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Remnant of the Late Holocene sand beach reveals ancient settlement-related sea level change from western Thailand

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Abstract: Archaeological findings and analysis of the sand beach at the Ban Khu Bua site in western Thailand indicate substantial sea-level shifts, which relate to sea-level regression during the late Holocene. This research focused on analyzing the paleo-shoreline and determining the age of ancient sandy beach deposits. Satellite imagery (Sentinel-2A) taken in 2021 facilitated classification of the paleo-coastal landforms into four main categories: colluvium, recent floodplain, old tidal flat, and old sandy beach. The latter, running predominantly north to south, is composed of fine to very fine sand characterized by sub-angular to round shapes, high sphericity, and well sorted. The sediment's mineral composition is primarily quartz, accompanied by smaller rock fragments, organic matter, heavy minerals, and feldspars. Optically Stimulated Luminescence analysis of quartz-rich samples from the inner and outer areas suggested deposition of the old sandy beach sediments between 1,500 and 3,000 years ago in the inner part, pre-dating the establishment of the Khu Bua community in the Dvaravati period. Continuous beach sand deposition along Thao U-Thong Road aligns with the community settlement approximately 200 to 1,000 years ago.

Keywords: Old sandy beach, OSL dating, sea-level change, Khu Bua, Ratchaburi

INTRODUCTION

The evolution of the low-lying plain of Thailand is attributed to global sea-level changes over the late Quaternary. Detailed studies of low-lying coastal regions have been related and often initiated in response to natural disasters, such as coastal erosion, storm surges, flooding, and by archaeological research (Surakiatchai *et al*., 2019). The Lower Central Plain, where major cities are currently situated, stands out as a notable example of an area vulnerable to coastal-related challenges (Nutalaya & Rau, 1981; Supajanya, 1981, 1983; Chonglakmani *et al*., 1983; Sinsakul, 1992; Choowong, 2002a).

Examination of geological features and landforms (Choowong *et al*., 2002b; Nimnate *et al*., 2015; Surakiatchai *et al*., 2019; Polwichai *et al*., 2023) and paleontology studies can help identify the indicators of past sea-level changes (Choowong *et al*., 2004). Archaeological evidence, particularly artifacts discovered near ancient communities along paleo-shorelines, such as boats, anchors, masts, and tools, (Supajanya, 1983; Hutangkura, T., 2014) and the integration of archaeological findings with past aerial photo records, where available, provides a comprehensive understanding of the history of sea-level changes in the central plain of Thailand (Choowong, 2002b; 2011).

The Dvaravati period refers to a historical era in Southeast Asia, spanning the 6th to the 11th century AD, 1,000 to 1,500 years ago. Among the Dvaravati ancient towns, Khu Bua in Ratchaburi Province, western Thailand, is one of 21 ancient communities situated along the paleo-shoreline in the central plain of Thailand, at elevations ranging from about 2 to 3.5 m above mean sea level (MSL) (Supajanya, 1981). In 1961, the Department of Fine Arts of Thailand excavated the Dvaravati site of Khu Bua, located about 18 km south of Ratchaburi Province (Figure 2a). The digital elevation model showed the distribution of ancient towns near the shoreline, such as Khok Sethi (1), Khu Bua (2), Nakhon Pathom (3), Khok Panom Dee (4), and Sri Mahosot (5) (Figure 1a). The locations of these ancient communities hold significant

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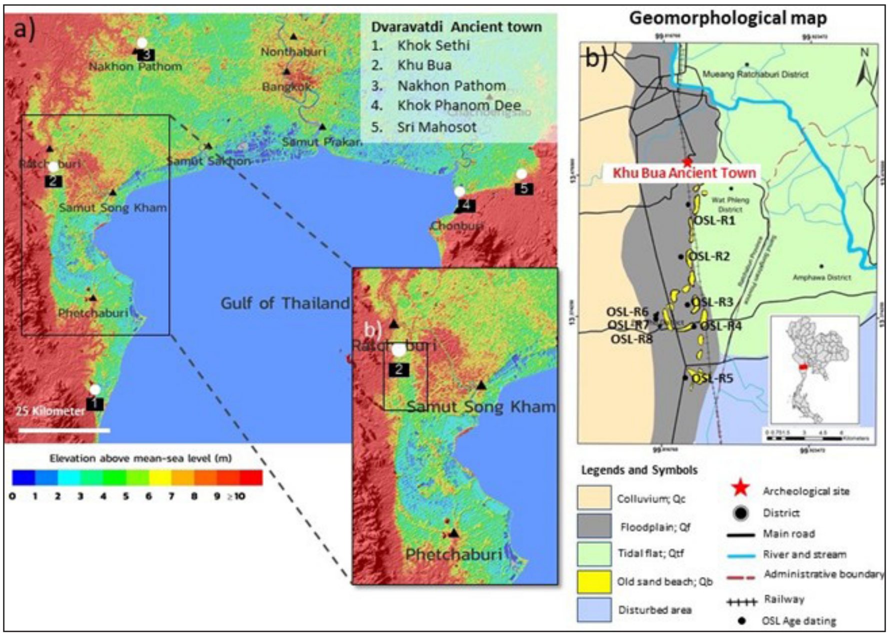

Figure 1: (a) A Digital Elevation Model along the Gulf of Thailand show the distribution of some ancient communities that are situated along the paleo-shoreline in the central plain of Thailand and (b) a geomorphological map, interpreted from Sentinel-2A imagery captured in 2021. The yellow areas on the map in (b) indicate the location of the old sandy beaches near the Khu Bua archaeological site.

clues about the sea-level changes in the lower Central Plain of Thailand.

To gain a deeper comprehension of the geological record concerning the rise and fall of the sea level, a combination of ancient landforms, sedimentological data, and radiometric dating techniques, such as radiocarbon dating, have emerged as indispensable sources of information for reconstructing the history of sea-level fluctuations (Choowong, 2011; Williams *et al*., 2016; Surakiatchai *et al*., 2019). However, Optically Stimulated Luminescence (OSL) analysis stands out as a robust method for dating Quaternary marine coastal features and landforms (Lamothe, 2016). When coupled with precise elevation measurements of each beach ridge and the provision of reliable dating outcomes, OSL analysis allows for the reliable dating of beach progradation. It also serves as a proxy for sea-level variations offering insights directly linked to sediment deposition at that time (Karpytchev, 1993).

OSL dating can determine the depositional age of quartz-rich sediments that were exposed to sunlight, covering a period ranging from several months to approximately 150,000 years ago (Murray & Wintle, 2000; Murray & Olley, 2002). Consequently, numerous studies on coastal sandy sediments have employed OSL dating. These include the dating of beach dune sequences in Australia (Banerjee *et al*., 2003), marine terrace sediments in Korea (Choi *et al*., 2003), beach ridge plains in Denmark (Nielsen *et al*., 2006), paleo shorelines in Tibet (Lee *et al*., 2009), coastal barrier spits in Germany (Reimann *et al*., 2010), and coastal dune and beach ridge deposits in Thailand (Nimnate *et al*., 2015; Surakiatchai *et al*., 2019; Miocic *et al*., 2022).

To understand how the ancient coastline in western Thailand evolved during the Dvaravati period, we undertook a chronological study of old sandy beach sediments in Ratchaburi Province to establish when they were deposited. These age determinations are crucial for estimating how regional sea levels changed when these old sandy beaches were forming. We also examined the physical characteristics of these beach sediments and shell fossils to give insights into the conditions and environments in which they were deposited, enhancing our comprehension of the paleo-shoreline and sea-level fluctuations linked to the ancient town in Ratchaburi Province.

MATERIALS AND METHODS

Study area and sampling location

Based on a detailed remote sensing interpretation (see Figure 1a) from the satellite image, a geomorphic map (Figure 1b) of this area was created to plan the sampling locations (OSL-R1 to -R8) to obtain evidence of sea-level changes, possibly delineating a single beach ridge (yellow color in Figure 1b). From the derived geomorphic map, four geomorphologic landforms were identified: colluvium, floodplain, tidal flat, and an old sand beach that was deposited along the Thao U-Thong Road.

The old sandy beach in Ratchaburi Province consists of a single discontinuous ridge (shown in yellow in Figure 1b), apart from associated tidal flat deposits (green in Figure 1b). This beach ridge is located about 20 km landwards from the present-day shoreline and in general is slightly discontinuous, curves in a north-south (N-S) direction, and is concave towards the sea (see Figure 1b). Five samples were collected along the Thao U-Thong Road, where the beach is located, and also from the rear of the paleo-beach, representing the innermost shoreline or boundary of sea-level incursion.

Sedimentological data

During field investigations, sedimentological observations encompassing parameters such as color (both sediment and mottling patterns), texture, concretions, fossil content, and contact boundaries were made. Observations were based on boreholes (Figure 2c and 2d) and sedimentary profiles (Figure 2b). Each layer of the ancient beach sand sediment from seven boreholes was subjected to grain size analysis. Physical characteristics of sand grains, including attributes such as roundness, sphericity, and sorting, were meticulously examined with the aid of a binocular microscope (Figure 2d). The percentage composition was estimated by comparison with the standard chart of sediment composition (Compton, 1962). Statistical values for grain size distribution were calculated using the graphic method of Folk & Ward (1957). Grain-size distributions are generally characterized by four principal parameters: the average grain size (mean); the spread of the sizes around the average (sorting); the symmetry or preferential spread to one side of the average (skewness); and the degree of concentration of the grains relative to the average (kurtosis).

The classification of roundness and sphericity follows Powers (1953). Through the sedimentological data, researchers have the geological data and characteristics of the ancient sandy beach in Ratchaburi Province.

Dating by OSL analysis

The period between the last sediment deposition (exposure to sunlight) and the current date can be determined through OSL dating, employing Equation (1) (Aitken, 1982):

Figure 2: Representative field investigations include (a) The Main Monument of Khu Bua Ancient Town and complete shell fragments found near the base of the monument during the excavation of this site. (b) A quarry near Ancient Monument No. 23-24, displaying biological evidence of marine regression, such as complete marine shells, a very thin oyster fragment bed (1–2 cm thick), calcrete nodules, and gypsum crystals. (c) A bird's-eye view of the old beach sand and the location of OSL-R6. (d) OSL-R2: Sedimentary texture and mineral composition observed under a microscope (left), and De (total absorbed radiation dose) age sampling taken from around 25 cm below the surface (right).

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

where the equivalent dose (ED; measured in Gy) is derived from the luminescence emitted during the OSL analysis of the sample, while the dose rate or annual dose (AD; expressed in Gy/Ka) is based on the concentration of three prevalent natural radioisotopes [uranium (U), thorium (Th), and potassium (K)] and the water content in the surrounding environment.

In the sample collection process, each sample (denoted as OSL1–5 in Figure 1) was divided into two portions and utilized to assess (i) the ED and (ii) the AD, which also included determining the water content. For ED sampling, the uppermost soil layer was removed, and excavation was conducted until the quartz-rich sediment representing the beach ridge became exposed (typically at a depth of approximately 30–50 cm; see in Figure 2d right). After creating a light-protected environment, the surface of the sediment profile was removed to prevent current exposure to sunlight. Subsequently, the quartz-rich sediment was collected following its lamination and bedding. To prevent any leakage of the ED signal, the samples were carefully placed in plastic tubes, promptly sealed to retain moisture, and then stored in lightproof plastic bags. Additionally, sand samples were collected at a 30-cm depth surrounding the ED sampling location and were utilized for measuring AD.

Determination of ED

For each ED sample from OSL-R1 to OSL-R8, quartz enrichment was carried out following established procedures (Takashima & Honda, 1989; Surakiatchai *et al*., 2019). Initially, a wet sieve with mesh sizes ranging from 60 to 200 was utilized to recover fine to very fine-grained sands within the diameter range of 74–250 µm. Subsequently, hydrochloric acid was employed to etch the sample, removing any carbonate components. Then, hydrofluoric acid was applied to eliminate potential feldspar contamination in the sample. The sample was subsequently washed with distilled water and dried at 100 °C. Finally, ferro minerals were separated using an iso-dynamic magnetic separator.

The ED measurements were conducted using a Risø TL/OSL reader located at the Department of Geology, Faculty of Science, Chulalongkorn University, Thailand. Each measurement involved a calibrated $^{90}Sr/^{90}Y$ beta radiation source and a blue light source (470–720 nm) (Bøtter-Jensen, 1997; Bøtter-Jensen *et al*., 2000). A detection filter with a diameter of 7.5 mm (Hoya U340) was employed for the OSL measurements, and the sample was preheated to 220 °C at a rate of 5 °C/s. Prepared quartz grains were affixed to a stainless-steel disc with a diameter of 9.8 mm using silicone oil. A single aliquot regenerative technique was used to assess all equivalent doses (Readhead, 1987; Murray & Olley, 2002). A fixed test dose of 10% of the natural dose was administered to account for any sensitivity changes. The resulting OSL-R1 and OSL-R6 decay curve for the respective OSL samples are illustrated in Figure 4a, and the OSL growth curve for each aliquot was derived based on this known artificial irradiation (Figure 4b). Subsequently, the ED was calculated for each aliquot of the sample following the SAR protocol.

For analysis of the ED datasets, four different age models were applied conceptually: (i) the central or average age model, (ii) the common age model, (iii) the minimum age model, and (iv) the finite mixture model (Takashima & Honda, 1989). The ED distribution and statistical parameters for the eight samples are depicted in Figure 5. The overdispersion (OD) value for OSL-R1 to -R8 was calculated and used to select the appropriate model (Duller, 2008; Liang, 2019). Specifically, if the OD value exceeded 0.25, the minimum age model was selected, and if it was less than 0.25 the average age model was used instead. The resulting OSL ages employed in this study are highlighted in bold font in Table 1 within the columns labeled “Age min” and “Avg age (y)”.

Determination of AD

A 300-g portion of the obtained grains (diameter < 90 mm) was dried and then packed in a plastic vessel for AD determination. As water aborbs part of the radiation, the water content was measured during this process. The concentrations of U (ppm), Th (ppm), and K (%) were measured by high-resolution gamma spectrometry (Table 1). Based on the measured concentrations of these three radionuclides and the water content, the AD values of each sample were calculated according to the standard table, including the calculated cosmic ray dose rate (Bell, 1979; Prescott & Hutton, 1994). The obtained AD value was corrected based on attenuation due to grain size distribution and water content (Aitken, 1982). The AD of each sample and error calculation were calculated as previously reported (Singh *et al*., 2017) and are summarized in Table 1.

Based on the obtained ED and AD of each sample, the OSL dates representing the last deposition of the sandy beach (OSL-R1 to -8 in Figures 4 and 5) were calculated and presented in Table 1.

RESULTS AND DISCUSSION

Physical characteristics of the beach sand in Ratchaburi

A comparison was made between the sediments of the straight main beach segment and the sediments of the curved segment, which lies up to 1 km to the west of the straight segment, of the old sandy beach (Figure 1b). The curved beach segment (OSL-R6 to -R8) shows

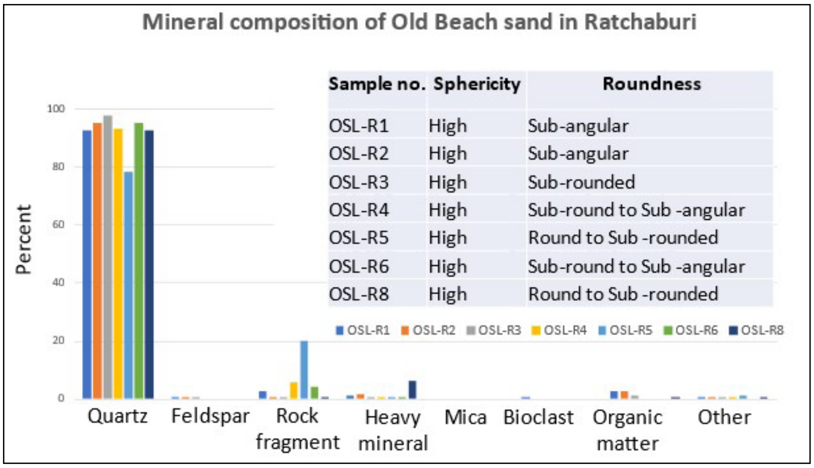

Figure 3: The mineral composition of five old sandy beach sediments revealed quartz as the major component in all samples, with minor constituents being rock fragments, organic matter, heavy minerals, and feldspar. Sand grains in these samples have high sphericity and roundness, and range between sub-angular to rounded.

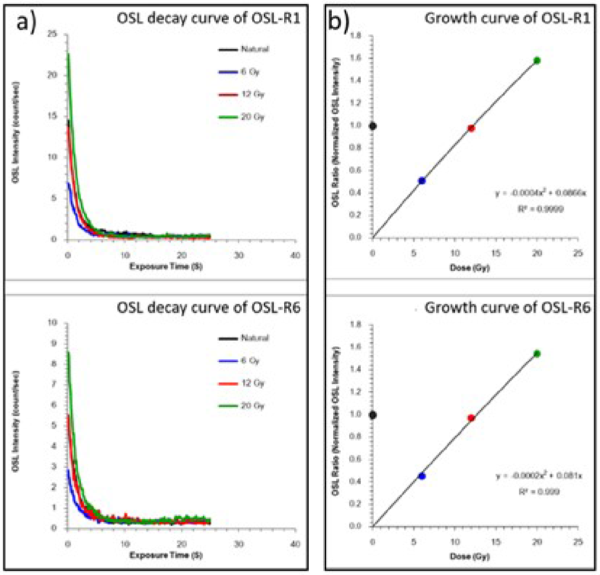

Figure 4: Representative OSL data, including: (a) decay curves and (b) growth curves of old sandy beach samples OSL-R4 and OSL-R6, where 'N' represents the natural dose (in black dots), and 'Single' (in blue dots), 'Double' (in red dots), and 'Triple' regenerative doses (in green dots), respectively.

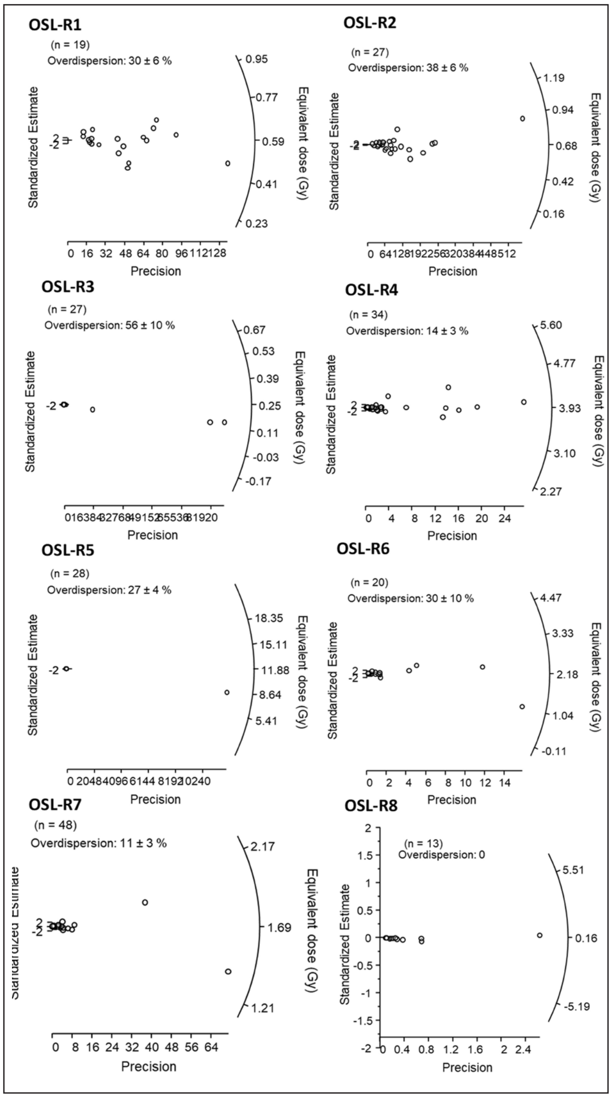

Figure 5: Radial plots illustrating the Equivalent Dose (ED) distributions for the eight old sandy beach samples, represented by white circles. Overdispersion (OD) was employed to determine the minimum or average age that best suited each sample.

coarse to very fine sand with a sub-round to round shape, high sphericity, and well to poorly sorted (Figure 2d left). The main part of the old sandy beach that is orientated in the N-S direction was mainly comprised of medium to fine-grained sand, moderately to poorly sorted, sub-angular to sub-rounded and high sphericity (Figure 3). The characteristics of the old sandy beach sediment is related to sea-level change from the Gulf of Thailand (GOT) shows very fine to coarse sand with a wide range of grain size depending on the source of the quartz grains: medium to coarse-grained sand from granite in Surat Thani (Polwichai *et al*., 2023), and very fine to medium-grained sand with high sphericity eroded from sedimentary rock and deposited as old beach ridges in the Chumphon area (Nimnate *et al*., 2015).

Table 1: The OSL-derived ages pertain to the old sandy beach sediments collected from Bore hole no. OSL-R1 to OSL-R8.

Samples	Lat (°N)	Long (°E)	Dists (km)	Elev (m)	Depth (m)	U (ppm)	Th (ppm)	K (%)	Moist (%)	Dose rate (Gy/Ka)	De Min (Gy)	De Avg (Gy)	Age min (year)	Age avr (year)
OSL-R1	13.46	99.84	1.95	3.20	0.40	1.18± 0.01	5.88± 0.07	0.56± 0.57	6.43	4.32± 0.03	0.54± 0.04	0.40± 0.12	**410 ± 12**	590 ± 4
OSL-R2	13.42	99.83	20.38	3.40	0.25	1.09± 0.01	5.70± 0.08	0.64± 0.60	11.36	4.14± 0.03	0.62± 0.05	0.68± 0.26	**430 ± 14**	470 ± 23
OSL-R3	13.39	99.84	16.93	2.70	0.25	1.25± 0.01	6.24± 0.08	0.25± 0.25	16.66	3.56± 0.03	0.24± 0.02	0.25± 0.14	**190 ± 5**	200 ± 13
OSL-R4	13.22	99.50	15.78	2.00	0.95	1.35± 0.01	6.02± 0.05	0.72± 0.25	21.88	0.37± 0.03	0.10± 0.04	0.16± 1.25	140 ± 5	**230 ± 1.77**
OSL-R5	13.33	99.84	13.33	3.40	0.45	1.33± 0.01	7.46± 0.05	0.66± 0.003	5.80	1.43± 0.03	1.66± 0.07	1.69± 0.48	9,900 ± 4	**1,010 ± 29**
OSL-R6	13.22	99.49	18.82	3.90	0.45	0.74± 0.01	3.79± 0.06	0.08± 0.003	5.59	0.45± 0.03	1.17± 0.14	2.18± 1.14	**1,520 ±20**	2,830 ± 1,490
OSL-R7	13.37	99.83	15.25	4.00	0.70	2.40± 0.02	14.12 ± 0.12	0.95± 0.95	24.25	7.49± 0.03	6.94± 0.14	11.88± 3.24	**3,130 ± 82**	5,360 ± 200
OSL-R8	18.49	99.49	18.49	4.40	0.35	0.76± 0.01	3.36± 0.05	0.09± 0.003	15.88	0.17± 0.03	3.73± 0.11	3.93± 0.83	2,600 ± 9	**2,740 ± 38**

Lat : Latitude. Long : Longitude. Dists : distance to the shore. De : total absorbed radiation dose.

The mineral composition of the old sandy beach sediments was predominantly quartz (more than 95%), with smaller proportions of rock fragments (4.8%), heavy minerals (1.5%), and feldspars (0.1%) (Figure 3). The old sandy beach was found at a depth of approximately 25–40 cm. The provenance of sediment originates from sandstones of the Carboniferous age in the northwestern part of the study area around 3 km away.

Age of the sandy beach deposits related to the Khu Bua archeological site

According to the derived OSL dates, the age of samples OSL-R1 to -R9 show a diverse distribution of OD values (Figure 5), which were used to determine the minimum or average age of each sample (Table 1). The old beach sands (samples OSL-R1 to -R5) suggest that the inner sandy beach sediments were deposited between approximately 3,130 ± 82 years ago for OSL-R7 to 1,520 ± 20 years ago for OSL-R6 and formed a curved beach (Figure 6 at OSL-R6 to -R8). Subsequently, the outer sandy beach sediments were deposited within a range of approximately 190 ± 5 years ago for sample OSL-R3 to 1,010 ± 29 years ago for OSL-R5 and formed a straight beach along the Thao U-Thong Road in a N-S direction, as indicated on the geomorphological map (Figure 6). The innermost inner beach ridge also suggests a high sea-level stand during the Dvaravati period (1,000–1,500 years ago), characterized by a curved beach. The deposition transitioned to a narrow, elongated beach southwards from the Ban Khu Bua Archaeological site.

Evidence for a period of regression is derived from archaeological findings at the base of the main monument, where shell fragments were discovered (Figure 2a). This could indicate that sea levels fell significantly after reached far inland during mid-Holocene, although no direct evidence of a beach was found for that time period. Two main beach deposition phases were evident: one occurring between 3,100 and 1,500 years ago for the curved beach and the other between 190 and 1,000 years ago for the straight beach in a N-S trend (Figure 6). Deposition of beach sands ceased during this time, transitioning to clay-rich sediments influenced by tides in the vicinity of Ancient remains No. 24 and 25, where a very thin shell bed (1–2 cm thick) was discovered (white dash-line in Figure 2b). Moreover, complete marine shells, such as gastropods and bivalves, were found (Figure 2b). Furthermore, the presence of gypsum crystals (Selenite) and calcrete nodules in a zone approximately 5 m thick along the shell bed, provides evidence of past seawater incursion and the subsequent crystallization of evaporite minerals in high evaporative conditions along coastal tidal flat depositional environment and very shallow strand-line lagoonal accumulation (the early stages of many ancient marine evaporite deposits) (Hardie & Eugster, 2006). This type of mineral deposit is commonly also found in coastal salt works (evaporative Salinas) and some natural coastal lakes where gypsum has either precipitated recently or in the past (Babel, 1986). In Ratchaburi Province, a narrow beach deposit is evident, situated along the main rural road (Thao U-Thong Road) and dating back to approximately 1,000 years ago, coinciding with the establishment of the ancient community. The maximum age of the beach ridges (paleo-shoreline) was determined to be 3,130 ± 82 years ago at an elevation of 4 m above MSL from the location where sample OSL-7 was collected, approximately 15.25 km perpendicular to the present shoreline (Figure 6).

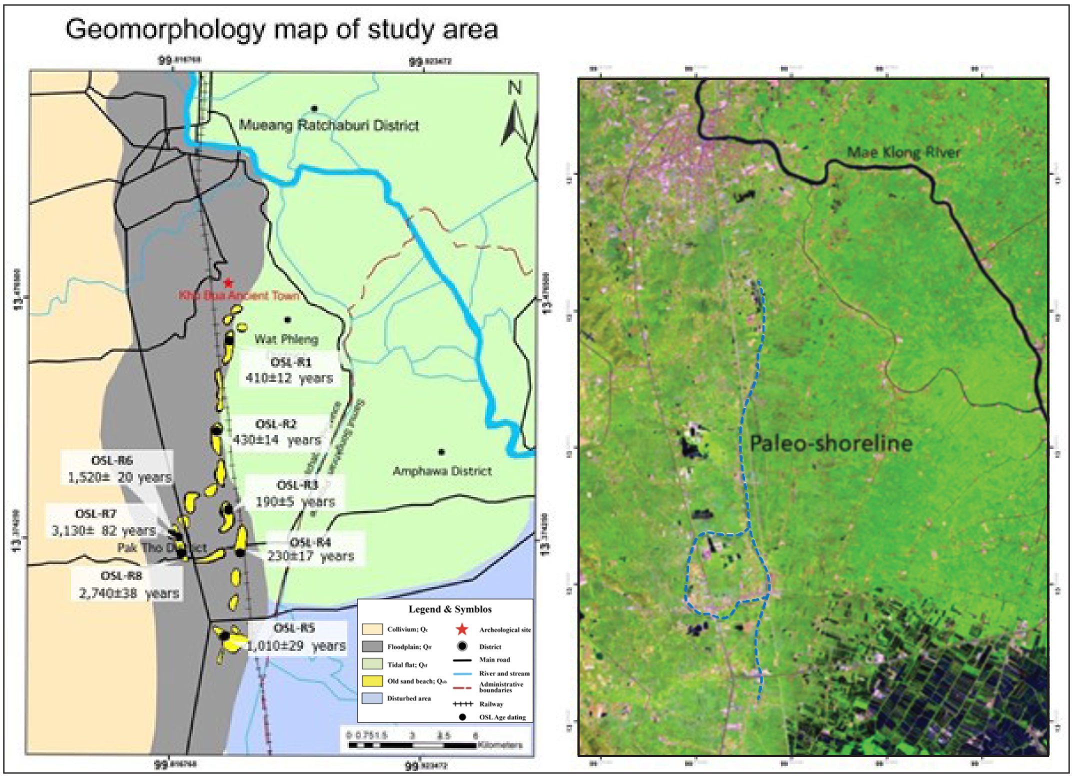

Figure 6: The age of the old beach sand deposit resulting from sea-level regression ranges from approximately 1,500 to 3,000 years ago in the inner part (3.9–4.4 m above MSL in OSL-R6 to OSL-R8) to about 200 to 1,000 years ago along Tow U-Thong Road (2.0–3.4 m above MSL), as observed at locations OSL-R1 to OSL-R4. Satellite images (infrared) reveal a paleo-shoreline (indicated by blue dashed lines) in Ratchaburi Province.

Sea-level evolution in Ratchaburi Province, western Thailand

During the Holocene Epoch, the lower central plain of Thailand experienced inundation by seawater, resulting in the deposition of old tidal flat sediments in this region (green color in Figure 6). Various types of beach deposits, including inner curved beaches and long, narrow beach formations along the Thao U-Thong Road (yellow color in Figure 6), were formed during regression periods. The sedimentation of tidal flat sediments near Ancient remains No. 24 and 25 in Ratchaburi Province is supported from the evidence of a shell bed in the clay layer. Beach sediment deposition occurred in a N-S direction, extending from the west of the present shoreline. These paleo beach ridges are characterized by slightly curved formations and continue into adjacent provinces, such as Bangkok, Samut Sakorn, Samut Prakan, and Samut Songkram (Hutangkura, 2014).

Furthermore, the age determination of beach deposits along the west coast of the GOT predominantly revealed the historical record of Dvaravati ancient communities that once existed along the coastline in the lower central plain. These communities include the Nakhon Pathom Ancient Town in Nakhon Prathom Province, U-Thong Ancient Town in Suphanburi Province, Lopburi Ancient town in Lopburi Province, Kid Kin Ancient Town in Saraburi Province, and Sri Mahosot Ancient town in Prachinburi Province. These ancient settlements share a similar age range, dating back to approximately 2,000 to 3,000 years ago (Hutangkura, 2014).

CONCLUSIONS

This study provides new findings in the history of sea level change using chronological (OSL dating) and archaeological evidence from the western part of the Central Plain of Thailand where the ancient shoreline is likely located far inland. The application of OSL dating to determine the ages of young Holocene beach sediments that relate the regression of sea level in the late Holocene Epoch within the coastal region of Ratchaburi Province. Eight samples were collected from Muang to Pak Tho Districts, covering the transition from older small curved beaches to the development of an extensive long beach sand system. The OSL dating technique, following the Single Aliquot Regenerative protocol, was applied to coarse-grained quartz.

In summary, the OSL dating results of the old beach sands provide valuable insights into the historical sea-level changes in the western part of the Central Plain of Thailand. The findings from OSL dating confirm the sea-level regression or stillstand during this period as suggested by Surakiatchai *et al*. (2018), followed by a subsequent regression towards the east, coinciding with the deposition of long beach sediments around 1,000 years ago. Subsequently, tidal flat sediments began forming 200 years ago towards the east, following the settlement of ancient communities in the area. Eventually, the environment transitioned into the present-day floodplain of the Mae Klong River due to sea-level regression to its current position. During the Dvaravati period, the paleo-shoreline related to the Khu Bua archaeological site was situated in an almost north-south orientation, at an elevation of approximately 2–3.4 m above MSL. This evidence is primarily derived from the presence of old beach sands, with a significant concentration along the Tow U-Thong Road. In other areas, such as the pit near Ancient remains No. 24 and 25 on the eastern side, the deposits primarily consist of tidal flat and mangrove sediments. This aligns with previous research that has suggested the paleo-shoreline throughout the Holocene period was characterized by a strip of mangrove ecology near the Khu Bua Archeological site (Hutangkura, 2014).

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AUTHORS CONTRIBUTION

PN, SS, SW – conceptualization, experiment design, collecting sample and laboratory analysis; PN – writing, review and editing manuscript.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the effort reported in this paper.

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