Additionally, two cross-checking ages of inner beach ridge and outer beach ridge (sample no. K6 and K3) represent the ages of 3,034±106 and 1,220±40 years ago, respectively. It is inferred that the formation of two beach ridges here was generated from wave current in the southwestern to northeastern direction because the ages of beach ridge plain in the southwestern part of the beach ridge are older than the northeastern part. Age gap of both beach ridges is approximately 1,000 years ago. Four OSL ages derived from the latter part of outer beach ridge (sample no. K7 to K10) indicate its formation during the late Holocene which provide the age from top to bottom in the period of 1,200±30, 2,100±140, 2,520±230 and 2,650±350 years ago with the depth of 20, 50, 65 and 85 cm, respectively. It is noted that the ages of 2,100±140 and 2,520±230 years ago belong to two candidate storm events which found at 50-58 cm and 65-72 cm depth.

4. Discussion

4.1. Diagnostic key of identifying storm deposits

The diagnostic keys to identify ancient washover deposits from storm surge presented in this paper were interpreted based on several evidences which found in stratigraphy and sedimentology. In general, swale situated in the coastal environment has been tied up calm water circumstance (low energy condition) that often provides such fine particles as silt and/or clay during the time of heavy rain fall and/or high tide, and then progressively settled down in pattern of suspended sediment concentration. The presence of these fine particles is, therefore, regarded as common sedimentation in swale (Williams et al 2016). However, the stratigraphic evidences found in cores of this study at Kui Buri swale, particularly sand layers with sharp lower and upper contacts interbedded with mud substrate of swale (discrete layers) were considered as one of the unusual features of sedimentation similar to many publications relevant to storm deposits across the world. Therefore, it reflects the background of an important reason in the fact that the energy of wave must be strong enough to be capable of overtopping the beach ridge, flowing landward into swale, and then forming the deposit within swale as a discrete sand. Further, according to sedimentary evidences including parallel and inclined lamination, mud rip-up clast, marine shell fragment layer, sharp lower and upper contacts, it is sure that these evidences indicate clearly the unusual process generated from high energy event which imported marine sediments of

each coastal zone into swale environment. For instance, laminated structures of sand layer indicate the interaction between flow regimes and bottom current of storm surge waves as observed by Phantuwongraj et al (2008) at the southern part of Kui Buri. Moreover, laminated sand also reflects the proximal part of washover deposits as a consequence of the rhythmic form of short-lived storm surges (multiple wave sets) as reported by Sedwick and Davis (2003) at the west-central Gulf Coast of Florida, USA.

In case of mud rip-up clasts found in core 2, this is also indicative of high energy event. Naturally, the occurrence of eroded mud surface or original surface within swale itself is nearly impossible because of low energy condition of swale current and, if there is no any coincidence of other external factors occurred such as water availability and current velocity (Allen 1982). In reality, mud rip-up clasts also indicate historical evolution in time-order which started from pre-existing fine-grained deposits; being ripped up from current velocity; transport of clasts in the dominated direction of current; and clast deposition on the top of layer or at the same layer of coarser sediments (Knight 2009). Several reports of mud rip-up clasts have been documented in coastal settings where mud rip-up clasts were transported in the time of desiccation in combination with wave current (Allen 1987a, b; Knight 1999, 2005, 2009; Picard and High 1973). However, the occurrence of mud rip-up clasts here is associated with shear stress of hydrodynamic action from an impulsive and strong event, which is capable of eroding materials of local swale surface (mud, silt) and settling down in the same layer of coarser grain synchronously similar to mud rip-up clasts often found in the studies of high energy event deposits (storm and tsunami) (Bennett and Bridge 1995; Ishizawa et al 2017; Kortekaas and Dawson 2007; Morton et al 2007; Phantuwongraj and Choowong 2012; Williams et al 2016). Because when visually examined the textures of clasts embedded within layer, it suggests that rip-up clasts embedded within storm layer look closely similar to muddy texture of locally pre-existing swale surface which is transported in combination with sand (Kongsen et al 2016) and possibly occurred as a consequence of high energy wave erosion on wet swale surface rather than such derivation of other processes as transport of longshore current during the time of sea level rise, tidal current and offshore origin.

Traces of abandoned channels have been remained observable in the western part of the area where Kui Buri River is located. However, these sedimentary structures found in sand sheets formed by fluvial transportation are impossible because the presence of marine organisms (calcareous foraminifera, ostracod scaphopod (tusk shell) and marine shell fragments were found in every candidate storm layer. They are an important and useful evidence of marine overwash (Liu and Fearn 1993, 2000a, b). Most species of foraminifers found belong to *Quinqueloculina* spp., *Spiroculina* spp., *Elphidium* sp., *Asterorotalia* sp. and *Ammonium* sp. which are of various specific marine habitats, living on sand surface related to open sea. They are commonly found along the Gulf of Thailand (Jumnonghai 1983; Melis and Violanti 2006). Most importantly, fossil of scaphopods (tusk shell) that commonly lives in the mud or sand surface of the sea by using their feet to burrow. It is almost impossible that these fossils would be in the harsh condition of this swale. The adaptation of some marine fauna may be tolerated to very low salinity due to increasing in rain water, but in the summer, the swale will become dry as the case of Williams (2010). It is implied that this swale is not the actual habitat for these marine microfauna. In any cases, swale water may be in brackish condition because in the period of sea level maximum. Sea water might be moved landward through a channel where its boundary is connected with the Gulf of Thailand. However, the dominant sedimentary structure (i.e. sharp contact) is too abrupt to be formed by landward or seaward gradual moving of sea level rise.

Slope wash or mass wasting process in this area can be ruled out because the elevation of topography here is not high enough to move sand-sized materials landward and to form sand layers in swale during heavy rainfall. Although, the instability of beach ridge formation can be moved landward to form a sand layer, but the composition of sand looks different. That is, the composition of beach ridge sand is at 99% in quartz content especially the outer beach ridge (ridge sediment 3), but the sand composition we found in this swale has relatively high concentration in bioclast content. This indicates that slope wash or mass wasting process in this area is impossible.

Prehistorical and historical tsunami event deposited in this area can also be ruled out. This is because no prehistorical and historical records of tsunami deposit were recognized so far. Only at the Andaman coasts of Thailand had been experienced devastating tsunami event (2004 Indian Ocean tsunami) and the prehistoric events (Jankaew 2008). However, some researchers have pointed out that the possibility of future tsunami may arrive into the Gulf of Thailand due to submarine tsunamigenic earthquake from the South-China Sea where the subduction zone is located. The nearest tectonic subduction zone close to the Gulf of Thailand is located at Manila Trench approximately 2,500 km. The magnitude Mw 9.0 submarine earthquake from Manila Trench modeled by Ruangrassamee and Saelem (2009) provided the tendency of the maximum wave height around 0.65 m that could direct towards the Gulf of Thailand coast. However, tsunami can be attenuated by wave diffraction around the southern part of Vietnam and Cambodia. Consequently, it is unlikely that sand layers observed here in this area were formed by tsunami process.

4.2. Sedimentary characteristics, sources and flow behavior

The comparison between grain size distribution curves of candidate storm and shore-normal beach sediments was carried out (Fig. 9). They can be separated by the presence of various modal distributions, varying in the various sizes of sediments existed in each coastal environmental zone and the depositional mechanism. Frequency distribution curves of beach sediments fall under fine and medium sand. In contrast, many candidate storm sand distribution curves exhibit the complex mixtures of multiple modes. It means that the sediments were transported from the mixtures of various sediment sources. Notably, modes of some candidate storm distributions also fall under the range of clay, silt and pebble (Fig. 9). The concordance of each mode reflects the correspondence of various sizes. The possibility of overlapping in sizes of both candidate storm and beach sediment distributions may indicate the environmental zone shown in frequency curve associated with transportation of wave run-up. It suggests that beach sediments were swept into the swale by high energy wave of coastal storm in the past obviously. Based on stratigraphy, all candidate storm layers were discriminated by the presence of sedimentary structures such as parallel and inclined landward lamination, mud rip-up clasts, marine shell fragment layer, sharp lower and upper contacts. These structures were analyzed along with the data derived from grain size analysis of candidate storm sediments. It is found that they reflect the impact of each flow regimes and inundation regimes of coastal storm wave. In the initial stage, multiple wave sets of storm surges have been progressively increased by strong wind speed of coastal storm (swash regime) (Masselink and van Heteren 2014; Morton and Sallenger 2003; Sallenger 2000). Later, they overtopped across the beach ridge and transported an amount of eroded sediment landward into swale. During this stage, the inundation regime occurred (Sallenger 2000) as a consequence of the increase of surge velocity and surge height which contributed to the sedimentary structures of shell fragment layer (Fig. 4B, 6C), laminated sand (Fig. 4A, 6B), mud rip-up clast (Fig. 6A), multiple set of reverse and normal grading (Fig. 5, 7) that associated with flow depth, indicating the upper flow regime conditions of a unidirectional, turbulent and high velocity flow (Cheel 1990; Fielding 2006). In this process, grain size frequency distribution curves of candidate storm sediments show the different modes when compared with curves of each coastal environmental zone of shore-normal beach sediments (Fig. 9). Moreover, mean grain sizes of cores 1, 2, 3 and 4 still interplay with wave energy, reflecting the coarser and heavier sand-sized grains settled down first at the location in the processes of rolling, sliding, saltation (cores 1, 2 and 3), where the most seaward side is located, forming the thickest sand layer (Liu 2007). While the influx of lighter sand-sized grains along with the surge current has been deposited as suspension (Core 4), thinner and finer landward deposits (wedge shape) can be formed (Fig. 2B). In the latter stage, lower flow regime condition resulting from the decrease of surge energy can lead to lamina flow condition and form unstructured candidate storm layer as observed in the mean grain size variation of candidate storm sediment of core 1 (Fig. 5).

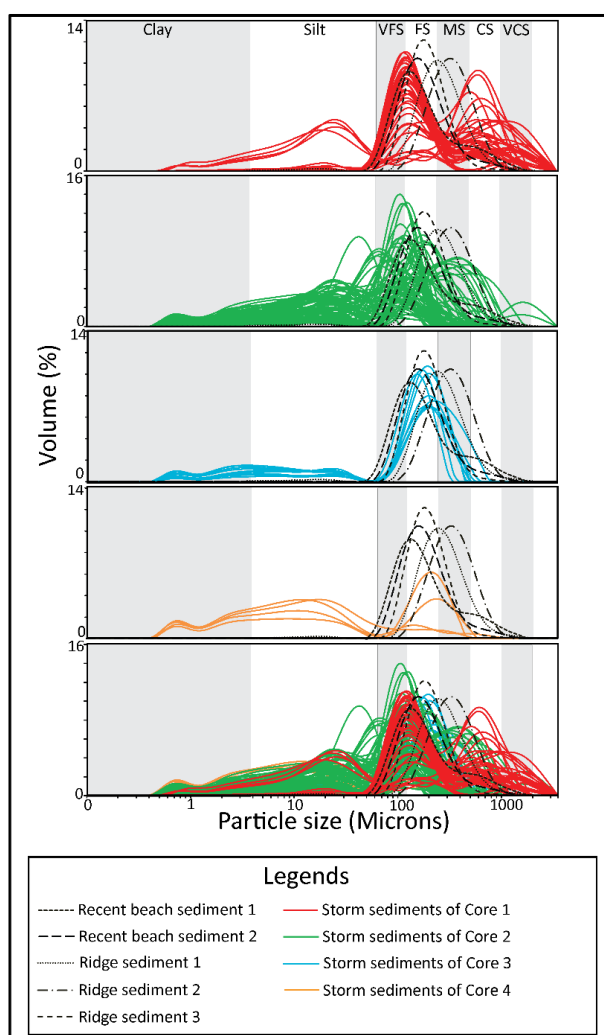


Fig. 9 Comparison on grain size distribution curves of shore-normal and candidate storm sediments. Curves of shore-normal beach sediments reveal only unimodal distribution, while sediments of candidate storm show bimodal and multimodal distribution.

However, based on grain size distribution curves of shore-normal beach and candidate storm sediments (Fig. 9), the difficulty to elucidate candidate storm sediments in the range of very fine sand to silt in this study was arisen because no sample of shallow offshore sediments was collected. The several finer sizes of storm sediments presented in comparative graphs may likely be transported from offshore during extreme coastal storm. As a consequence of wind speed and high wave energy generated from extreme coastal storm, these could cause stirring up of entire water column in relation to resuspended fine particles (fine sand, very fine sand, silt and mud) at sea bottom surface where its depth is not too deep (Shanmugam 2008). Also, the absence of finer sand at recent beach is considered as normal circumstance because the surf zone and/or breaker zone have had significant impacts on recent beach. Some of fine-grained particles are subjected to oscillatory water movement. Carrying seaward by those waves from the breaker zone suggested by Bagnold (1963) and Ingle (1966) with beach adjoined to open-sea, on an average, sediment grains smaller than 0.150 mm ($> 2.75 \phi$), will be dispersed evenly within the water column and be carried offshore in continual suspension. Additionally, grains smaller than 0.150 mm ($> 2.75 \phi$) commonly are absent from beach sand along open coasts and that the majority of grains smaller than 0.140 mm are probably in suspension under all wave conditions (Friedman 1967).

An ability to differentiate environmental zone between river, beach, dune, and berm can be made by plotting statistical parameters derived from grain size analysis, including mean grain size against sorting, mean grain size against skewness, mean grain size against kurtosis (Folk and Ward 1957; Friedman 1961; Mason and Folk 1958). These plots are very beneficial because sources of sands that belong to various environmental settings have statistically natural difference of dynamic process (Friedman 1967). The attempt has been made in this paper to differentiate storm and beach sediments (Fig. 10, 11). The clearest and nearly completed grouping of separation between candidate storm and shore-normal beach is the plot of mean grain size against sorting (Fig. 10A).

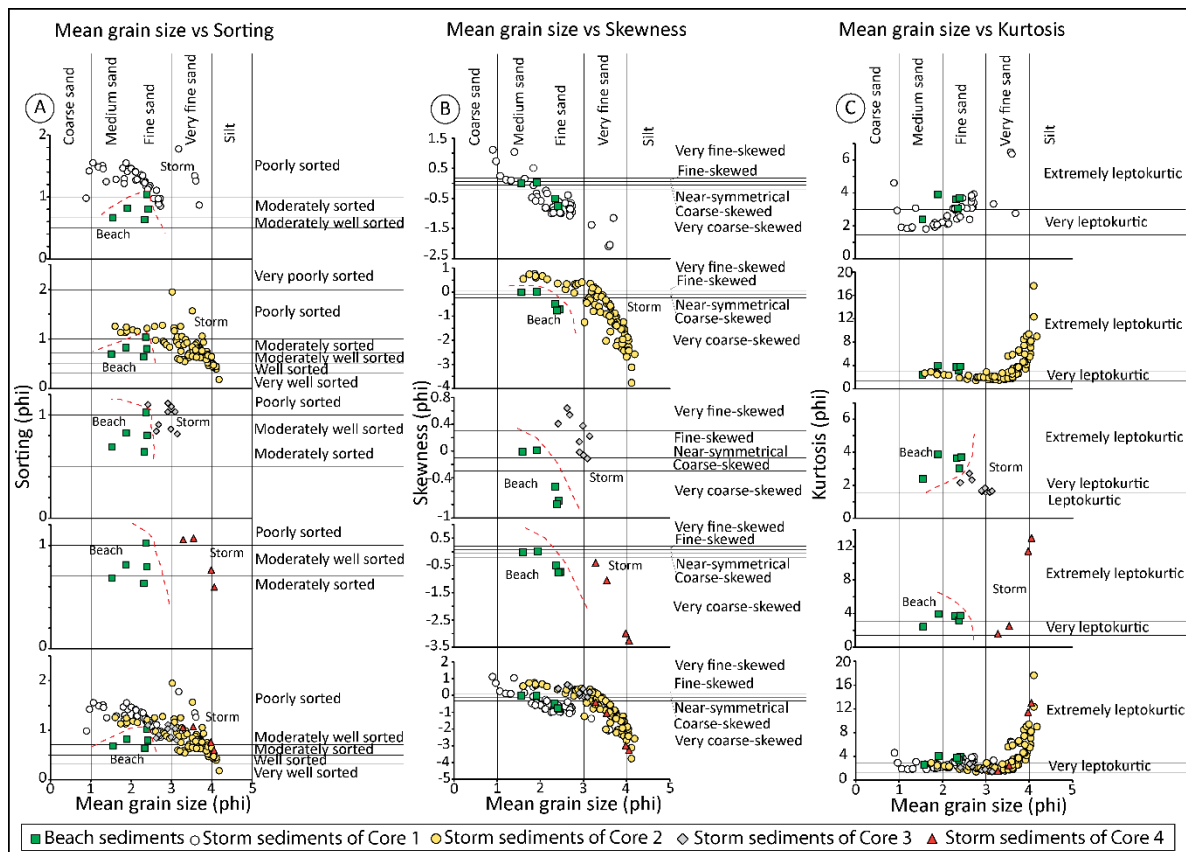


Fig. 10 Plot of statistical parameter obtained from grain size analysis of shore-normal beach and candidate storm sediments showing (A) mean grain size versus sorting, (B) mean grain size versus skewness and (C) mean grain size versus kurtosis.

Apparently, grain size parameters of shore-normal beach seem to be the proximal group that dissimilar to grain size parameters of coastal storm. Statistical trends of plotting of candidate storm sediments are observable at the plot of mean grain size against skewness, mean grain size against kurtosis and skewness against kurtosis (Fig. 10B, C, 11C). Plot of mean grain size against skewness shows statistical trend of direct variation (the more mean grain size decrease, the more the skewness value decrease) (Fig. 10B). On the other hand, plots of mean grain size against kurtosis and skewness against kurtosis show statistical trend of reverse variation. They seem that the more mean grain size decrease, the more kurtosis values increase (Fig. 10C) and the more skewness values decrease, the more kurtosis value increase (Fig. 11C). Mean grain size, skewness and kurtosis values of candidate storm sediments tend to be clearly associated each other and they are found to be statistically significant as well.

come from? Based on the results of OSL-based chronology and a correlated AMS age, our assumption seems to be the fact that in the period of the last 7,000 years this location should be a sea floor that storm-induced sediment transport may come from offshore origin in the pattern of bottom-current flow, providing the deposits of very fine sand-sized materials. This is backed up by the results of grain size analysis present in 20 candidate layers that all of the material sizes fall under in range of very fine sand to silt. However, during early to middle Holocene, the swale here is likely to be a lagoon that there has been barrier beach connected to the open sea. Lagoon has a high preservation potential for the deposits of extreme coastal storm barrier beach sand itself is a major sediment source. When storm surges overtopped the barrier beach in landward direction, they transported this source of sand into lagoon. Multiple layers of sand sheets intervening with pure mud are of the evidence to confirm their deposition in the lagoonal environment. Then, during middle to late Holocene, gradually sea level falling (marine regression) caused the inversely erosive performance of transgressive beach ridge and barrier as reworked sediment to form prograded beach ridge. This progradation of beach ridge occurred continuously. The elevation of beach ridge can protect the overwash process not to deposit in lagoon anymore. Only washover sediment can overtop on beach ridge that make the difficulty to distinguish it from shore normal deposit.

5. Conclusions

In this study, sedimentological characteristics of ancient storm unveil our better understanding in history of coastal severe disaster like typhoons or tropical storm events. The preservation of geological records of extreme storms along the coastal zone of the Gulf of Thailand has confirmed that the area is sensitive for such an extreme storm event. Definitely, at Prachuap Khiri Khan southern peninsular Thailand at least 21 layers of candidate coastal storm layers provide, as sedimentological records, insight into the analog for further research. These sedimentological analogs can be applied to the area that owns similar geomorphological and geological conditions in this region. Grain size distributions and statistic parameter plots of candidate storm and shore normal beach sediments can assist to differentiate them in this study. These plots were found to be statistically significant especially the plot of mean grain size against skewness, mean grain size against kurtosis and skewness against kurtosis. As a result, shore normal-beach deposit was commonly described by unimodal distribution; whereas, candidate storm sediments appear to show multimodal, bimodal and unimodal distribution, even in the same layer. We also discovered sedimentary structures of storm deposit similar to what have been well described in many literatures. They include parallel and inclined landward laminations, mud rip-up clast, layer of shell fragments, pebble, normal and reverse grading, sharp lower and upper contacts, finer and thinner landward wedge-like shape deposit as well as marine microorganism, i.e. foraminifers, ostracods and scaphopods (tusk shell). All these sedimentological characteristics described in this paper can be applied as diagnostic key (locally-valid indicator) or geological proxies of storm deposits. OSL-based chronology and correlation with AMS age reported by Williams et al (2016) provide the sensibility of preservation potential of coastal storm frequency in the period of the middle to late Holocene. Linkage and application of this kind of paleotempestological research will increase our better understanding in such an extreme hazard and being part of our responsibilities to mitigate the risk for coastal communities.

Acknowledgments: This research was funded by The 90th Anniversary Ratchadapisek Somphot Endowment Fund of Chulalongkorn University, Climate Change and Disaster Management Cluster (CU59-060-CC) and Thailand Research Fund (BGR5780008). The authors would like to thank the editor and anonymous reviewers for providing constructive comments to improve this manuscript significantly.

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Geomorphic criteria for distinguishing and locating abandoned channels from upstream part of Mun River, Khorat Plateau, northeastern Thailand

P. Nimnate¹ · M. Choowong¹ · T. Thitimakorn¹ · K. Hisada²

Received: 14 October 2016 / Accepted: 22 April 2017
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Abstract In order to develop geomorphic criteria for distinguishing and locating abandoned channels and meandered belts, in this paper we examined geomorphologic characteristics from the Mun River, one of the main rivers in the Khorat Plateau, northeastern Thailand. Upstream of Mun River originated at southwestern rim of the Khorat Plateau where the river now cuts through sandstone basement. Meandering process shaped meander from upstream ending at low-lying plain about 30 km downstream from the Mun Bon Dam reservoir, and this process displays given values of geomorphic parameters including sinuosity index (SI), channel width (W) and radius of curvature (Rc). Sinuosity index was calculated to express the sinuosity of the channel. The relationship between W and Rc helps to predict channel stability and also comprehend the possibility of cutoff process. As a result, paleo- and recent flow directions of the Mun River are similar from southwest to northeast. Geomorphic parameters from eight river reaches have changed through time since 1974–2015. Two abandoned channel belts were identified, and they own an average channel width of 35 and 16 m, whereas the Mun River nowadays is of 12.7 m. SI values of two abandoned channel belts are categorized as meandering river system. Relationship between meander migration rate and bend curvature suggests that the Mun

River possesses low erosion rate between 0.71 and 2.64 m/year since 1974 to the present. This rank of Rc/W ratio suggests stable state of river bank migration. Different migration indicates discontinuous meandering process from individual belt. Lateral migration rate was also decreased after Mun Bon Dam was constructed upstream.

Keywords Meandered belt · Sinuosity index · Mun River · Khorat Plateau · Radius of curvature

Introduction

Early researches on fluvial geomorphology emphasized on how to describe the variety of fluvial landforms in different environments. More scientific work stimulated by requirements of river management took place in the 1930s and 1940s, notably the experimental work on the Mississippi meanders (Friedkin 1945) that analyzed how meanders develop and migrate downstream (Hooke 2007). Recently, one challenge is on how to measure long-term development of meanders both from surface and subsurface conditions. For example, channel stability using radius of curvature (Rc) has been carried out from seventeen rivers in Sweden (Williams 1986), Red and Mississippi River (Thorne 1991) and Beatton River (Neal 2004). Changes of river channels from human interference have also been challenged (Hooke 1995, 2013; Chaimanee et al. 2006). Human activities can sometimes induce channel change more significantly than those induced by natural events as floods, droughts and landslides (Surian and Rinaldi 2003; Ashraf and Liu 2013).

Analysis of aerial photographs and remotely sensed data has wide applications in detecting and mapping landforms, measuring temporal changes in fluvial landforms. In order

✉ M. Choowong
monkeng@hotmail.com

¹ Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit (MESA RU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

² Earth Evolution Sciences, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

to understand such a meander change as a channel migration from one place to another and the relict of river in the past (abandoned channel), historical maps have been used to provide much information on morphologic changes of large river, but they sometimes have a limitation in accuracy of production. The additional information sources apart from historical maps including air photographs, satellite images and cross-sectional surveys contribute a wealth of information to geomorphologic research of river channel change (Chaimanee et al. 2006; Ashraf and Liu 2013). To explain past river dynamics and infer possible future trends, it is crucial to have a sound link between morphologic changes and their causes, which can be natural or, quite of, related to human interventions (Ziliani and Surian 2016). As for geomorphic parameter, the channel sinuosity, meander wavelength and bend radius of curvature have agreed with the R_c values predicted by Langbein and Leopold equation (Langbein and Leopold 1966; Williams 1986).

None of the works related to river morphology in northeast Thailand has been focused on geomorphic parameters of planform. Therefore, this research is the first of its kind in analyzing geomorphologic criteria of the Mun River, the largest meandering river on the Khorat Plateau. Particular focus is paid on river planform parameters (SI, RC and W) for characterizing, describing and comparing the recent Mun River and abandoned channels. The Mun River flows northward from Mun Bon Dam locating at Khon Buri District (Fig. 1). Some parts of the Mun River show anastomosing channel morphology, but it overall displays as meandering pattern. SI, R_c and W were also compared between pre- and post-dam construction.

The purpose of this work is to distinguishing and locating abandoned channels from upstream part of the river that flows from the south (Sankamphaeng Mountain Range) to the north (near Nakhon Ratchasima downtown). The additional purpose is to explain the change of such channel planform parameters from 1974 to 2015. We also aim to understand the difference between recent and past river landform developments at similar geological setting and geomorphic effects arisen after the construction of Mun Bon Dam. We hypothesize that such an alteration after dam construction can be determined using river planform parameters including channel width, channel length, down valley length and lateral migration rate for considering the river behavior (Nanson and Hickin 1983; Godaire 2010).

Study area

The Mun River is one of the right tributaries of the Mekong River. The river originates from Khao Yai National Park in Nakhon Ratchasima Province and flows through southern

part of the Khorat Plateau for almost 700 km until joining with the Mekong at Ubon Ratchathani Province. At upstream part of the Mun River where the Mun Bon Dam is located, river flows almost from south to north heading to Nakhon Ratchasima downtown. The Mun Bon Dam is 32 m in height. The construction was started in November 1986 and finished in January 1989 (Sorlalum and Mairaing 2007). Dam obstructs the upstream part of the Mun River aiming to storage water supply for agriculture in the Nakhon Ratchasima and nearby provinces.

In the past 20 years (1980–2000), land use in Nakhon Ratchasima Province was altered by the expansion of economic and population growth result in reducing agriculture, forest and living areas (Li et al. 2012). Because many sand pits are now excavating at downstream point bar of the Mun River especially in Chalermprakiat District, it causes the changes of river flow locally. However, the study area is not affected from sand pit operation, but at Mun River floodplain, some land uses have changed due to factory (approximately 120 km²) and agricultural area (approximately 80 km²) in the northernmost part (see Fig. 5b). Therefore, the study area is selected from upstream part of the river between latitudes 14° 20' and 14° 58', and longitudes 101° 30' and 102° 20' to avoid the effect from those land use changes (Fig. 1). The area covers downstream of the Mun Bon Dam extending to only 30 km of Khon Buri District and continues northward to Chok Chai District of Nakhon Ratchasima Province (Fig. 1).

Local geology

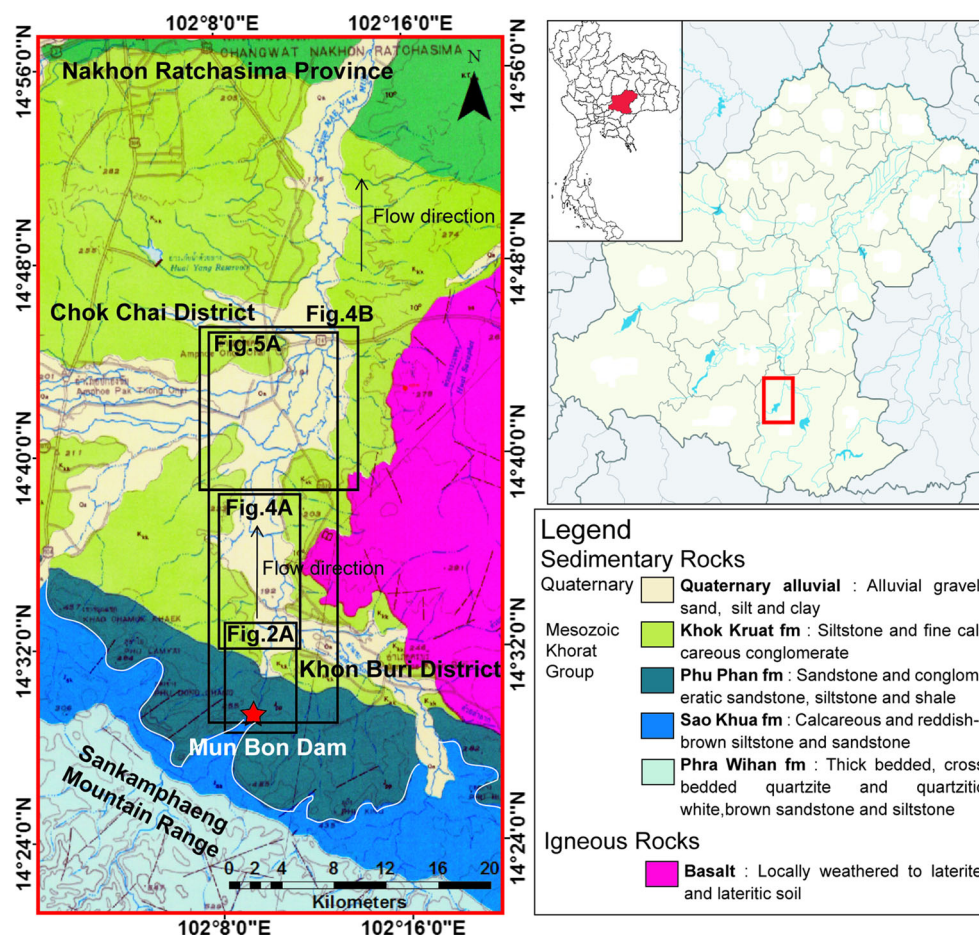
The study area is occupied by clastic sedimentary rocks of Mesozoic continental red beds, so-called the Khorat Group. The Khorat Group is stratigraphically subdivided into eight formations from bottom to top as the Nam Phong, Phu Kradung, Phra Wihan, Sao Khua, Phu Phan, Khok Kruat, Mahasarakham and Phuthok formations. The age is inferred to Jurassic and Cretaceous (Meesook and Saengsrirachan 2011; Horiuchi et al. 2012). The upstream catchment reservoir (Mun Bon Dam) is located at narrow plain between sandstone beds of the Sao Khua and the Phu Phan formations. The study area is covered by unconsolidated Quaternary alluvial sediment (Dheeradilok 1993), and it is underlain by Phu Phan and Khok Kruat formations of the Khorat Group.

Materials and methods

Aerial photograph and orthophotograph interpretation

Three series of aerial photograph with scale 1: 15,000 (1974) and 1: 50,000 (1986) and satellite image

Fig. 1 Index map of northeast Thailand (*upper right figure*) showing location of the study area (*red block*) overlying on geologic map scale 1:250,000 (*left figure*) (modified from Department of Mineral Resources 1984). *Star* indicates location of Mun Bon Dam. Four *black rectangles* show detail of geomorphic changes in Fig. 2a, the abandoned channel in Fig. 4a, b and location for calculating Rc value in Fig. 5a



(1974–2011) were studied. Orthophotograph with scale 1:4000 taken in 2011 was interpreted for comparing the change of Mun River channel dimension over 37 years (Table 1). Geometric correction was performed both of scanned aerial photographs (1974 and 1986) and orthophotograph (2011) for removing distortions from the raw images. The suitable numbers of ground control points (GCPs) were identified throughout the images in the exact landmark such as intersection of the road or man-made construction for acquiring the low root mean square error (RMSE). The numbers of GCPs were selected at least five points per one aerial photograph for calculating the lowest RMSE. The acceptable criteria of RMSE for this study are less than or equal to 10. The GIS analysis was carried out by using ArcGIS 9.3 software. All materials were georeferenced in WGS1984 UTM (Zone 48N) coordinate system. Geomorphic units especially river channels were compared from three periods of time (1974, 1986 and 2011). Oxbow lakes, meander scars and floodplain were identified clearly from aerial photograph taken in 1974 (Fig. 2b–d). These geomorphic units were differentiated and classified from different tone of color, size, shape, texture and pattern. The Mun River for this study was divided into eight rivers

reaches. Each reach covers 1–1.5 km long. These river reaches were subdivided into five segments with no specific criterion for detailed comparison (Fig. 2a).

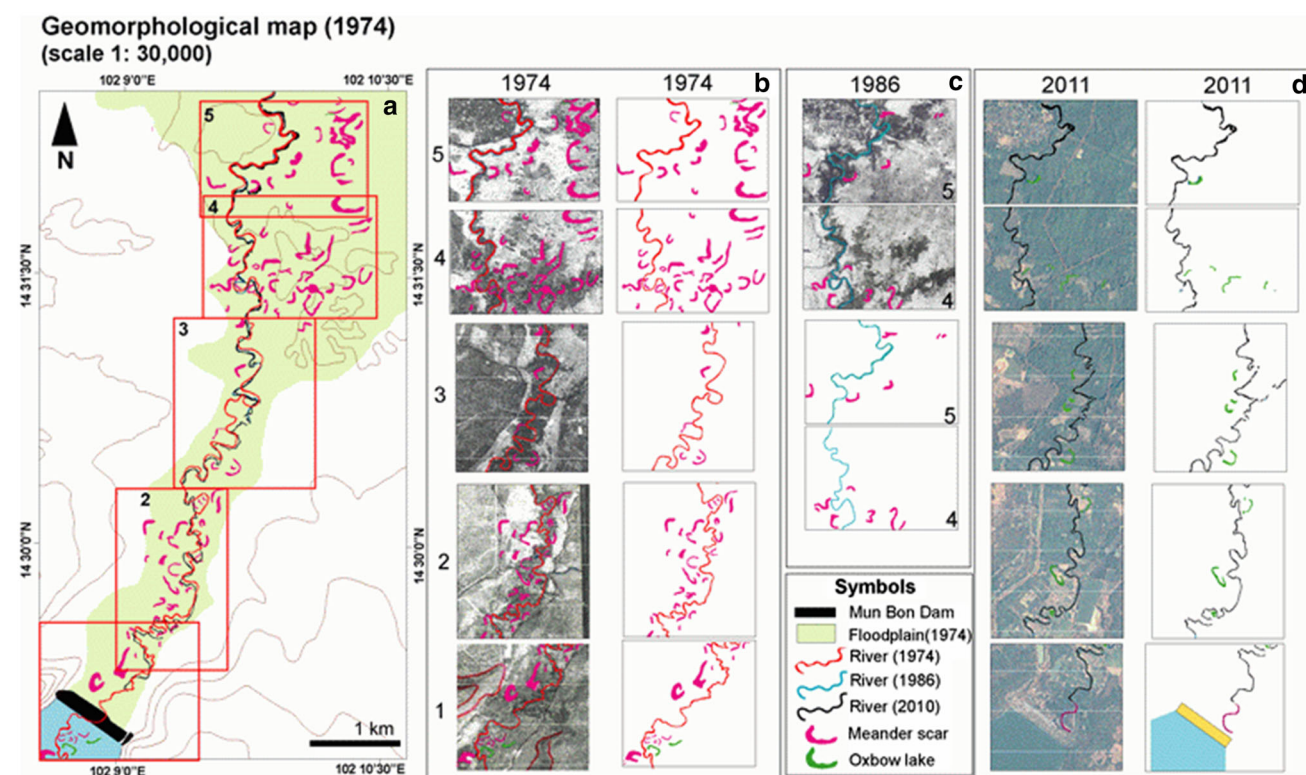
Geomorphic planform analysis

The condition of river meanders and trend of channel migration were commonly evaluated from geomorphic planform variables (Julien 1985). In this study, sinuosity index (SI), meander wavelength (Lm), radius of curvature (Rc) and channel width (W) were analyzed and estimated for comparing river behavior (Mun River) and the characteristic of river in the past (abandoned channels). Moreover, the effect of the Mun Bon Dam on the river planforms was determined during the pre (1974–1986)- and post (2004–2015)-dam construction (Table 2).

Modified plan view sketch of idealized SI, Lm, W and Rc is shown in Fig. 3a, b. Geomorphic analysis including sinuosity and channel width was carried out in form of size and length of the river and abandoned channels (meander scars) by Arc Map 9.3 using measure tool for distance measurement. Adding line tool command was used for measuring size of W, Lm, down valley length and channel

Table 1 Data types and sources of data for determining geomorphologic changes and calculating geomorphic parameters in this study

Data type	Acquisition date	Resolution	Source
Aerial photographs	December 1974	Black and white photographs scale 1:15,000	Royal Thai Survey Department
Aerial photographs	March 1986	Black and white photographs scale 1:50,000	Royal Thai Survey Department
Aerial photographs	November 1994	Black and white photographs scale 1:50,000	Royal Thai Survey Department
SPOT images	March 2004	>30 m	Geo-Informatics and Space Technology Development Agency
Orthoimages	April 2011	Color photographs scale 1:4000	Geo-Informatics and Space Technology Development Agency
SPOT images	November 2015	>30 m	Geo-Informatics and Space Technology Development Agency

**Fig. 2** Comparison of geomorphic landforms interpreted from air photographs taken in 1974 (1:15,000), 1986 (1: 50,000) and orthophotograph taken in 2011 in five rivers reaches. Meandered

scars were dominant. Temporal change of channel migration was observed in the upstream part of the Mun River

length. These river planforms were sized and calculated three times for averaging each parameter. The error of this method may derive from photograph rectification process and the uncertain resolution of original pictures from different sources. Other reasons are either the riparian vegetation covering part of river bank or the photographs taken from different seasons. However, we selected the best locations to delineate river boundary for this study.

SI and meandering ratio are common indicator of channel behavior (Ferguson 1975; Leigh 2006; Ibisate et al. 2013). SI is calculated from channel length divided by

down valley length. In this work, we analyzed trend of sinuosity over time, change of sinuosity between recent Mun River and its abandoned channel from eight reaches measured from aerial photograph taken in 1974 and 2011 [Fig. 4c (upper)]. Eight river reaches were separated by the number of abandoned channels distributing on the Mun River floodplain. W is measured as average width of abandoned channels and the Mun River in 2011 from the Mun Bon Dam to Chok Chai downtown area (see Fig. 4a, b). Recent and abandoned channel width was measured and grouped into two categories as small (≤ 20 m) and

Table 2 Geomorphic parameters comparison before and after the Mun Bon Dam construction

Before the Mun Bon Dam construction																
Location	1974							1986							Migration rate	
	L (m)	W (m)	CL (m)	DL (m)	SI	Rc	Rc/W	L (m)	W (m)	CL (m)	DL (m)	SI	Rc	Rc/W		
1	366.63	10.50	366.63	193.84	1.89	77.70	7.40									
2	518.50	13.20	518.50	242.94	2.13	116.77	8.85	404.00	8.40	518.50	208.00	2.49	100.11	11.92	1.85	0.00
3	361.00	8.50	361.00	192.00	1.88	76.31	8.98	278.00	5.80	278.00	183.00	1.52	55.57	9.58	0.82	2.70
4	208.64	14.10	208.64	190.00	1.10	58.96	4.18	216.00	12.80	216.00	169.00	1.28	45.53	3.56	1.18	1.46
5	278.00	7.80	278.00	110.00	2.53	69.52	8.91	242.00	8.40	242.00	80.50	3.01	68.50	8.16	1.27	1.96
6	430.00	22.00	430.00	194.30	2.21	98.87	4.49	439.00	21.60	439.00	219.00	2.00	95.62	4.43	2.64	1.25
7	457.00	16.00	457.00	123.00	3.72	152.78	9.55	433.00	19.00	433.00	141.00	3.07	124.56	6.56	1.58	3.57
8	377.00	15.10	377.00	200.00	1.89	79.78	5.28	361.00	15.60	361.00	191.00	1.89	76.48	4.90	1.84	2.17
9	712.00	13.50	712.00	252.80	2.82	192.08	14.23	732.00	12.40	732.00	248.00	2.95	204.39	16.48	1.25	1.43
10	460.00	14.70	460.00	93.00	4.95	195.95	13.33	426.00	13.10	426.00	97.30	4.38	163.33	12.47	0.71	7.87
After the Mun Bon Dam construction																
Location	2004							2015							Migration rate	
	L (m)	W (m)	CL (m)	DL (m)	SI	Rc	Rc/W	L (m)	W (m)	CL (m)	DL (m)	SI	Rc	Rc/W		
1	395.00	12.00	395.00	114.00	3.46	124.82	10.40	365.00	14.80	365.00	135.00	2.70	95.63	6.46	1.70	0.14
2	442.00	20.70	442.00	233.00	1.90	93.80	4.53	433.00	16.10	433.00	227.00	1.91	92.11	5.72	1.34	0.06
3	282.00	12.60	282.00	176.00	1.60	56.69	4.50	269.00	11.70	269.00	176.00	1.53	53.79	4.60	1.93	0.15
4	207.00	11.40	207.00	186.00	1.11	55.64	4.88	221.00	11.70	221.00	197.00	1.12	57.87	4.95	1.27	0.11
5	311.00	8.10	311.00	112.00	2.78	83.04	10.25	295.00	7.39	295.00	110.00	2.68	76.85	10.40	1.90	0.23
6	446.00	15.00	446.00	224.00	1.99	96.82	6.45	468.00	9.81	468.00	223.00	2.10	104.42	10.64	1.13	0.08
7	381.00	14.80	381.00	112.00	3.40	118.65	8.02	339.00	9.48	339.00	125.00	2.71	89.01	9.39	1.36	0.09
8	407.00	13.50	407.00	200.00	2.04	89.34	6.62	393.00	11.20	393.00	188.00	2.09	87.50	7.81	1.35	0.10
9	715.00	14.60	715.00	290.00	2.47	175.89	12.05	730.00	27.00	730.00	258.00	2.83	197.59	7.32	1.08	0.07
10	452.00	13.60	452.00	99.70	4.53	178.55	13.13	468.00	16.70	468.00	105.00	4.46	182.19	10.91	0.84	0.06

L = meander wavelength; W = channel width; Rc = radius of curvature and migration rate

medium-sized river channels (20–200 m) (Robert 2003). Average channel width was measured and calculated from three locations in each group of abandoned channel and river reach (three replications). W and SI from eight rivers reaches of recent Mun River and abandoned channel group were plotted [Fig. 4c (lower)].

Rc, Lm, W and migration rate/year of recent Mun River channel before and after dam construction were compared. Aerial photographs taken in 1974 and 1986 were used for pre-dam analysis; subsequently, satellite images taken in 2004 and 2015 from Google Earth were zoomed and merged together. After all of four series air photographs with scale of 1: 2000–1: 2500 were rectified as georeferences in the same process (see detail in the aerial photograph and orthophotograph interpretation section). Geomorphic planform variables were measured, calculated

and compared from ten locations (Fig. 5a). Rc is normally measured from historic aerial photographs in comparison with the modern one (Nanson and Hickin 1983). Rc displays degree of tightness of the river bends. Rc can be calculated from Eq. (1) (Williams 1986).

$$Rc = LmSI^{1.5}/[13(SI - 1)]^{0.5} \quad (1)$$

If Rc value is high, the river bend will close to each other. On the other hand, wider bend shows low Rc value. Lm, W and channel sinuosity were measured, calculated and plotted as scattered graph to compare the change of Rc of the Mun River bend from four periods of time (1974, 1986, 2004 and 2015) (Fig. 5b). Change of channel width of ten locations which were selected randomly was also measured (Fig. 5c). Lateral migration rate was carried out from bank line variation (shifting bank line) over time interpreted from aerial

Fig. 3 Parameters of Muller's sinuosity index (SI) (*left*). SI is calculated from AB/CD (Ghosh and Mistri 2012). Modified plan view sketch shows idealized river meander and geomorphic parameters such as wavelength, bend width and radius of curvature (Williams 1986)

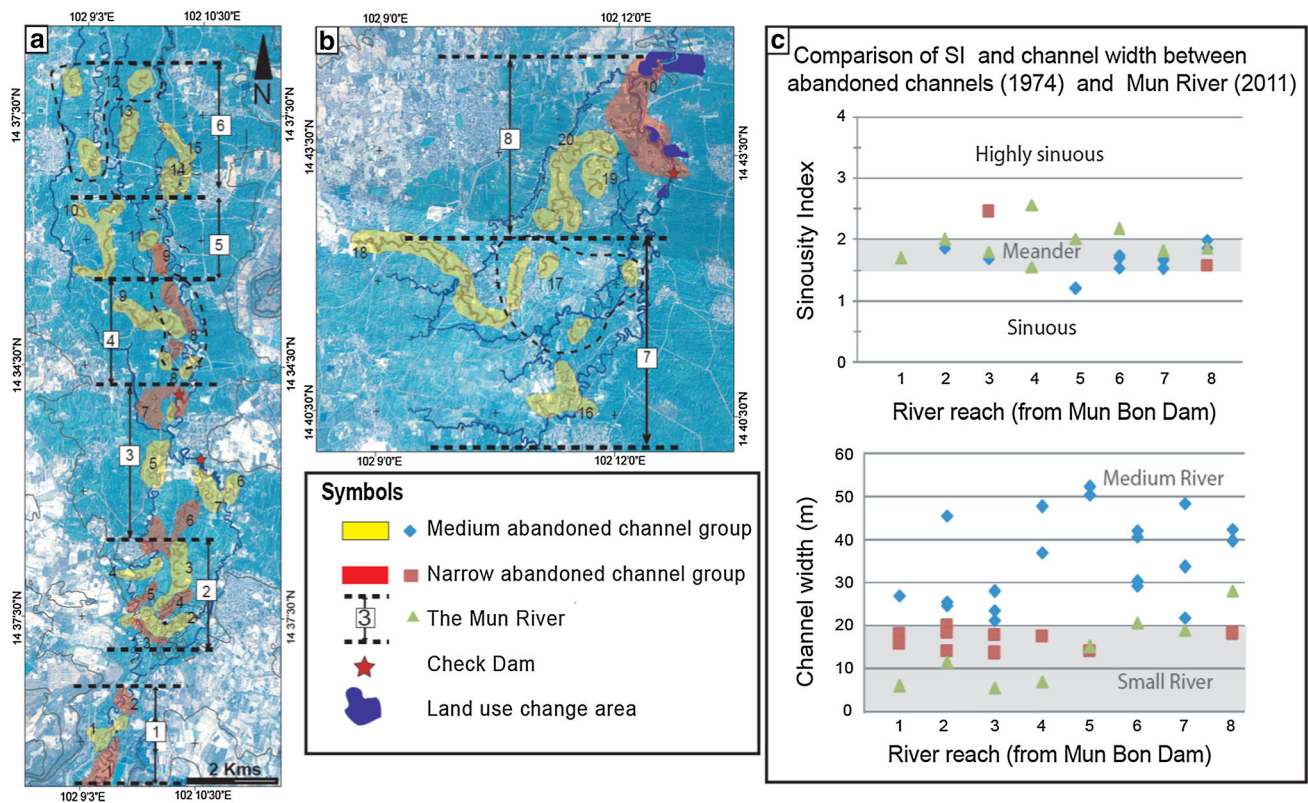
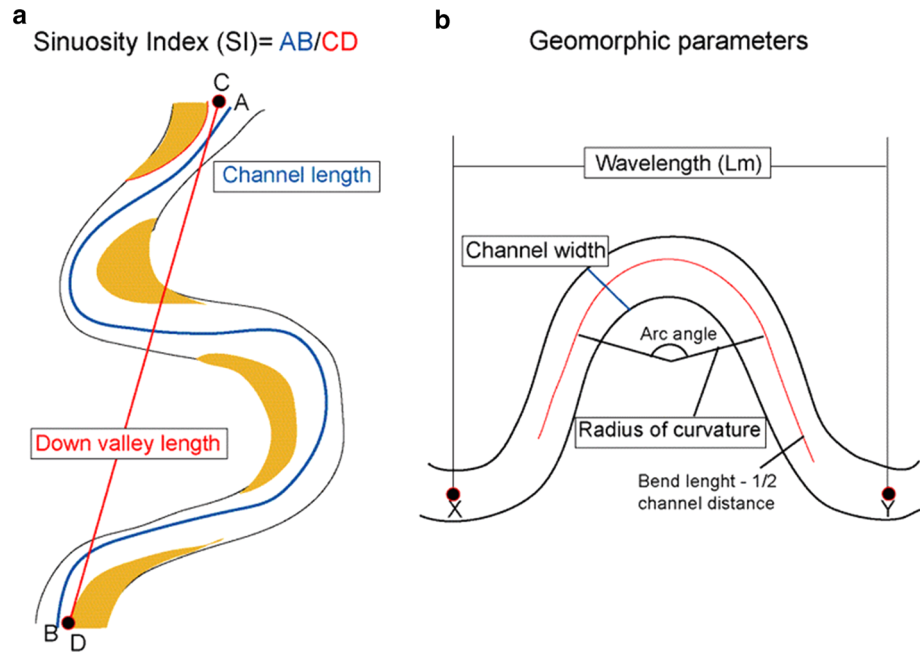


Fig. 4 Location of abandoned channels, two different sets of meandered scars derived from aerial photographs taken in 1974 were categorized as medium- and small-sized abandoned channel group depending on size of channel width (**a**, **b**). Channel width and SI of

abandoned channel (1974) and recent Mun River (2011) from Mun Bon Dam to distributaries on low gradient plain are shown in scattered graphs (**c**). SI of all groups was classified as meandering river (>1.5) (**c top**)

photograph and satellite image (Melville and Coleman 2000). Meander migration rate per year before and after the Mun Bon Dam construction was measured and calculated.

Result was shown as graph in Fig. 5d. Channel stability is then derived from relationship between migration rate per year and Rc/W (Fig. 5e) (Nanson and Hickin 1983).

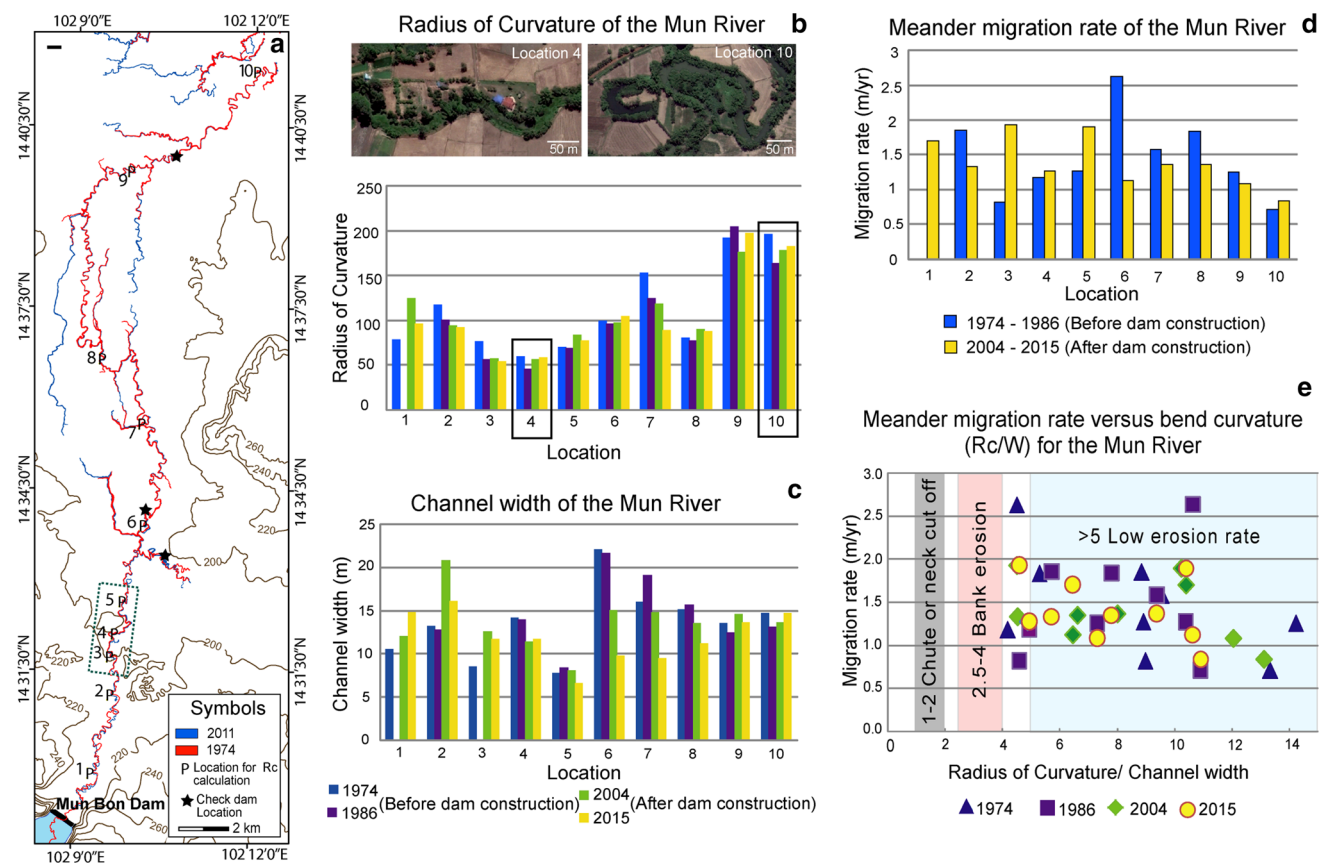


Fig. 5 Locations for calculating Rc value in 1974 and 2011 and river changing map (a). Graph b shows Rc trend in 1974, 1986, 2004 and 2015. Low and high value of Rc is shown in locations 4 and 10 on satellite images. Channel width measured from ten locations is shown in graph c. Meander migration rate before 1974 and after the Mun

Bon Dam construction is shown in graph d. Meander migration rate versus bend curvature (Rc/W) for the Mun River exhibited in graph e. Most of the Mun River selected bends in ten zones were categorized in low erosion rate zone (light blue color)

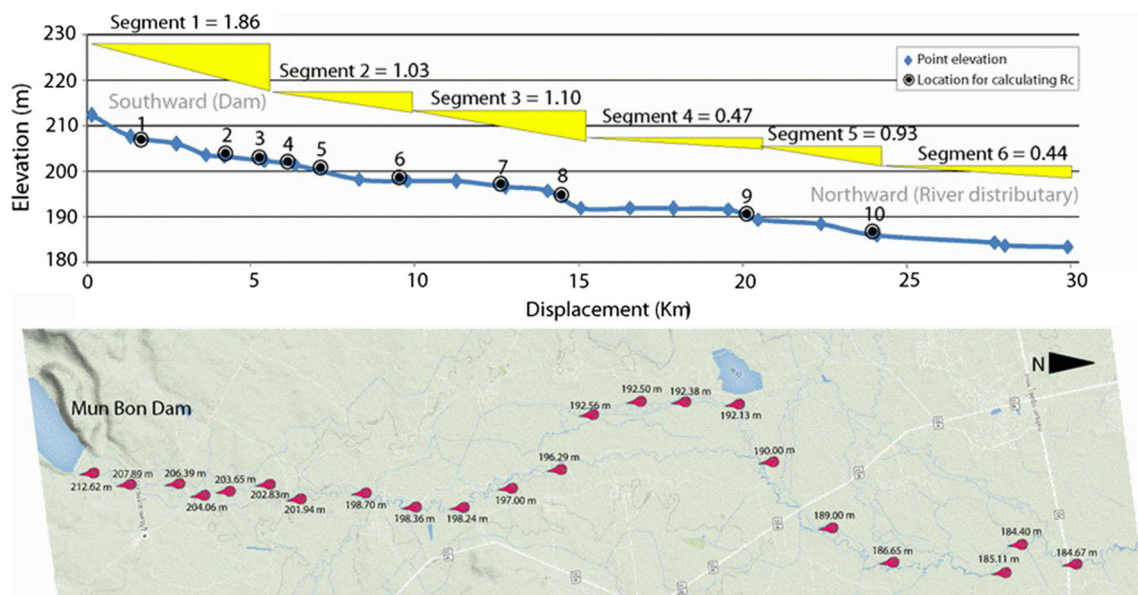


Fig. 6 Longitudinal profile extending from Mun Bon Dam to Mun River distributaries was plotted from 22 point elevations along the river showing gradual inclines to the Khorat Basin in the north. Six

segments of gradient calculated from vertical distance divided by horizontal distance. Slopes slightly change from dam to river distributaries from 1.86, 1.03, 1.10, 0.47, 0.93 to 0.44 m/km

Alluvial plain longitudinal profile was estimated by the point elevation along the Mun River using Google Maps Find Altitude. The Google image was taken in 2015. The distance from Mun Bon Dam to Mun River distributaries in Chok Chai District was measured on the topographic surface. Total 22 point elevations along the Mun River were plotted between elevation above mean sea level (msl) and the distance from the Mun Bon Dam (displacement). In this study, the area is divided into five segments (also see Fig. 6). Each segment is approximately 5 km long. The gradient is expressed as meter per kilometer.

Results

Locating abandoned channel from aerial photographs

From Mun Bon Dam to downstream, geomorphic units were classified from air photographs taken in 1974, 1986 and 2011. Each geomorphic unit is related to geologic setting. Geomorphologic map (scale 1: 30,000) shows the detailed geomorphic changes from five rivers reaches (1–5) (Fig. 2). Change in channel morphology of the Mun River within 37 years was observed from a set of historical aerial photographs and orthophotograph taken in 1974–2011. Geomorphic units including river channels, oxbow lakes and meandered scars were interpreted and compared in terms of width and locations from different periods of time.

As a result, meandered scars were dominant in every reach. A temporal change of channel migration was observed extensively from reach 1 (Fig. 2b, d) where the upstream part of the Mun River is located close to the Mun Bon Dam. Some abandoned channels disappeared, and the Mun River channel was decreased in sinuosity of channel from 1974 to 2011 (reach 1). At reaches 2 and 3 (Fig. 2b, d), the process of channel migration occurred at the inner and outer bends where neck cutoffs were dominant. Meandered scars were mainly recognized in the left side of the Mun River bank in reach 2. At reaches 4 and 5 (Fig. 2a), several meandered scars were distributed on the right side of floodplain, and they are wider than the recent Mun River channel. Flow direction of Mun River (in 1974, 1986 and 2011) on the reach 5 follows same channel, but it shifts gradually to the left side (Fig. 2a). Abandoned channel cannot be recognized from air photograph, only oxbow lakes can be seen.

Geomorphic planform analysis

Meandered scars are located mainly in the right side of the Mun River bank. Based on Fig. 4a, b, locations of abandoned channels were divided into eight reaches from the

present Mun River channel. SI and W from recent river at all reaches were compared with abandoned channels detected from 1974 (Fig. 4c).

Sinuosity index (SI) and channel width (W)

SI and W of paleo-Mun and abandoned channels were measured and plotted in forms of scattered graph for determining relationship between size of abandoned channel and the recent Mun River existed in the same area. Measurement of channel widths was carried out and compared with recent Mun River from aerial photographs taken in 1974. Figure 4c (bottom) shows different W from abandoned channel group and the recent Mun River. An average channel width of 35, 16 and 13 m was found from medium-sized and small-sized abandoned channel and the recent Mun River, respectively. Average value of the Mun channel width is similar to small size abandoned channels. Trend of channel width was slightly increased especially from reach 5 to reach 8 (wider) from upstream (dam) to downstream of recent Mun River. Sizes of medium abandoned channels varied (highly distribution). Small abandoned channel width shows stability and slightly changed from 0 to 6 m. These river channels developed in the same geologic setting (on Khok Kruat formation) and same gradient of the terrain.

The comparison of SI among medium-sized abandoned channel, small-sized abandoned channel groups and the recent Mun River is shown in Fig. 4. Most of SI was categorized as meandering river (Hooke 2007; Masalimova et al. 2015) with SI value between 1.5 and 2 (gray color in Fig. 4c top). The other zones display highly sinuous (>2) and sinuous zone (<1.5). Average SI as 1.74, 2.00 and 1.88 represents medium-, small-sized abandoned channels and the recent Mun River, respectively.

Radius of curvature (Rc) and meander migration

Rc values before and after Mun Bon Dam construction were determined from 1974, 1986, 2004 and 2015 together with channel width and meander migration rate versus bend curvature (Rc/W) from different period of time. Rc has changed throughout ten locations (Fig. 5a, b). Low Rc and river bend wide were depicted on satellite image from locations 3 and 4. On the other hand, Rc in locations 9 and 10 shows high value and the river bend is tight. Channel widths of the Mun River measured from photographs in 1974, 1986, 2004 and 2015 were also compared. At location 5, the river shows narrowest and decrease in channel bend and width comparing with the other location after Mun Bon Dam construction (Fig. 5c). Meander migration rate per year before (1974–1986) and after (2004–2015) dam construction is shown in Fig. 5d.

Channel stability evaluation was also measured from historical aerial photographs in comparison with modern channel. R_c/W from ten locations measured from 1974, 1986, 2004 and 2015 was plotted against migration rate (Fig. 5e). R_c/W values can predict the behavior of river. Three main processes were categorized from graph based on R_c/W ratio including the occurrence of chute or neck cutoffs (1–2), bank erosion (2.5–4) and zone of low erosion rate (>5) (Nanson and Hickin 1983). Result from air photographs interpretation from the years 1974, 1986, 2004 and 2015 within the study area shows low erosion rate with meander migration rate between 0.71 and 2.64 m/year (Fig. 5d, e).

River planform parameters interpreted from 1974 aerial photographs reveal location of different size abandoned channel on both sides of the Mun River bank. SI and abandoned channel width indicate meandering river flow in the past with wider channel than the present (Fig. 4c, bottom). Clearly, R_c of the Mun River can be used to indicate meander characteristic. In place, far from Mun Bon Dam, river comprises the closer bend with high R_c value. Channel widths of recent river after the Mun Bon Dam construction are generally decreasing from locations 4–8, whereas they increase in locations 1–3. Slight change in channel width is shown in locations 9 and 10. Lateral migration rate decreases after the Mun Bon Dam construction in locations 2, 6, 7, 8 and 9, while lateral channel shifting was found at locations 3, 4, 5 and 10. In conclusion, the relationship between migration rate and bend curvature indicates that the Mun River can be categorized as low erosion rate river.

Alluvial plain longitudinal profile

The alluvial plain longitudinal profile is derived from the estimated altitude topography of total 22 point locations from the Mun Bon Dam to the Mun River distributaries (Fig. 6). The calculated gradient from six segments exhibits approximately 1.86, 1.03, 1.10, 0.47, 0.93–0.44 m/km from the river of segments 1–6, respectively (Fig. 6, top). These topographic gradients were slightly changed from dam area to low gradient plain making that the study area becomes very low gradient topography. The Mun River flows on gradually and slightly inclined plane to the Khorat Basin in the north direction. The point elevations range between 212.62 and 184.67 m above msl.

Discussion

Evidence of abandoned channel

The deposition on point bar and erosion at the outside bend of channel in each meander begin to preferentially erode its

banks toward the outside. This causes the river migrate toward the side and downstream. Narrow neck of looping meander can also get cutoff during flood event and forms oxbow lake (Reynolds et al. 2012). Thus, many landforms in this study area including oxbow lakes, meandered scars and levees are present on floodplain (Fig. 4a, b). The occurrence of abandoned channel is resulted from the meander that reaches the maximum value of sinuosity (Li et al. 2012).

Abandoned channels were observed clearly from aerial photographs taken in 1974 more than the other periods because land utilization has changed in Nakhon Ratchasima Province due to the agriculture, housing area, domestic animals and increasing the number of factory nearby the river (Gosa 2012). The number of abandoned channel reflects the time of cutoff in the past and related the meander development (Li et al. 2012). Moreover, abandoned channels recognized from this area have their variety of channel sizes existing on the same geological terrain. Two different sets of meandered scars were categorized as medium- and small-sized abandoned channel groups. Channel width was divided into wide (>200 m), medium (20–200 m) and narrow-sized channel (<20 m) (Robert 2003).

The width of small abandoned channels shows slight change from 0 to 6 m and similar in size with the recent Mun River. Small abandoned channels were found near the recent river; thus, it indicates the relation to the Mun River cutoff process. Increasing in width of medium-sized abandoned channel may result in increasing of sediment supply and decreasing in channel stability in the past (Miall 2014). Thus, it may occur in different conditions of fluvial process. Water velocity, discharge and sediment load in the past are among physical factors that are different from the present. Water naturally drains from big drainage basin from highland area of the Sankampaeng Mountain Range to downstream. The higher amount of water volume and the faster velocity of river flow compared with the present form make the river to flow easier and faster throughout channel. The more stream power in higher discharge and velocity can carry the large amount of sediment. Then, both lateral and vertical erosions made channel wider and meander can swing freely in the past more than present. Width of abandoned Mun channels that wider than present indicates the existence of these abandoned channels in place far from headwater (at the middle river reach) and developed on small channel gradient (Li et al. 2012). In conclusion, the comparison of SI of medium-sized abandoned channel, small-sized abandoned channel groups and the Mun River revealed that most of them can be categorized as meandering river (Hooke 2007; Masalimova et al. 2015) which usually develops on low gradient floodplain and inclusive of sand and silt deposit (Hogan and Luzi

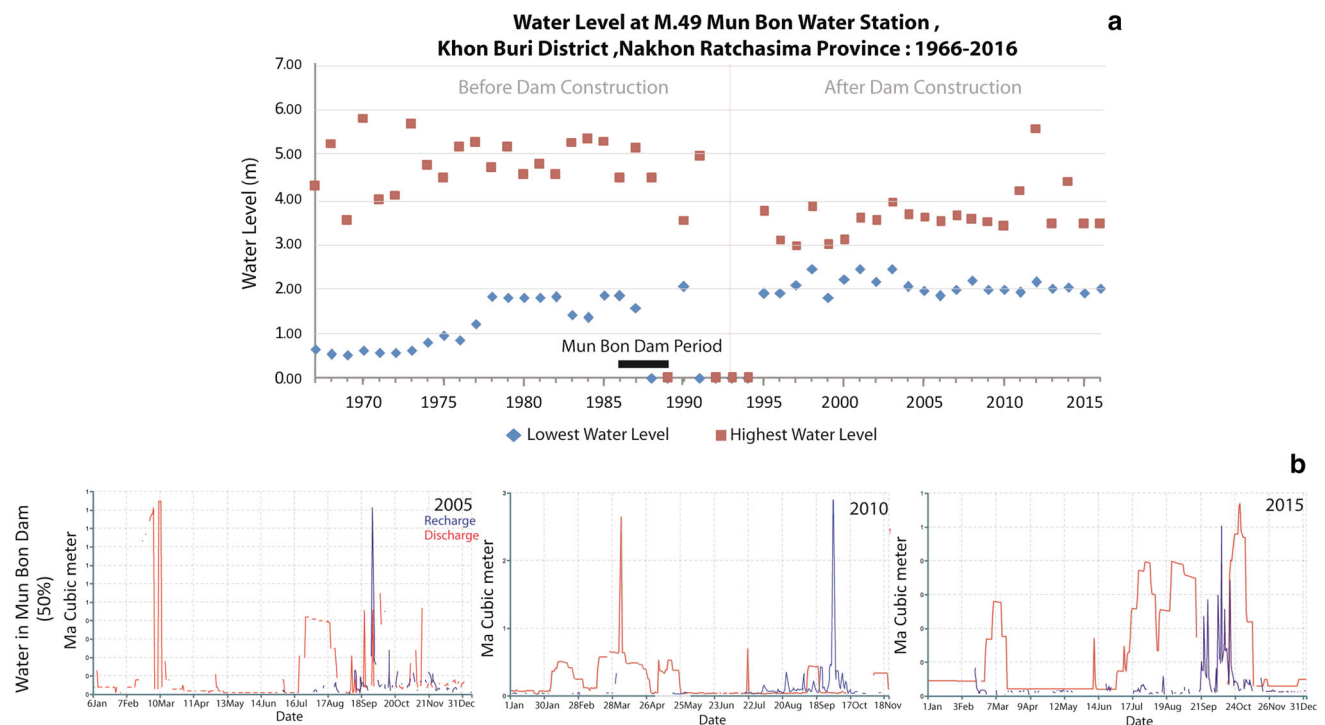


Fig. 7 Water level at station no. M49 (Khon Buri District, Nakhon Ratchasima Province) showing the lowest and highest water levels in 1966–2016 (a). Water recharge and discharge to the Mun Bon Dam in 2005, 2010 and 2015 (b)

2010). Channel width was slightly increased from dam site to downstream area of the recent Mun River (Reaches 4–8 in Fig. 4c, bottom). Channel width in the downstream part of the study area was possibly affected by check dam, digging out of Mun River. Land use change from factory and agriculture can provide an effect on the river channel (Gosa 2012).

Geomorphic parameters before and after Mun Bon Dam construction

Temporary base levels of the Mun River were probably modified after the Mun River was dammed. Dam is often regarded as the most dominant form of human impact on fluvial systems (Ronald et al. 2013). Two primary drivers of change to fluvial system in respond to dam change include flow regime and changes in sediment regime. Flow and sediment regime modifications occur over short period; however, geomorphic impacts can extend over tens to hundreds of years (Marren et al. 2014). The discharge data from water station no. M49 in the study area show the difference in water level before and after dam construction from 1966 to 2016 (Fig. 7a). Water level in Mun River is higher than the period after Mun Bon Dam construction about 1–3 m. On the other hand, the lowest water level increased from 1 to 2 m after dam construction (Royal Irrigation Department Thailand 2013). In case of sediment regime when the river

reduces flow discharge, the river continues meandering and becomes high sinuosity (Li et al. 2012). However, in the study area, the relationship between Rc and bend migration shows low erosion rate from 2004 to 2015 (Fig. 5e). Channel width and meander migration rate from locations 6 to 10 also decreased (Fig. 5c, d) because the topographic elevations from locations 6 to 10 are lower than those recognized from the Mun Bon Dam area.

The apparent change of channel width and migration rate after dam construction is from the evidence of fluvial geomorphologic change in this area (Fig. 5c, d). The comparison of channel width before and after the Mun Bon Dam construction notably shows expansion of channel width in locations 1, 2, 3, 9 and 10 (Fig. 5c). However, channel width decreased in locations 4–8. River channel shows the increasing in lateral migration rate in locations 3, 4, 5 and 10, but the rate reduces in locations 2, 6, 7, 8 and 9 (Fig. 5d). The different migration rate occurs in individual bend because lateral accretion is not continuous process or it occurs episodically (Melville and Coleman 2000). Additional reason is made by the effect on river channel (channel width) rectification that riparian on the side of floodplain was found.

River bank erosion

In this study, the degree of tightness of meander bends is also represented by Rc. The wide bend shows low Rc value

while high R_c value implies tight river bend (Fig. 5b). R_c trend from 1974, 1986, 2004 to 2015 shows slight change with similar trend in the same location. The lowest and highest R_c values were shown in locations 4 and 9. Relationship between meander migration rate and bend curvature suggests that the Mun River in Khon Buri and Chok Chai areas possesses low erosion rate since 1974 to the present (Fig. 5e). Migration rate versus bend curvature (R_c/W) is less than 5 that coincides as stable river bank.

The Mun River bank in this area is mainly composed of silt and clay layer in the upper part (1–2 m from surface). On the other hand, the lower part (2–4 m) is associated with compacted clay layer with iron concretion and weathered red siltstone and sandstone bedrock. They are resistant to lateral erosion. Very low water level and slow flow velocity may also inhibit river bank erosion. In such a case, aerial photographs were once again used for measuring lateral migration rates of river bend. Meander migration rate versus bend curvature (R_c/W) of the Mun River was plotted and is shown in Fig. 5e. The value of R_c/W ranges from 1 to 2. This value indicates that chute or neck cutoffs can be formed (dark gray color in Fig. 5e). Bank erosion exists in zone where R_c/W ranges from 2.5 to 4 (red color in Fig. 5e). Low erosion rate occurs in zone of R_c/W more than 5 (Nanson and Hickin 1983). Flow direction of Mun River (in 1974, 1986 and 2011) on reach no. 5 follows the same channel as previous direction with slightly meander migration to the left side (also see Fig. 2a). Migration rate per year (locations 1–5) also increased from 2004 to 2015 (after the Mun Bon Dam construction) (see location 4 in Fig. 5d).

Effect of geomorphic parameters to floodplain after dam

In this study, we found that geomorphic parameters have an effect on floodplain topography. Slightly higher floodplain topography of the area between locations 3 and 5 could lead to natural obstacle (Fig. 5a). Due to decreasing in velocity of river flow, sediments were carried by slow water flow regime. Then, they were settled and deposited. This process results in the increasing of later migration rate and SI (Fig. 5c, d). R_c of location 10 is also highest value because the curvature of river became closer. The other possible factor is from the construction of many check dams. Check dams are used for irrigation purposes and measuring the water level (see the location in Fig. 5a). The hydrological balance possibly changes sediment budget and water volume in a downstream area because of the effect of water drainage (Marren et al. 2014). Flow regulation causes reversing natural flow seasonality.

Water recharge and discharge from the Mun Bon Dam from 2005, 2010 and 2015 show different water level.

Recharge represents natural situation when river flows to the dam. According to Fig. 7b, the highest peak of recharge is about September to October, but the highest peak of discharge is around March (2005 and 2010) and October (2015). These peaks confirmed seasonal variation of water discharge in the Mun River after the Mun Bon Dam construction (Royal Irrigation Department Thailand 2016).

Likewise, the Mun Bon Dam is also used for irrigation purpose. Broadly thought, dam is likely to be reduced the magnitude and frequency of medium to high flow and the variability of low flows is likely to be raised where water is released for irrigation purpose (Marren et al. 2014). Therefore, water level in summer period decreases, but in winter period it increased in discharge volume more than naturally condition. Consequently, the Mun River channel may change from this factor depending on the degree of river erosion. However, because the nature meander process in this area shows different migration rate in individual bend and bank composition varies from one area to the others, thus, the river width is wider from some locations (see locations 1, 2, 3, 9 and 10 in Fig. 5c). Dam is highly effective to sediment traps, whereas channel migration is a discontinuous process. Several studies of dam impact have reported a reduction in meander migration rates (Richard et al. 2005; Marren et al. 2014). In the context of floodplain impact, the reduction in sediment load may enhance rate of bank erosion and lateral migration. Composition of river bank sediment and slow flow velocity in the study area are of important factors for limiting river bank erosion. Sediment supply and bank erosion are reduced; therefore, lateral migration rate tends to decline. Decrease in lateral migration rate can be seen in locations 6–9.

Conclusions

1. Sinuosity index of abandoned channels and recent Mun River indicates meandering river system. Abandoned channels were observed clearly on floodplain from aerial photographs taken in 1974 at both sides of the recent Mun River floodplain. Two different groups of abandoned channels have the variety of channel size. This can be explained by geomorphic parameters in the area. Stream power and velocity from highland of this drainage basin (Sankampaeng Mountain Range) are capable of carrying large amount of sediment to form floodplain downstream; thus, the river can be shifted laterally and naturally.
2. The construction of Mun Bon Dam has slightly affected the geomorphologic changes in the Mun River course especially river migration. The seasonal change of water discharge and recharge is also indirect

factor affecting meandering process after dam construction. The peak of discharge is common in summer (March to April) but recharge is on September. Increasing in channel migration can be seen at some locations, but lateral migration rate was decreased after dam construction. In the study area, the different migration rate occurs in individual bend; thus, the lateral accretion is not continuous process.

3. Alteration in river planform parameters such as channel width and radius of curvature might be the influence of dam construction to the development of meandering river. Some meander bends decrease in channel width; in contrast, the others become wider. This is because the discharge fluctuation leads to the change of sedimentary regime in some locations.
4. High topography and small hill may behave as natural obstruction leading to the reduction in the Mun River flow velocity and contribute to sediments deposition. By this reason, lateral migration rate has increased and channel has become sinuous.
5. As a whole, radius of curvature of recent Mun River and abandoned channels in Khon Buri and Chok Chai areas indicates low erosion rate. R_c is associated with the degree of tightness of the river bend. R_c shows similar trending from 1974 to 2015.
6. Channel stability of the Mun River from the past to present behavior poses the value more than 5. Therefore, it suggests that low rate of erosion occurs probably because of very low gradient topography to the north, low water level with slow flow velocity and resistant bank composition.

Acknowledgements The 90th Anniversary of Chulalongkorn University Endowment provides fund to PN. MC received fundings from Ratchadapisek Somphot Foundation Endowment (WCU58-18-CC), Thailand Research Fund (BRG5780008) and National Research Council of Thailand (NRCT) for running river process project around Thailand. Authors would like to thank editor and two anonymous reviewers for valuable comments that make the improvement in this manuscript significantly.

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