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Original Article

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

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Abstract

This study aimed to increase the understanding of the history of late Quaternary coastal evolution. An analysis was carried out on the optically stimulated luminescence (OSL) dates of 12 quartz-rich samples collected from the Chanthaburi paleo-sand spit and 37 samples from beach ridges at Sam Roi Yot National Park in the upper Gulf of Thailand. The single-aliquot regenerative technique was employed after OSL sample treatment. As a result, both equivalent dose and annual dose provided OSL signals that were internally consistent. The derived OSL ages were in good agreement with the stratigraphic evolution of the spit and beach-ridge progradation. OSL dating of the paleo-sand spit revealed that the age ranged from 17,210 to 1,370 years. The average lateral migration rate of the sand spit varied from 0.2 to 1.8 m/year. The OSL age of the beach ridge plain from Sam Roi Yot National Park started from 10,200 to 880 years. The beach ridge plain had 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

1. Introduction

Among various types of coastal landforms, the orientation of a sand spit and the series of beach ridges are significant clues to the progradation and evolution of the coast and the paleocurrent direction. Therefore, systematic dating of the spit and beach ridge collected perpendicular to the shoreline is useful to illustrate the shoreline development at any site of interest. The precise altitude of each spit and beach ridge coupled with reliable results of dating can remarkably reveal the migration rate of beach-ridge progradation as well as serving as one of geological proxies of sea level change (Karpytchev, 1993; Szkornik, Gehrels, & Murray, 2008; Tribe, 2008;). At present, it is widely accepted that accelerator mass spectrometry radiocarbon dating is the most reliable scientific dating method, in particular for the Quaternary period (Hajdas, 2008). However, in practice, radiocarbon dating requires specific organic samples which are rarely preserved in beach sand or sand spit and may be contaminated by modern roots (Kilian, Geel, & Plicht, 2000). Therefore, we applied optically stimulated luminescence (OSL) datings of sand grain to estimate the rate of deposition of a sand spit and beach ridge. In contrast to the other scientific dating methods, OSL dating is able to date quartz-rich sediments representing the last exposure to daylight during the transportation process. Mathematically, the date can be presented as expressed in equation 1 (Aitken, 1985).

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

where the equivalent dose (ED) (in Gy units) is the luminescence intensity emitted during stimulation of the sample by an optical source, i.e. light. Whereas, the annual dose (AD) in units of Gy/yr is the annual dose determined

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from the concentration of natural radioisotopes, i.e. uranium (U), thorium (Th), and potassium (K), surrounding the sample.

OSL dating is beneficial for late Quaternary dating with reliability of the age ranging from about months to 150,000 years old with an error of around 5-10% (Murray & Olley, 2002; Murray & Wintle, 2000). In addition, based on a literature review, a number of studies using OSL dating on coastal sand were successfully demonstrated, 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 Sam Roi Yot National Park (SRY) beach ridge plain were dated. The dates obtained were useful to estimate the average local and lateral migration rate or the regional evolution of the sea level change or both in the period of spit and beach ridge development.

2. Study Area and Sample Location

The paleo-sand spit in this study was located about 15 km landward from the present-day shoreline of Chanthaburi Province at the eastern part of Thailand (Figures 1A and 1B). According to the coastal geomorphologic map (Department of Mineral Resources of Thailand [DMR], 2001), at least 9 units of different geomorphologic landforms are 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, the paleo-sand spit at Chanthaburi is composed of 12 ridges generally lying in northwest-southeast and slightly concaves toward the land in the northeast direction at the end of spit (Figure 1B). The spit ridge is about 0.4-1.14 km wide. At present, the spit ridges are covered in some parts by bushes and trees and were disturbed mainly by human communities in particular for shrimp farming. The north-western 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.

The 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 the SRY beach ridge plain, long and parallel ridges along the coastline were described. Shallow swales were also found in between the ridges making it an irregular and undulating terrain of beach ridge plain.

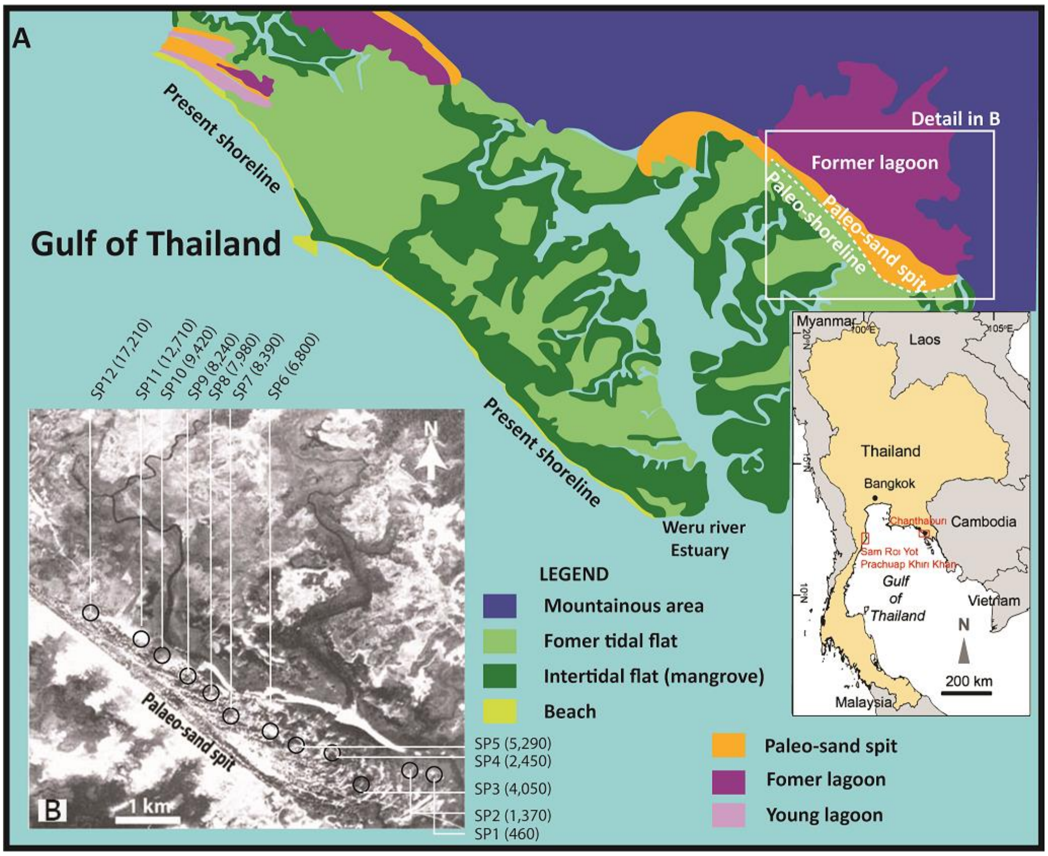

Figure 1. (A) Geomorphological map of Weru estuary at Chanthaburi with geomorphic landforms and location of paleo-sand spit (background geological map from DMR (2001); (B) close up of aerial photograph with locations and OSL age dating along paleo-sand spit and results of dating of each spit are shown in Table 1.

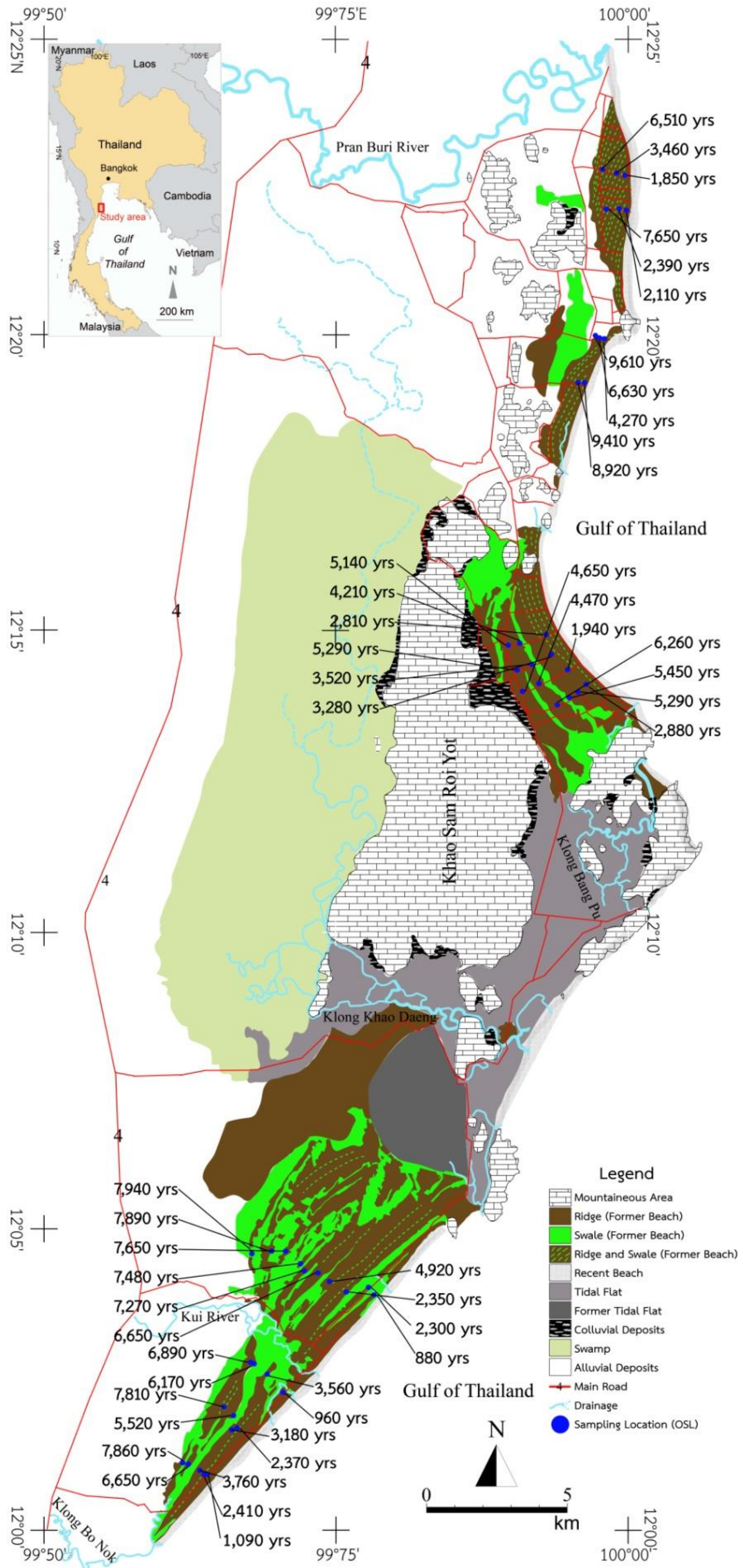

Figure 2. Geomorphological map of Pran Buri, Sam Roi Yot National Park and Kui Buri with OSL ages of beach ridge. The locations of OSL samples are listed along each transect for each location in Tables 2 to 4.

3. Materials and Methods

We interpreted several series of aerial photographs and satellite images taken at different periods of times. At Chanthaburi, an aerial photograph taken in 1954 was interpreted to locate a site for specific sample collection for OSL dating. At Pran Buri and Kui Buri aerial photographs taken in 1955 (ID 23962) and in 1954 (ID 49472) with hydrographic charts 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 sand were collected from the 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 time; therefore, no comparison in water content in different seasons was 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 sand were collected additionally surrounding the ED sampling location. This part was used for AD evaluation.

Beach ridge plains at Pran Buri consisted of three sets of ridges with erosional lines recognized clearly as indicated by dash lines in Figure 2. Because beach ridge plains are narrow, only a transect line was designed for OSL sampling. At Bangpu village in SRY, two transect lines were assigned almost in a west-east direction. In the southern part of SRY, a large beach ridge plain at Kui Buri was selected. Sets of beach ridges intervening with swales were common. We collected OSL at depths of 30-50 cm from the surface to avoid land surface modifications (Figure 3D).

In the sample preparation process, two portions of samples were prepared for ED measurement and AD measurement including water content. ED measurements were carried out in subdued red light whereas the AD measurements including the water content were prepared with light exposed. The methodology for measuring the ED and AD and examples of each sample analysis are given below. Similar methods were applied to all samples collected from Chanthaburi and Sam Roi Yot coasts.

3.1 Equivalent dose (ED) measurement

A wet sieve was employed to recover grains 74–250 µm in diameter (Takashima & Honda, 1989). This fraction was then etched with HCl for carbonate-fragment elimination. In addition, in order to avoid the effect of alpha dose rate, hydrofluoric acid was used to remove the quartz skin (Takashima & Honda, 1989). Thereafter, the ferro-minerals were eliminated using an iso-dynamic magnetic separator. In order to check the homogeneity of the samples, all treated quartz samples were tested by X-ray diffraction (XRD). The results revealed purification of the alpha quartz. In addition, it was constrained by samples that had significant infrared (IR)-stimulated signal compared to a 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 $^{90}Sr/^{90}Y$ 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 ^{o}C with the rate 5 ^{o}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 to assess 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. An example of OSL measurement of sample number SP-2 is given in Figure 3.

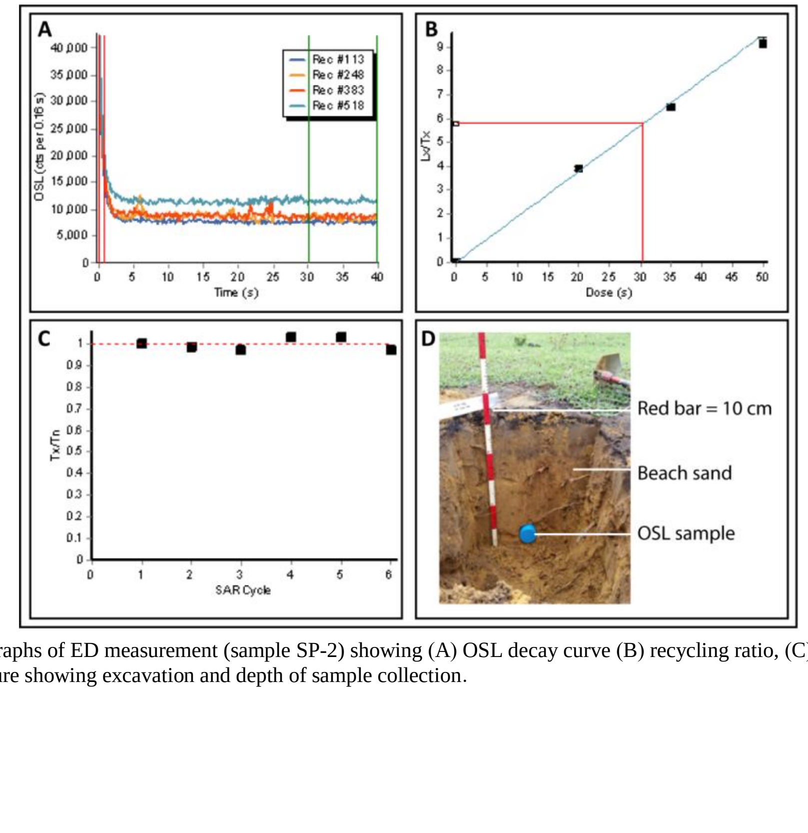

Figure 3. Example of graphs of ED measurement (sample SP-2) showing (A) OSL decay curve (B) recycling ratio, (C) OSL growth curve and (D) field picture showing excavation and depth of sample collection.

In Figure 3A, blue lines correspond to the OSL decay curve of the N. Meanwhile, the other colored lines correspond to the additional doses (R_1–R_3). As an integral part of the SAR protocol, behavior of the samples was 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 a Tx/Tn graph within the range of 0.9–1.1 (Figure 3C).

In order to perform an OSL growth curve and ED estimation, OSL signals were calculated by integration of the first 2 sec of data and subtracting the background (30–40 sec). As demonstrated in Figure 3B, for example, black squares represent OSL signal (Lx/Tx) of R_1-R_3 which show a general trend in the 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 sec or 4.23 Gy (1 sec = 0.141 Gy). In terms of growth curve, some samples showed a slight exponential trend, but not clearly. All seemed to show a linear trend. However, we calculated age results and compared between linear and exponential trends. Calculated ages were somewhat different but did not exceed 300 years. In terms of beach evolution, we could accept this difference in age because we consider age on a millennium scale. As mentioned above, the SAR technique was employed and the results of one disc represented a single-aliquot ED. In this study, 10 discs of aliquots per sample were measured. The series of ED results is shown. For instance, the ED obtained from the measurement of sample SP-2 was in the range of 3.50-9.67 Gy. Among the seven available ED measurements, most values were in the range of 3.81-5.04 Gy. Only one ED value of 9.36 Gy was measured from sample SP-2. In contrast, sample SP-10 revealed a sparse distribution of the ED that ranged between 9.09 and 9.43. According to Duller (2008), four different age models that could be applied in the analysis of ED datasets were the (i) central or average age model, (ii) common age model, (iii) minimum age model, and (iv) finite mixture model. It was 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, the AD measurement of each sample was also derived from natural radioisotope 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 the standard table proposed by Bell (1979) including the calculated cosmic ray dose rate (Prescott & Hutton, 1994). Thereafter according to Aitken (1985), the AD obtained was reduced by attenuation factors based on both grain-size distribution and water content. The AD of each sample and error calculation were calculated according to Singh *et al.* (2017) (Table 1). A comparison between the AD measurements of all samples, the AD measurement of sample SP-10 (AD=0.33±0.03 Gy/ka) was less than all of the other samples. This was based on the low concentrations of U (0.28±0.04 ppm), Th (0.68±0.16 ppm), and K (0.03±0.06%), whereas the water content was high (3.6%) (Table 1). Sample SP-2 had the maximum AD and the highest radionuclide concentration in %K (2.16±0.12), whereas %K values of the other samples were less than 1.0 (Table 1).

In this preliminary work, the AD errors were low, while the ED errors were quite high. However, since our results of OSL datings explain beach ridge evolution on a millennium scale, the 10% dating error is acceptable. However, in further studies it should be calculated through advanced statistics (Galbraith & Roberts, 2012).

4. Results and Discussion

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

Based on both ED and AD measurements obtained, the OSL dates of each sample were evaluated according to

Table 1. OSL dating results of 12 sand samples collected from the paleo-sand spit at 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 could not be used for interpretation because of many errors possibly from incomplete (break down) of the selected quartz grain.
Abbreviations: U, uranium; Th, thorium; K, potassium; W, water; AD, annual dose; ED, equivalent dose; OSL, optically stimulated luminescence.

equation 1. The OSL ages indicated that the paleo-sand spit at Chanthaburi began to form 17,210±1280 years ago (SP-12) and stopped forming around 1,370±200 years ago (SP-2) (Table 1). The general trend indicated that all 12 units of sand spit ages displayed a decreasing trend as expected for the migration of spit in the southeastward direction. However, sand spit samples SP-3, SP-4, and SP-7 through SP-9 are of very similar ages and essentially contemporaneous because of the overlapping error ranges. Very close OSL ages were also obtained from sand spit samples SP-9 and SP-10.

In addition, according to the distance between each unit of sand spit with the implement by OSL dates evaluated in this study, the rate of sand spit deposition and migration can be contributed. According to progradation rates estimated from this study, the rate of sand spit can be divided into three phases. First, the initial phase when the sand spreads moderately around 0.25-0.45 m/year at around 6,300 years (from sand spit samples SP-2 through SP-6). Second, during the formation of the spit, samples SP-7 and SP-8 showed OSL dates that were short and similar at 410 years (cal. 8390-7980 years). The calculated rate of the sand spit spread was a more rapid rate up to around 1.80 m/year. Finally, during the formation of spit samples SP-10 to SP-12, the spit migration rate decreased down to 0.2-0.50 m/year. In summary, the average rate of paleo-sand spit deposition from Chanthaburi was estimated at around 60 cm/year throughout 16,800 years for the period of 1,370±200 to 17,210±1280 years. However, we interpreted two OSL age results from SP-11 and SP-12 that might be reworked and preserved the age of original alluvial sources because the paleo-shoreline around 12,000-17,000 years ago was located several meters below the present mean sea level.

4.2 OSL ages of the beach ridge plain from the SRY

At the southern part of the Pran Buri area, two transect lines were designed (Figure 4). The OSL date from the first transect provided the age of the innermost beach ridge up to 10,200 years ago where the sample was collected 300 m away from the recent shoreline. The maximum age of the beach ridge in the second transect was 9,610 years in the place where the sample was picked up 470 m away from the present shoreline. At the northern part of the Pran Buri area, the age of the beach ridge from the first transect was 7,650 years from the ridge located 750 m away from the recent shoreline. The age of the beach ridge from the second transect was 6,510 years from the ridge located 940 m inland from recent shoreline (Table 2).

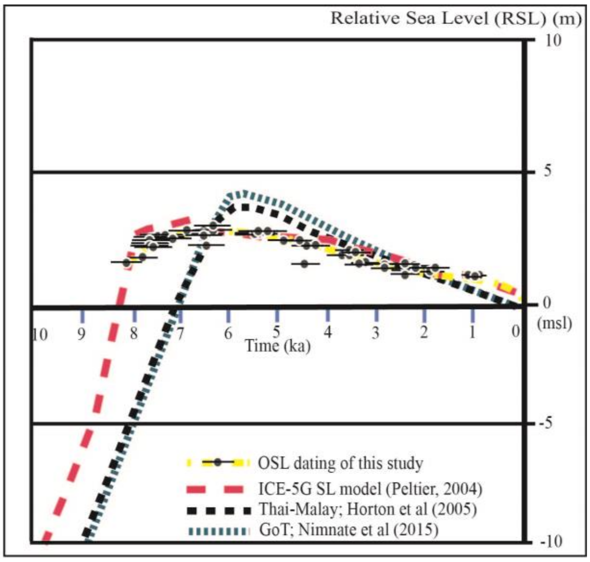

Figure 4. Plot of OSL datings in comparison with sea level curve from Chumphon, Gulf of Thailand beach ridge plains and paleo-sand spit (Nimnate *et al.*, 2015), Thai-Malay peninsula (Horton *et al.*, 2005) and ICE-5G sea level model (Peltier, 2004).

At the SRY area, the OSL samples were collected from 4 transects. The first transect was located at the northernmost part. The OSL date provided the age of the beach ridge at 6,260 years located 1,450 m away from recent shoreline. At the second transect, the age of 4,650 years was detected from the ridge located 1,900 m from the recent

Table 2. OSL dating results from the beach ridge plain at 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

Abbreviations: U, uranium; Th, thorium; K, potassium; W, water; AD, annual dose; ED, equivalent dose; OSL, optically stimulated luminescence.

shoreline. The beach ridge at the third transect showed the age up to 5,290 years 1,800 m away from recent shoreline. At the southernmost final transect, the age of the ridge was 5,140 years where it is located 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 account for the sea level discussion because they were probably reworked and preserved the older age from the original sources of sand.

At Kui Buri, the OSL dating was carried out from 3 transects. At the first transect, the age was 7,860 years dated from the ridge located 1,070 m away from the recent shoreline. The beach ridge at the second transect provided an age of 7,810 years at 1,350 m from the recent shoreline. The third transect provided an age of 6,890 years from the ridge located 1,700 m away from recent shoreline (Table 4).

Based on the obtained OSL age dating coupled with the aerial photograph interpretations from Pran Buri, the paleo-environment was an open sea from 10,000-2,000 years ago. The ridge and swale (former beach ridge plain) were formed 2,000 to 1,000 years ago. At the SRY area, the paleo-environment was a semi-enclosed bay 6,500-2,000 years ago. Pran Buri and SRY, ridge and swale from Kui Buri were formed 2,000 to 1,000 years ago. The coastal plain at Kui Buri formed as a bay shape that was connected to the open sea 8,000-2,000 years ago. The tidal flat formed extensively 2,000 to 1,000 years ago, and thereafter the former and recent beach ridge and swale were formed.

Table 3. OSL dating results from the beach ridge plain at Sam Roi Yot National Park.

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

Abbreviations: U, uranium; Th, thorium; K, potassium; W, water; AD, annual dose; ED, equivalent dose; OSL, optically stimulated luminescence.

Table 4. OSL dating results from the beach ridge plain at 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

Abbreviations: U, uranium; Th, thorium; K, potassium; W, water; AD, annual dose; ED, equivalent dose; OSL, optically stimulated luminescence.

4.3 Implication for sea level history

The evolution of SRY, Pran Buri, and Kui Buri coastal plain at the western part of the Gulf of Thailand is comparatively equivalent with the evolution of paleo-sand spit from the eastern side of the gulf in terms of temporal progradation. The results of the OSL datings confirmed that the paleo-environment from both sides of the Gulf of Thailand was once an open sea during the late Pleistocene. However, the age of the coastal plain development was somewhat different from place to place. At Chanthaburi, the sand spit showed a series of continuous curved ridge formations from the late Pleistocene to late Holocene, whereas the west coast of the gulf mostly preserved the record of the middle Holocene highstand. Only the maximum age of the beach ridge at Pran Buri provided an age of 10,200 years which comparatively corresponded with the age of the late Pleistocene marine transgression. It suggested a very rare preservation of the transgressive beach ridge. Most of the beach ridge at the SRY gave a maximum age of 6,260 years which suggested the age of the highstand. Similarly, the beach ridge at Kui Buri provided an age of 7,860 years which can be related to the highstand as well. All of the OSL datings were plotted into a sea level curve and the results showed that the ages seemed likely equivalent with the sea level curve from the ICE 5G SL model (Peltier, 2004). However, the altitude of the highstand level during the middle Holocene from this study was somewhat different from the beach ridge plain and paleo-sand pit at the Chumphon estuary and Thai-Malay peninsula where Nimnate, Chutakositkanon, Choowong, Pailoplee, & Phantuwongraj, (2015) and Horton *et al.* (2005) reported the age of the highstand of about 6,500 years and the highstand was about 4 m above the present sea level.

Interestingly, the OSL results showed that the late Pleistocene beach ridges observed at Chanthaburi were likely formed as a strandline in a very limited environment for a strandplain to be developed. Therefore, this strandline is likely to be the only evidence of a Pleistocene beach ridge in the upper Gulf of Thailand. The absence of the late Pleistocene beach ridges elsewhere along the coast of the upper Gulf of Thailand 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 a small scale barrier system around the SRY coastal plain (Surakiatchai, 2005) was the additional reason to confirm the environment of this coastal plain. However, anomalous 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 the baymouth spit. The baymouth bar 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.

5. Conclusions

This study showed that OSL chronology can be used to calculate the rate of spit and beach ridge deposition for further discussions on the history of sea level change and coastal evolution history at the upper Gulf of Thailand. This OSL age dating technique is suitable for a beach ridge where organic materials (peat, charcoal) are rare or not available. In this study, the uncertainty of OSL dating is approximately less than 10% which is acceptable for a beach ridge plain. Although, the method is acceptable, the discussion on age results from OSL may contain complications because the samples possibly did not preserve the real age of the latest deposition or they were reworked.

We recognized that the paleo-sand spit was located about 15 km further inland from the present shoreline at Chanthaburi at the eastern part of the Gulf of Thailand. The OSL dating from this spit provided ages that ranged from the late Pleistocene to late Holocene. The spit itself has significant evidence of paleo-shoreline and the continuous formation through the Holocene can tell us the episodic evolution quite clearly. The results of OSL dating from the spit in the eastern part and beach ridge plain in the western part of the Gulf of Thailand showed that the paleo-shoreline was located far inland from the present-day shoreline during late Pleistocene and early Holocene.

At the Chanthaburi paleo-sand spit, the dates revealed that it developed from 17,210±1280 to 1,370±200 years ago. Combining the OSL ages with the number of sand spits and the distance from each dated spitting ridge, we derived an average lateral migration rate of 0.6 m/year (sand spit samples SP-2 through SP-12). The OSL age of the beach ridge plain from the SRY that started from 10,200 to 880 years ago provided the rate of eastward progradation of 0.4-22 m/year. The OSL dating can be applied as one step in developing a better understanding of coastal evolution particularly in places where the beach ridges were formed as a spit and beach ridge plain. Further work is needed to constrain the dates by other scientific methods if samples are available.

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