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การกำหนดอายุด้วยวิธีลูมิเนสเซนส์ของตะกอนชายฝั่งจังหวัดสงขลาในปลายยุคควอเทอร์นารี ประเทศไทย

Optically Stimulated Luminescence Dating Revealed the Late Quaternary Coastal Sediments in Songkhla Coast, Thailand

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บทคัดย่อ

วัตถุประสงค์และที่มา : ตะกอนชายฝั่งตามแนวชายฝั่งจังหวัดสงขลายังคงขาดข้อมูลลำดับเหตุการณ์ทางธรณีวิทยาที่จำเป็นในการอธิบายวิวัฒนาการของชายฝั่ง ในการศึกษาครั้งนี้จึงมีวัตถุประสงค์เพื่อกำหนดอายุของตะกอนชายฝั่งทางฝั่งทะเลสาบสงขลา เพื่อใช้เป็นการศึกษาเบื้องต้นในการก่อตัวของทะเลสาบสงขลา

วิธีดำเนินการวิจัย : ศึกษาพิกัดทางภูมิศาสตร์และและความสูงจากระดับน้ำทะเลเพื่อสร้างแผนที่ภูมิประเทศ โดยระบบเครือข่ายการรังวัดด้วยดาวเทียมแบบจลน์ (The Global Navigation Satellite System with the real-time kinematic, RTK GNSS network) และใช้ท่อพีวีซี (PVC) ทึบแสงในการเก็บตัวอย่างตะกอนจากสันทรายชุดเก่าและที่ราบหลังสันทราย เพื่อนำไปกำหนดอายุของชายฝั่งด้วยวิธีลูมิเนสเซนส์ (Optically-stimulated luminescence, OSL) และเทคนิค Single aliquot regenerative dose (SAR).

ผลการวิจัย : จากการศึกษาด้วยระบบรังวัดแบบจลน์และการทำแผนที่ภูมิประเทศพบว่ามีสันทรายชุดเก่าสองชุดและที่ราบหลังสันทราย ซึ่งมีอายุ 10,000, 30,500 และ 39,200 ปี และมีตัวอย่างตะกอนที่อายุเกินกว่าเทคนิคสามารถตรวจวัดได้

สรุปผลการวิจัย : การกำหนดอายุด้วย Quartz OSL ให้ผลสรุปว่าสันทรายชุดในสุดและที่ราบหลังสันทรายมีอายุในช่วง 30,000-40,000 ปีก่อน ซึ่งเป็นช่วงที่มีสภาพอากาศแบบชื้นก่อนที่สภาพอากาศจะแห้งแล้งและหนาวจัดขึ้นในปลายยุคน้ำแข็งครั้งล่าสุด (late glacial maximum) ในขณะที่ที่ราบหลังสันทรายชุดนอกเป็นตะกอนชายฝั่งที่อายุน้อยที่สุดมีอายุราว 10,000 ปีก่อน เกิดขึ้นเมื่อระดับน้ำทะเลสูงขึ้นในช่วงต้นสมัยโฮโลซีน (Holocene) หลังจากนั้นชายฝั่งทะเลสาบสงขลาปรากฏเพียงตะกอนที่ราบน้ำทะเลขึ้นถึงเท่านั้น อย่างไรก็ตามผลของการกำหนดอายุตะกอนพบช่วงเวลาที่ขาดหายไปของลำดับชั้นหินหรือเวลาความไม่ต่อเนื่อง (hiatus) ในปลายยุคน้ำแข็งครั้งล่าสุด

คำสำคัญ : วิวัฒนาการทางธรณีวิทยา ; การกำหนดอายุด้วยวิธีลูมิเนสเซนส์ ; สภาพแวดล้อมบรรพกาล ; เทคนิค Single aliquot regenerative dose (SAR) ; ทะเลสาบสงขลา

Abstract

Background and Objectives : Coastal sediments along the Songkhla coast still lack chronological data to describe their evolution. The objective of this study was to determine the chronological ages of the lagoonal side of the Songkhla coastline area, with the purpose of conducting a preliminary investigation into the development of the Songkhla lagoon.

Methodology : The topographic map of the coastal sediments that were classified early were taken with the real-time kinematic survey by the Global Navigation Satellite System. Samples were taken from the old ridges and plains behind the ridges using a light-blocking (PVC) cylinder tube and dated by optically stimulated luminescence (OSL) with the single aliquot regenerative dose protocol.

Main Results : A field survey by GNSS-RTK confirmed the two old ridges and plains parallel to the Songkhla lagoon coast in Hatyai district. The dating results were 10.0, 30.5, 39.2 ka (thousand years), and a saturated equivalent dose sample.

Conclusions : Quartz OSL dating revealed that the inner old ridge and plain behind the ridge were deposited during the humid period approximately 30–40 ka before the drought period in the late glacial maximum (LGM). At the same time, the youngest sediment here was the outer plain behind the ridge that was deposited 10 ka ago when the sea level transgressed in the early Holocene. Since then, only tidal flat sediment has been found on the lagoon coast. However, in this area, there was a hiatus during LGM.

Keywords : geological evolution ; OSL dating ; paleoenvironment ; single aliquot regeneration ; Songkhla lagoon

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Introduction

The Quaternary period, which spans from the last 2.6 Ma years to the present, has experienced frequent warm and cold climates. The sea level fluctuates several times due to the expansion and contraction of the ice sheet, directly affecting the coast. In the global marine isotope stage MIS5e (128 ka ago), the climate and sea level were similar to the present-day state. From then on, the climate became colder and drier during 100-10 ka and reached the coldest at the end of the last glacial maximum (LGM) (21 ka) (Anderson *et al.*, 2013). However, Southeast Asia had a short period of wet climate, approximately 40-35 ka ago (Shi *et al.*, 2001; Tauseef *et al.*, 2022). This climate and sea level fluctuation affects the coastal landscape and the habitat of plants, animals, and humans. Moreover, this environmental change is associated with a notable increase in the frequency of catastrophic events such as storm, drought, flood and heat wave (IPCC, 2021). Therefore, it is essential to predict future situations, which can aid humanity in preparing for, protecting against, and preventing potential future cascading disaster from threatening their livelihoods.

Understanding both the past and present climates as well as sea levels are necessary in order to comprehend and predict the future climate. A small number of studies in Thailand has been successfully investigated various past climate and environment using different dating techniques such as radiocarbon dating, thermoluminescence (TL) and optically stimulated luminescence dating (OSL). However, most previous studies on Pleistocene climate have focused on the upper zone of Thailand, whereas no precise chronological information in other parts of Thailand has been found, particularly in Southern Thailand (Chawchai *et al.*, 2013; Ngernkerd *et al.*, 2021; Saminpanya & Denkitkul, 2020). Thus, this study focused on the lower zone of Thailand and aimed to obtain paleoenvironment and paleoclimate data, especially on the Songkhla coast.

Songkhla coast, in Southern Thailand, is characterized as a sandy beach in the NW-SE direction and a lagoonal system in the north direction. The climate in Songkhla coastal area is subject to warm and wet, which is influenced by two monsoons; from November to December, the northeast monsoon blows from the South China Sea and the Gulf of Thailand to the east coast of southern Thailand, while from May to October, the southwest monsoon blows from the Indian Ocean to the west coast. The rainfall on the Songkhla coast is 2,076 mm/year, and the average temperature is 28 °C (Noppradit *et al.*, 2021). In addition, the tidal range of Songkhla is less than 1 m (Trisirisatayawong *et al.*, 2011).

The Quaternary geomorphology of the Songkhla coast has been divided into three different sedimentary types, including 1) beach ridges, 2) old lagoons and 3) tidal flats (Chaimanee & Tiyapirach, 1983). These were deposited by wind, wave action, tide, fluvial activities and longshore current. This area revealed a sequence of quartz-rich beach ridges that were probably formed over times during marine transgression and regression (Shennan *et al.*, 2015). This sequence may be considered to be a time series of coastal evolution. At least two former beach ridges lay slightly parallel to the present-day shorelines, approximately 2 km apart, and were 2 and 6 km in length, respectively. Furthermore, the two old ridges were separated by an old lagoon.

To obtain chronological data of these two old beach ridges, to date various methodologies have been utilized effectively to identify multiple types of solid earth material, including radiocarbon dating, for organic-rich matters, which is rare on sandy beaches. In contrast, minerals such as quartz can be found in nearly all geological material, particularly in sand ridges. Therefore, trapped charge dating is an appropriate method for our current investigation as it can directly assess sediment grains to determine the ages of coastal events. Trapped charge dating encompasses three distinct methods: TL, OSL, and ESR (electron spin resonance). TL is commonly employed for dating ceramic and heated objects. However, using TL to date sediment might result in a significant overestimation of age (Preusser *et al.*, 2008). Currently, ESR may be used for a diverse range of appropriate materials, including coral, fossil teeth, stalagmites, and quartz minerals. It has the potential to reach nearly every Quaternary period. Nevertheless, the scarcity of experts in the field of ESR dating, the intricate and time-intensive analytical processes, and the vast number of factors to consider in age estimation contribute to the challenges. These factors impose a substantial constraint on the range of ages that can be generated (Duval *et al.*, 2020). Therefore, OSL dating is highly recommended for accurately estimating the age of sediments located along the coast of the Songkhla region.

OSL dating is a reliable method used to estimate the period of time a mineral found in sediment has been buried (Preusser *et al.*, 2008; Schmidt & Zöller, 2016). It may provide accurate results for periods ranging from a few months to 150 ka, with an error margin of approximately 5-10% (Murray & Wintle, 2000). A dating error of 10% is considered acceptable (Galbraith & Roberts, 2012). The mechanism of the luminescence phenomenon can be described by the band theory (Aitken, 1985; Preusser *et al.*, 2008). OSL dating method was applied by (Noppradit *et al.*, 2019) to date Songkhla coastal sediments at the seaside, as classified by (Chaimanee & Tiyapirach, 1983). They found that coastal sediments were observed during the last interglacial (ca. 127 ka), late Pleistocene (58-34 ka), and Holocene (7-3 ka) periods. This recent study revealed the first chronological data and paleoenvironment by OSL dating method on this side of the Songkhla coast. So far, however, there have been no detailed chronological ages of categorized coastal sediment on the lagoonal side. Therefore, this present study aims to obtain chronological ages and geological processes on the lagoon side of the Songkhla coastal area.

The present study seeks to obtain additional chronological data from classified coastal sediment on the lagoonal side, which will help to fill in these research gaps using the OSL dating technique. This project provided a significant opportunity to advance the understanding of geological processes, environment, and climate during the late Quaternary in southern Thailand. Moreover, it would enable the opportunity to predict future situations such as coastal storms (Kongsen *et al.*, 2021; Rushby, 2022), sea level fluctuations (Rushby, 2022), tsunamis (Brill *et al.*, 2012), and earthquake (Brill, 2012; Brill *et al.*, 2012; Noppradit, 2013) in order to prepare for and prevent catastrophic events.

Methods

The topographic map was preliminarily generated by 30m-SRTM via NASA services (Farr *et al.*, 2007). For confirming the elevation of the sampling points, the real-time kinematic (RTK) survey was carried out by Topcon hyper SR based on the reference points in Kanplumjit *et al.* (2015). Samples were taken in the different geological units as shown in Figure 1 (b) between 0.4 and 1.1 meters below the surface to avoid material mixing caused by human activities or at least 0.3 meters beneath the ground (Aitken, 1985; Duller, 2014). The sediments in this area were classified by Chaimanee & Tiyapirach (1983).

The samples were collected using a light-blocking (PVC) cylinder tube. These tubes were then sealed with black plastic to prevent exposure to light during transport to the laboratory. The PVC tubes containing the collected samples were opened in the dark room and separated into two parts. The middle part of the tube was used for luminescence intensity measurement (equivalent doses), while the outer parts of the tube were used for physical and chemical analysis (water content and concentration of U, Th and K).

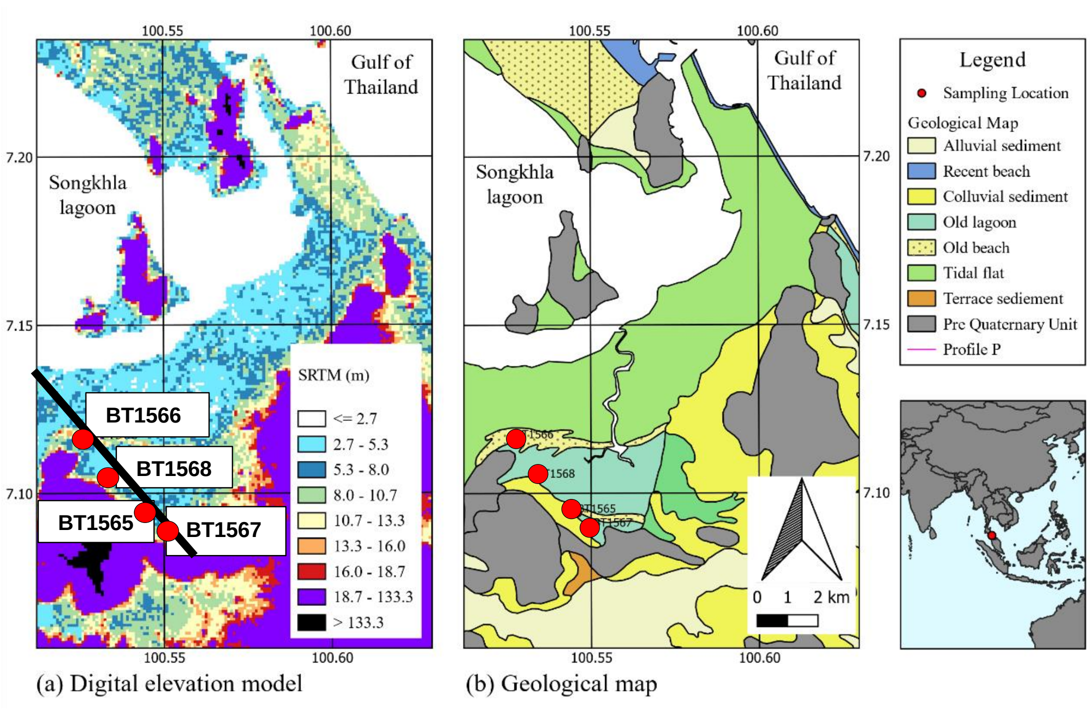

Figure 1 Sampling locations lay on the digital elevation model (a) and the geological map (b).

For luminescence intensity measurement, the samples were continuously processed in the dark room with red light LED (640± 20 nm) lamps. Then, the sediment samples were differentiated as sand and clay sediment according to Thien (1979) and treated with 10% hydrogen peroxide and 10% hydrochloric acid to remove organic and carbonate matter, respectively. The samples were then washed with deionized water. The washed samples were then further treated with 48% hydrofluoric acid for 45 minutes to remove approximately 25 µm of the mineral surface to minimize alpha irradiation in the environment and dissolve any remaining feldspars. The minerals were separated by sodium polytungstate ($3Na_2WO_4 \cdot 9WO_3 \cdot H_2O$) solution with densities of 2.62 and 2.70 g cm^{-3} for quartz extraction. Fluorides that could have remained during hydrofluoric acid etching were eliminated by rinsing the quartz separates in 10% hydrochloric acid to destroy fluorides. Finally, the quartz samples were prepared into 25 aliquot discs per samples.

Luminescence measurement was analyzed by the single aliquots regenerative dose, SAR (Wintle & Adamiec, 2017) with the Riso DA15 TL/OSL reader. The reader was equipped with the 90Sr/90Y beta source delivering 0.12 ± 0.01 Gy s^{-1} to the coarse grains. The OSL signals were stimulated by LEDs emitting at 470 ± 5 nm for 40 s and EMI9235QB15 PMT with the Hoya U-340 filter. In the preheating step, 240 °C was chosen to preheat the sediment samples because these samples were taken from the same area as Noppradit *et al.* (2019). Each sample was measured for 25 aliquots except for BT1566, where the OSL signal exceeds the saturation value.

The analyzed OSL data were proceeded by R software with 'Luminescence' package version 0.9.19 (2022-03-10)(Kreutzer *et al.*, 2012). Because these samples were possibly formed by water and wind processes; they were assumed to be well bleached. Hence, the central dose model (CDM) was adopted to extract and improve the statistical value of the equivalent dose (Galbraith & Roberts, 2012; Kreutzer *et al.*, 2012).

The samples from the outer part of the tube were processed in normal light conditions. These samples were crushed and placed above the ZnS (Ag) scintillator in a confined tray for a month, and the thick source alpha counting was used to determine Uranium and Thorium concentration. Potassium concentration was measured by the inductively couple plasma - optical emission spectroscopy (ICP-OES). The water content was measured in the laboratory by weighing it before and after drying in an oven. The results were expressed as a percentage by weight using equation (1) in Lowick & Preusser (2009). In order to compensate for fluctuations in hydrological conditions during the whole burial period, a 5% uncertainty in water content was considered. (Aitken, 1985; Preusser *et al.*, 2008; Wallinga & Cunningham, 2015) The dose rates were calculated via the radioactive elements and geographical setting (Prescott & Hutton, 1994) by the Dose Rate and Age Calculator or DRAC (Durcan *et al.*, 2015). Then, the age of sample was calculated following the following equation (Durcan *et al.*, 2015; Preusser *et al.*, 2008).

$$\text{Luminescence age (a)} = \frac{\text{Equivalent dose or } D_e \text{ (Gy)}}{\text{Dose rate (Gy a}^{-1}\text{)}}$$

Results

The present study seeks to obtain additional chronological data from classified coastal sediment on the lagoonal side using the OSL dating technique. Thus, the digital elevation model (SRTM) and the geological map of the Department of Mineral Resources (DMR) need to be addressed here. The SRTM data reveals two ridges: the inner ridge and the outer ridge, which are parallel to the lagoonal coast between two ridges, as shown in Figure 1 (a). The elevations of these two ridges were 3.9 m and 3.6 m, respectively. Figures 1 (b) is a geological map of the sampling location, which indicated these two ridges as the sediments deposited by waves and wind. Then, the sediment samples were collected in this area. The elevation of these sampling points (orthometric height) and their geographical locations are reported in Table 1, and their topographic profiles are presented in Figure 2.

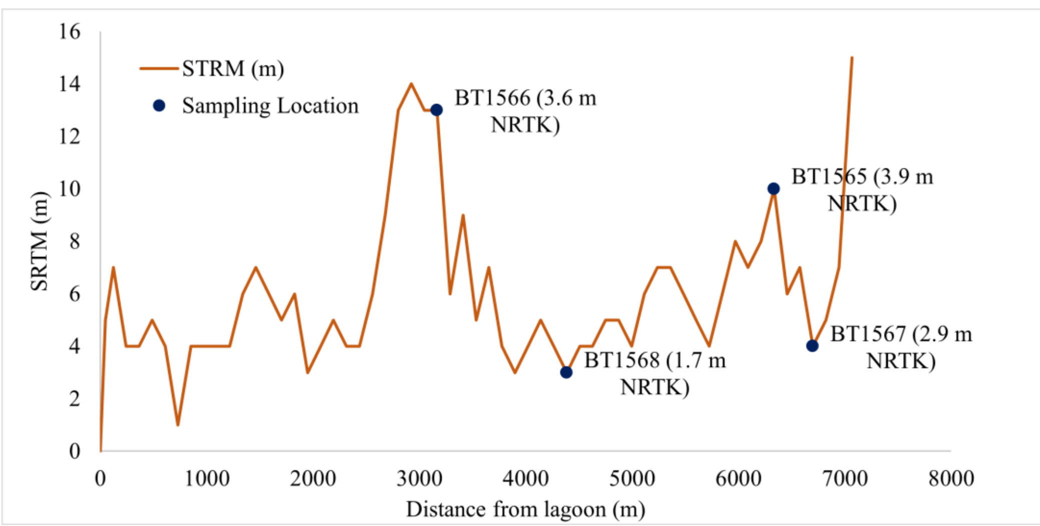

Figure 2 The elevation profile of the study area from the digital elevation model with the RTK elevation.

Table 1 Sample list with the geographical location surface, altitude and depth.

Sample ID	Latitude (^{0} N)	Longitude (^{0} E)	Surface altitude (m)	Depth (m)
BT1565	7.094	100.546	3.9	1.1
BT1566	7.116	100.528	3.6	1.1
BT1567	7.090	100.551	3.6	0.5
BT1568	7.104	100.534	1.7	0.4

Samples that were collected from the ridges (BT1565 and BT1566) mainly consisted of sand (fine to coarse sand), while the plain behind ridges (BT1567 and BT1568) mainly consisted of clay (sandy clay). The dose rate of the sample varied between 1.70 ± 0.06 Gy ka^{-1} and 8.27 ± 0.49 Gy ka^{-1}. The results of the ICP-OES and calculated dose rates are given in Table 2. Overall, the radioactive element analysis of clay samples was substantially higher compared to sandy samples. 'n' represents the number of aliquots accepted, which indicates the total number of final equivalent dose values accepted after applying the selection criteria. The majority of aliquots rejected have a low recycling ratio (> ± 10%).

Table 2 Sample list with water content, radioactive element concentration (U, Th, and K), dose rate ($\dot{D}$), number of aliquots accepted (n), equivalent doses (*De*) and ages.

Sample ID	Water content (%)	Th (ppm)	U (ppm)	K (%)	$\dot{D}$ (Gy ka^{-1})	n/N*	D_e (Gy)	Age (ka)
BT1565	7.8	6.55±0.77	3.91 ± 0.26	0.33±0.03	1.70±0.06	25/25	51.84±1.64	30.5±1.5
BT1566	8.5	6.76±1.28	4.54 ± 0.39	2.59±0.26	1.81±0.13	0/3	>720	>398
BT1567	29.5	29.43±2.95	8.37 ± 0.88	2.63±0.26	5.03±0.24	23/25	197.36±7.55	39.2±2.4
BT1568	28.3	9.43 ± 0.78	9.43 ± 0.78	7.21±0.72	8.27±0.49	24/25	82.99±3.26	10.0±0.7

After OSL dating measurements were made using the SAR protocol, the curvature of OSL curves was related to the equivalent dose using interpolation projected onto the paleodose, with the exception of BT1566, for which interpolation cannot be projected onto the equivalent dose, as shown in Figure 3 (B). The OSL ages of samples BT1565 and BT1566, collected from two former beach ridges at a depth of 1.1 m below the surface, were 30.5 ± 1.5 ka and over 398 ka, respectively. The two samples from two former lagoons (BT1567 and BT1568), collected at depths of 0.5 and 0.4 m below the surface, produced ages of 39.2 ± 2.4 and 10.0 ± 0.7 ka, respectively.

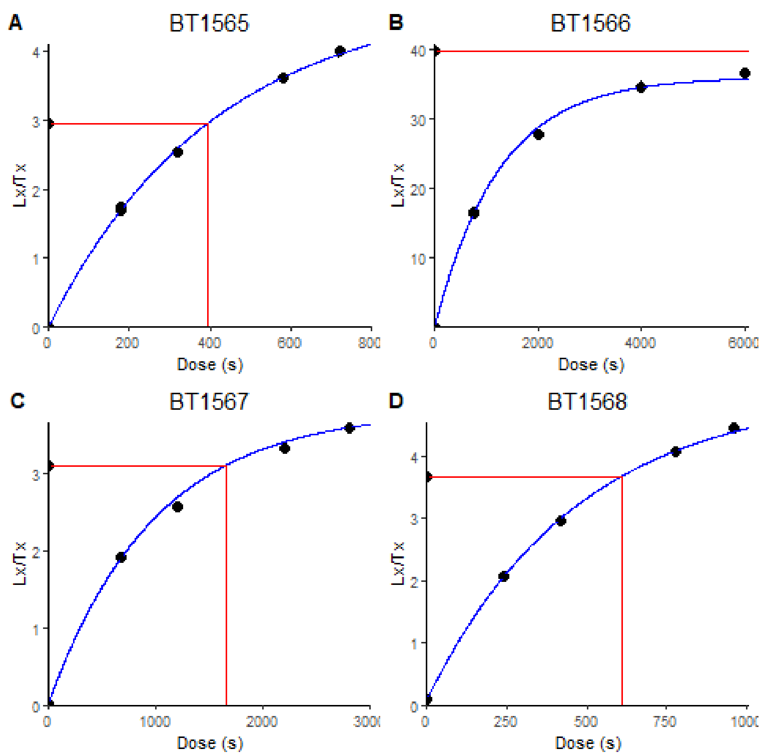

Figure 3 Dose-response curve of BT1565-BT1568

Discussion

Regarding the results of radioactive element concentration, the high radioactive element in sandy clay can be explained by the deposition of weathering products from the higher area of the clayish plain. The variation of radioactive elements had an additional impact on the environmental dose rate, primarily through the surrounding sediments.

The SAR- generated dose response curve of the samples shows the final equivalent dose using interpolation. However, the higher equivalent dose of BT1566 tended to be curved due to its saturation level. The natural OSL signal of BT1566 was extremely high, even though the regenerative signal was 720 Gy (6,000 s irradiated). The growth curve of the samples is presented in Figure 3.

The distribution of the equivalent dose in Figure 4 illustrates patterns of distribution resulting from the heterogeneous samples. The scatter of repeated paleodose measurements indicates a relatively well-bleached sample in general. While the equivalent dose distribution of the samples, displays a unimodal distribution in general (Preusser *et al.*, 2008) with only one aliquot having a significantly higher dose in BT1565 and BT1568 and two aliquots possessing a lower and higher dose in BT1567, the higher value may contain some residual signal (incompletely bleached).

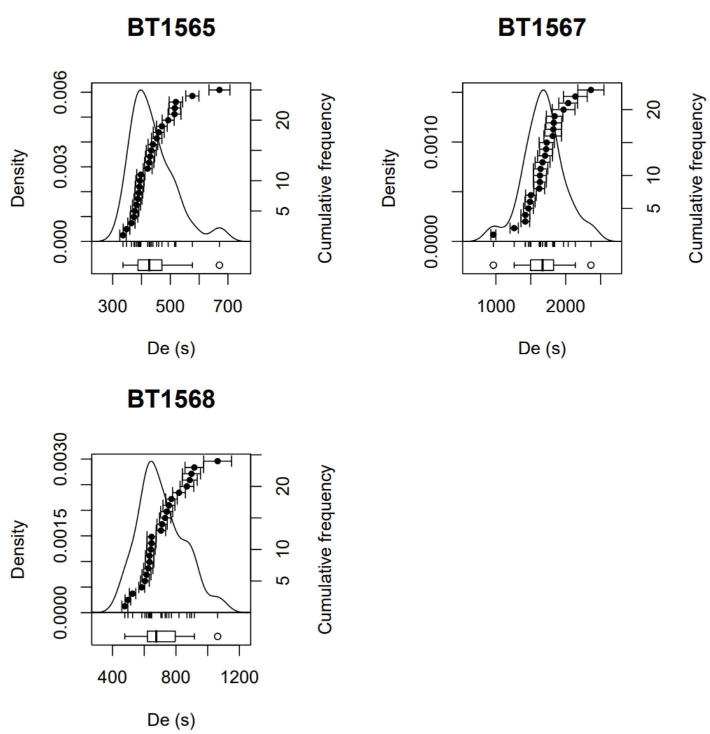

Figure 4 Distribution of equivalent doses of BT1565, BT1567 and BT1568 (noted that, 1 s dosed = 0.12 Gy)

In addition, some quartz grains might be attached to a radioactive mineral such as zircon, which is commonly ca. 3-7% in the study area and contributed to the high intensity of the natural luminescence signal. In contrast, the signal with a lower dose or intensity likely represents the grains that were zeroed prior to deposition. In this study, the equivalent doses (after being processed by CDM) were greater than 51 Gy (51, 82, 197, and

>720 Gy), while their standard errors ranged from 5 to 7% (< 10%). Equivalent doses and age calculation results are presented in Table 2.

Geological interpretation

During the glacial period (100 – 10 ka), Southeast Asia's climate seemed to be colder and dryer than the present. However, some researchers hypothesized that there was a short period of wet climate, approximately 40-35 ka (Shi *et al*., 2001; Tauseef *et al*., 2022). This study can also confirm this hypothesis. The chronological data in this study agrees well with Saminpanya & Denkitkul (2020) that, before 33 ka, the climate in SEA was wet and cool. They suggest that the vegetation kept humidity in the local area. In addition, some results of this study are similar to those found in Yang *et al.* (2004) who indicate: evidence of a warm and humid climate between 40-30 ka. A rise in ocean surface temperature provides abundant moisture and leads to the weathering process of hydrolysis in the study area.

Then, the inner sand ridge was possibly formed during this period. The major sandy component of this ridge reflected the high energy of media (water); it was possibly the beach ridge landform throughout that period. While there was a plain behind that ridge, the clayish unit of BT1567 indicated a low energy during their deposition. However, the age of BT1565 (30 ka) which collected from the inner sand ridge was slightly younger than BT1567 (39 ka). The younger age of BT1565 might have been deposited by the aeolian process. When the sand ridge originally formed by the current was in a dry condition with a strong wind, the wind possibly blew the sand to redeposit again. This resemblance condition of climate is confirmed by Ngernkerd *et al.* (2021), that the dry climate induces wind prevailing to form dunes during the warm and dry (45-28 ka) climate in the Korat Plateau. Since then, there was no deposition evidence until the early Holocene (ca. 10 ka). The outer ridge began forming where BT1566 was collected, and this ridge protected the place behind them from waves and current energy. Since then, a clayey-rich sediment was deposited. BT1568 was collected at this location. However, the OSL dating of BT1566 was not successful, because the natural signal was above the highest dose point (720 Gy) and its age was more than 398 ka.

The location of BT1566 was nearby the archaeological site where the ancient brick kilns were (Sattayasansakul, 2005). Hence, this collected site is possibly part of this activity. This dated sample is older than other samples, which might be the result of sediment disturbance caused by brick kiln activities. The collected sample might be from more than 1 m below the surface, suggesting that it could be an older material than that before the outer ridge formed.

The plain area in front of the outer ridges was classified into a tidal flat (Chaimanee & Tiyapirach, 1983; DMR, 2007). This characteristic of sediment confirms the effect of the tide which happens in the present Songkhla lagoon. This tidal flat reflected the forming of the Satingpra Peninsula, which is the barrier system to protect wave energy in the Songkhla lagoon. For these reasons, this study confirmed that the Songkhla lagoonal system is younger than 10 ka (10,000 years). Furthermore, the chronological data in the Satingpra Peninsula area (Chaimanee, 1989; Tongsang, 2016, 2021; Tongsang *et al.*, 2019) reveal that the Satingpra Peninsula were all younger than 7 ka.

Conclusions

Quartz OSL dating in this study was successfully dated in 3 of 4 samples by the SAR protocol. The OSL chronology result showed this coastal sediment was developed at 10.0±0.7, 30.5±1.5, and 39.2±2.4, and the certainly undatable sample indicates at least 398 ka ago due to the limitations of quartz OSL dating. The three ages and the tidal flat sediment reflected that the lagoon side of Songkhla coast and Satingpra Peninsula occurred during the late Pleistocene to the early Holocene.

This study confirmed two geological events in this area. 1) In the 40–30 ka before LGM, which was in global MIS3, the climate here tended to be humid. 2) After LGM ca. 10 ka, the climate became humid (after being dry and cool during LGM) due to the presence of an outer ridge along the southern coast of the Songkhla lagoon. Moreover, this will be helpful in confirming the duration of the Satingpra Peninsula formation.

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