

LUMINESCENCE DATING OF BRICK FROM NAKHON KALONG CITY ARCHAEOLOGICAL SITE IN NORTHEASTERN THAILAND

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Abstract

Nakhon Kalong, located in Ban Khon Sawan, Khon Sawan District, Chaiyaphum Province, Northeastern Thailand, is an archaeological site associated with the Dvaravati period (12th-16th Buddhist centuries). The site features distinctive characteristics of Dvaravati culture, including a moated settlement, earthen ramparts, laterite structures, sandstone sema markers (bai sema), and a large sandstone Buddha image. The bricks used in construction at the site were subjected to a heating process prior to use, which makes them suitable for luminescence dating. In this study, brick samples obtained as rubble from excavation sites in Ban Khon Sawan were analyzed to determine their age. The accumulated dose was measured using Optically Stimulated Luminescence (OSL) dating, while the annual dose was determined by Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). The annual dose was measured at 2.80 ± 0.67 mGy per year, and the accumulated dose was found to be 2.92 ± 0.24 Gy. These values yield an estimated luminescence age of $1,042 \pm 263$ years. The dating results are consistent with historical records, confirming the occupation of Nakhon Kalong during the Dvaravati period.

Keywords: Accumulated dose; Annual dose; Ban Khon Sawan; Dvaravati period; Optically Stimulated Luminescence; Luminescence dating

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Introduction

Nakhon Kalong in Ban Khon Sawan is located at 15°55'54"N and 102°16'52"E, 300 m above sea level, in Khon Sawan district, Chaiyaphum province, Northeastern Thailand. Ban Khon Sawan or Nakhon Kalong has been an ancient city since its origin. When Phraya Khunhan discovered the city, he found that the area was fertile and had a variety of plants and fruits. Crows flew in to find food in the fertile area and forgot to return to their nests. Hence, the name of the town "Nakhon Kalong".

The Ban Khon Sawan community, or Nakhon Kalong town, was a large ancient settlement with evidence and traces of people living there since the Dvaravati period, between the 12th and 16th Buddhist centuries (Wakadoun, 2024). Archaeological finds include traces of ditches and ramparts, pottery and Sema stones, or bai sema, Buddhist boundary markers that were once used to demarcate the sacred area of places of worship. Sema stones, found in large quantities, testify to the prosperity of the community and especially to the prominence of Buddhism. The most important feature of the Sema stones of Ban Khon Sawan is that they are made of sandstone. They are stone slabs carved with patterns and decorated with images of Jataka scenes narrating the life of the Buddha, executed with considerable artistic skill.

There were also fragments of coarse pottery that had been fired at low temperatures. Most of them had a smooth surface, some were decorated with rope patterns or carved and painted. In addition, five standing ancient Buddha images from the Dvaravati period were found, carved from red sandstone and so damaged that only the bodies remained. The villagers have restored the heads and some parts of the bodies, with the exception of a large statue about 3 m high. It is in perfect condition but not yet fully carved. Many people in Chaiyaphum province worship it and call it "Luang Por Yai" or "Phra Yai Dvaravati". It is assumed that the Buddha image was erected when the Khmer were in power in the nearby region. The ancient Buddha image in Ban Khon Sawan was usually inspired by Indian art, as can be seen from the clean robe without wrinkles, the round face, connected eyebrows in the shape of a bracket, flat nose, thick parted lips, straight stance, and often the posture of a sermon with both hands. These forms were presented only in the Dvaravati style (Murphy, 2010). This statue is highly revered by the people of Chaiyaphum Province.

After the end of the Dvaravati culture, the Ban Khon Sawan area continued to be inhabited during the Khmer period, between the 16th and 18th

Buddhist centuries. During investigations, parts of pillars, door frames, and other architectural components arranged in the Sema building were found, as well as strong brown glazed clay vessels (Khmer jars). However, absolute dating had not yet been applied in this area.

There are various absolute dating techniques that provide accurate dates for sediments, soil, pottery, ceramics and burnt flint, e.g. radiocarbon dating, electron spin resonance (ESR) dating and luminescence dating.

Radiocarbon dating, or ¹⁴C dating, is a scientific method that can accurately determine the age of organic material up to about 60,000 years (Margariti *et al.*, 2023). This method can be applied to materials such as wood, charcoal, bones, shells, peat, ivory, seeds, grains, and charred food remains. However, the half-life of ¹⁴C is relatively short, so it cannot be used to date samples older than 50,000 years, nor is it suitable for inorganic materials.

Electron spin resonance (ESR) dating is a technique that can date materials based on the accumulation of electrons and holes in their crystal lattice (Moreno *et al.*, 2017). This method can be applied to materials that are hundreds of thousands of years old, beyond the range of radiocarbon dating. However, ESR dating is not always reliable, and its accuracy depends on several factors, such as environmental influences, heating events, and uranium enrichment.

Luminescence dating refers to a group of methods in which trapped charges are used to determine the age of crystalline materials since their last exposure to sufficient heat or sunlight (Wallinga *et al.*, 2002). This method can date sediments that are as young as a few years to over a million years old (Murray and Olley, 2002). It has been applied to feldspars in the ceramic industry, prehistoric ceramics (Tatumi *et al.*, 1998; Pacompia *et al.*, 2023), pottery (El-Fiki *et al.*, 1994; Zarie *et al.*, 2001; Bonsall *et al.*, 2002; Wang, 2009; Janz *et al.*, 2015; Chuenpee *et al.*, 2021; Elghareb, 2021; Carstea (Elekes) *et al.*, 2024; Wei *et al.*, 2024), the deposition of sediments (Hossain, 2003; Spencer and Owen, 2004; Punpate *et al.*, 2005; Thamó-Bozsó *et al.*, 2007; Harriët, 2008; Rhodes, 2011; Kim *et al.*, 2012; Cano *et al.*, 2020; Mahan *et al.*, 2023; Peng *et al.*, 2023; Sanjurjo-Sánchez *et al.*, 2024) brick (Puttagan *et al.*, 2019; Pailoplee *et al.*, 2025) unheated flint (Ageby *et al.*, 2024a; 2024b) or archeological material. The main minerals used are quartz or feldspar (Aitken, 1970: 1998). Trapped charge accumulates in minerals over time as energy is absorbed from ionizing radiation such as ²³⁸U,

^{232}Th , ^{40}K and cosmic rays. When light releases the trapped charge, the resulting signal is referred to as optically stimulated luminescence (OSL), whereas when heat serves as the agent, it is known as thermoluminescence (TL).

The time elapsed since the last daylight exposure or heating or luminescence age is calculated by dividing the accumulated dose (AD) by the annual dose (D). The accumulated dose is the total amount of absorbed energy per mass ($1 \text{ J kg}^{-1} = 1 \text{ Gy}$ (gray)) of mineral due to natural radiation since zeroing, measured by comparing natural luminescence signals with those induced through artificial irradiation (Preusser *et al.*, 2008). The annual dose is a measure of the absorbed dose per time unit, determined by analyzing concentrations of the major radionuclides (^{238}U , ^{232}Th , ^{40}K) in the sample material using methods such as gamma spectrometry, neutron activation analysis (NAA), inductively coupled plasma mass spectrometry (ICP-MS).

In the present study, bricks from the archaeological site of Ban Khon Sawan were analyzed using Optically Stimulated Luminescence (OSL) dating. The luminescence ages obtained through this technique were compared with historical records, confirming the construction period of the bricks.

environmental impurities. Subsequently, the samples were crushed using a hammer and chisel, followed by careful grinding with an iron mortar. The resulting grains were then sieved to obtain a size range of 90-150 μm (Vichaidid and Danworaphong, 2021). At this stage, the samples were further divided into two grain size fractions: fine grain (1-90 μm) and coarse grain (90-150 μm).

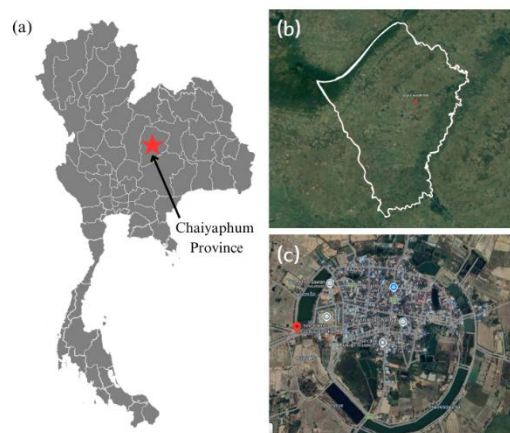


Figure 1. (a) Map of Thailand with Chaiyaphum Province marked (red star). (b) Ban Khon Sawan archaeological site and (c) Close-up of Ban Khon Sawan

Materials and Methods

Sample Collection

The samples, consisting of sediments with brick rubble, were collected from the Ban Khon Sawan excavation site, Khon Sawan District, Chaiyaphum Province. Figure 1 presents the site: (a) a map of Thailand with Chaiyaphum Province marked, (b) the Khon Sawan District, including the town plan, and (c) the moat and earthen rampart.

To prevent light exposure, both brick and sediment samples were carefully collected. Table 1 details the sample names and information, while Figure 2 provides sample photographs.

Preparation of Samples

The samples, consisting of sediment containing brick rubble from each site, were divided into two parts. The first part was prepared under subdued red light for the determination of the accumulated dose (AD), while the second part was prepared under ambient light for the determination of the internal annual dose (Din).

In the preparation of the first part, the brick rubble was meticulously scraped to remove approximately 1-2 mm of its surface layer. This step aimed to eliminate potential light contamination and



Figure 2. Brick sample. ASSC1

Table 1. Sample codes and descriptions

Sample code	Sample feature
ASC1	Brick rubble at 40–60 cm depth.
SD1	Surrounding sediments near ASSC1.
ASC2	Brick rubble at 60–80 cm depth.
SD2	Surrounding sediments near ASSC2.

The coarse grains were subjected to etching in 15% hydrochloric acid (HCl) for 15 min to remove carbonates, followed by thorough washing with distilled water. The samples were then etched in 45% hydrofluoric acid (HF) for 40 min to eliminate feldspar and remove a thin surface layer of the grains. After HF etching, the samples were soaked in water and etched again in 15% HCl for 15 min to eliminate fluorides formed during the HF treatment. The samples were subsequently rinsed with distilled water and dried at 40°C for 24 h.

Once dried, the cleaned samples were immersed in Sodium Polytungstate (SPT) and centrifuged at 2,000 rpm for 1 h to separate quartz grains from heavy minerals (Tudela *et al.*, 2012). The purified quartz grains were then rinsed with distilled water and acetone, sequentially, before being stored in opaque plastic containers for accumulated dose measurement.

For the OSL measurement, stainless steel discs provided by Freiberg Instruments were coated with a thin layer of silicone (2 mm). Quartz grains were evenly sprinkled onto the discs, and any non-adhering grains were removed by gently tapping the discs.

Accumulated dose Calculation

The accumulated dose was determined using the Lexyg Research TL/OSL Reader (Richter *et al.*, 2013), which is equipped with a $^{90}\text{Sr}/^{90}\text{Y}$ beta source with a dose rate of 0.06 Gy/s and a 525 nm green LED, at the Amata Siam Science Center in Bangkok, Thailand. The OSL measurement was conducted using a modified version of the single aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2003). In this study, preheating at 200°C/125°C was selected for accumulated dose determination, and eight aliquots were measured for each sample. The SAR protocol used for accumulated dose determination is detailed in Table 2.

Annual dose Calculation

Fine-grain samples were used to determine the concentration of natural radioisotopes, specifically ^{238}U , ^{232}Th , and ^{40}K , using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) (Thermo Fisher Scientific Inc., USA). These concentrations facilitate the calculation of the internal annual dose (D_{in}).

To estimate the external annual dose (D_{ex}), the surrounding sediment was lightly ground using a mortar, and the grains were sieved with a 90 μm mesh to obtain a particle size range of 0–90 μm . LA-ICP-MS was employed for this measurement.

The total annual dose (D) consists of three components: the internal annual dose (D_{in}), the external annual dose (D_{ex}), and the cosmic ray dose (D_{c}). D_{in} originates from radiation emitted by ^{238}U , ^{232}Th , and ^{40}K within the brick, while D_{ex} results from radiation emitted by the surrounding sediment. These contributions were evaluated by measuring the concentrations of radioactive elements, whose decay products emit alpha (α), beta (β), and gamma (γ) radiation.

D_{c} was also included in the total annual dose. Its intensity is influenced by the geographical coordinates and elevation of the sampling site, with

attenuation due to sample depth. The cosmic dose rate was derived based on location and elevation and remained consistent across all sampling sites, with minimal variation.

The annual dose can be determined using the following equation:

$$D = D_{\text{in}} + D_{\text{ex}} + D_{\text{c}} \quad (1)$$

The age was determined using the following equation:

$$\text{Ages} = \frac{AD(\text{Gy})}{D(\text{Gy/y})} \quad (2)$$

Results and Discussion

The concentrations of those radioactive elements were then used to estimate D_{in} and D_{ex} based on the online Dose Rate and Age Calculator (DRAC) (Durcan *et al.*, 2015) using the conversion factors from Adamiec and Aitken (1998) grain size attenuation factors respectively from Bell (1979). The results of the concentration of ^{238}U , ^{232}Th and ^{40}K in the samples are shown in Table 3.

Table 2. SAR protocol used for accumulate dose determination

Run	Operation
1	Give dose (N, R1, R2, R3 (repeat))
2	Preheat at 200°C (5°C/s) for 50 s
3	OSL measurement, L_x
4	Test dose
5	Cutheat at 125°C (5°C/s) for 50 s
6	IRSL measurement, only last cycle
7	OSL measurement, T_x
8	Return to run 1

Table 3. Concentration of U, Th and K in the samples used to calculate the annual dose (D) of the samples.

Sample code	Concentration		
	^{238}U (ppm)	^{232}Th (ppm)	^{40}K (%)
ASC1	4.71±0.05	7.58±0.39	2.19±0.03
SD1	6.32±0.08	12.74±0.65	3.62±0.02
ASC2	3.84±0.04	8.15±0.51	2.41±0.06
SD2	4.59±0.07	14.62±0.74	5.34±0.09

The OSL decay curve describes the reduction in luminescence intensity over time when a sample is optically stimulated after radiation exposure. The initial intensity reflects the number of trapped charge carriers, directly correlating with the absorbed dose. Higher doses yield stronger initial signals before fading to the background level.

Figure 3 illustrates this relationship in the ASSC1 sample, where the natural dose shows the lowest initial intensity, increasing with additional doses of 1.65 Gy, 2.7 Gy, and 4.5 Gy. This confirms the direct correlation between dose and luminescence intensity.

In contrast, the OSL growth curve represents luminescence intensity as a function of radiation dose. At low doses, this relationship is typically linear, but saturation may occur at higher doses as trapping sites fill up.

Figure 4 illustrates this trend by showing the OSL growth curve of the ASSC1 sample, where luminescence intensity increases linearly with dose. By comparing the natural OSL signal with this curve, the accumulated dose can be determined. The intersection of the natural signal with the growth curve provides an estimate of the total absorbed radiation dose before laboratory irradiation.

The age of all samples was determined by dividing the accumulated dose (AD) by the annual dose (D). Table 3 presents the results for AD, D, and the calculated OSL ages, which fall within the estimated range of the brick rubble at $1,042 \pm 53$ years. The obtained OSL ages align with estimates derived from the online dose rate and age calculator for quartz using standard conversion factors. Furthermore, the luminescence dating results are consistent with the historical records of Nakhon Kalong, which was established during the Dvaravati period.

Conclusions

In this study, the OSL-SAR method was used to date brick rubble-containing sediments from the excavation site at Nakhon Kalong in Ban Khon Sawan, Khon Sawan District, Chaiyaphum Province, northeastern Thailand. This site is a significant ancient settlement with evidence of continuous habitation dating back to the Dvaravati period (12th-16th Buddhist centuries).

The annual dose was estimated based on the concentrations of uranium (U), thorium (Th), and potassium (K). The resulting OSL age of the brick rubble was $1,042 \pm 263$ years, aligning with historical records of Nakhon Kalong's establishment during the Dvaravati period. These results confirm the reliability of luminescence dating for determining the age of heated materials such as brick rubble, pottery, sediments, volcanic tephra, and colluvial wedges.

However, external factors such as post-depositional processes, water content variations, and radiation flux changes may affect luminescence signals and should be carefully considered for accurate age estimation.

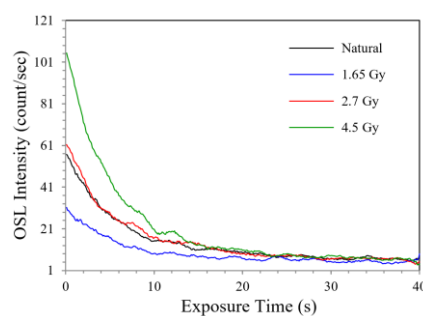


Figure 3. OSL intensity decay over time for the ASSC1 sample under different radiation doses (Gy)

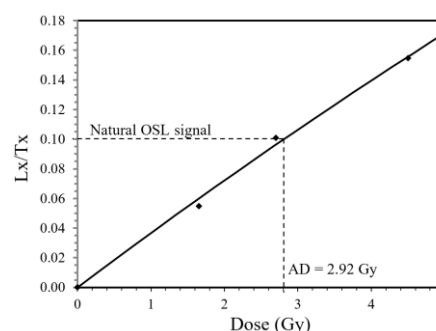


Figure 4. OSL growth curve for the ASSC1 sample as a function of additive dose, with the accumulated dose (AD) determined from the curve

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References

- Adamiec, G. and Aitken, M.J. (1998). Dose-rate conversion factors: Update. *Ancient TL*, 16(2):37-50.
- Ageby, L., Jakathamani, S., Murray, A.S., Jain, M., and Rades, E.F. (2024a). Feasibility of rock surface luminescence dating technique for measuring the burial ages of unheated flints. *Quaternary Geochronology*, 83:101566. <https://doi.org/10.1016/j.quageo.2024.101566>
- Ageby, L., Shanmugavel, J., Jain, M., Murray, A.S., and Rades, E.F. (2024b). Towards the optically stimulated luminescence dating of unheated flint. *Quaternary Geochronology*, 79:101471. <https://doi.org/10.1016/j.quageo.2023.101471>

- Aitken, M.J. (1970). Dating by Archaeomagnetic and Thermoluminescent Methods. In: Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 269(1193):77-88. <https://doi.org/10.1098/rsta.1970.0087>
- Aitken, M.J. (1998). An Introduction to Optical Dating: The Dating of Quaternary Sediments by the Use of Photon-stimulated Luminescence. Oxford University Press, <https://doi.org/10.1093/oso/9780198540922.001.0001>
- Bell, W.T. (1979). Thermoluminescence dating: radiation dose-rate data. *Archaeometry*, 21(2):243-245. <https://doi.org/10.1111/j.1475-4754.1979.tb00258.x>
- Bonsall, C., Cook, G., Manson, J.L., and Sanderson, D. (2002). Direct dating of Neolithic pottery: progress and prospects. *Documenta Praehistorica*, 29:47-59. <https://doi.org/10.4312/dp.29.5>
- Cano, N.F., Ayala-Arenas, J.S., Javier-Ccallata, H.S., and Watanabe, S. (2020). OSL and EPR dating of shells and sediments from Congonhas II sambaqui, Santa Catarina, Brazil. *Radiation Physics and Chemistry*, 167:108240. <https://doi.org/10.1016/j.radphyschem.2019.03.044>
- Carstea (Elekes), A., Gligor, M., Bucurica, I.A., Dulama, I.D., Radulescu, C., Stirbescu, R.M., Stanesco, S.G., and Gheboianu, A.I. (2024). Analysis and structural investigations on neolithic painted pottery from suplacu de barcău/porț-corău archaeological site. *Journal Of Science And Arts*, 24(3):705-724. <https://doi.org/10.46939/J.Sci.Arts-24.3-b05>
- Chuenpee, T., Upakankaew, K., Jantaravik, Y., and Dharmmanon, W. (2021). Thermoluminescence dating of ancient pottery sherds from Ban Pong Manao archaeological site, Lopburi Province, Thailand. *Journal of Applied Sciences*, 21(1):42-50. <https://doi.org/10.3923/jas.2021.42.50>
- Durcan, J.A., King, G.E., and Duller, G.A.T. (2015). DRAC: Dose Rate and Age Calculator for trapped charge dating. *Quaternary Geochronology*, 28:54-61. <https://doi.org/10.1016/j.quageo.2015.03.012>
- El-Fiki, S.A., Abdel-Wahab, M.S., El-Faramawy, N., and El-Fiki, M.A. (1994). Dating of ancient Egyptian pottery using the thermoluminescence technique. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 94(1-2):91-94. [https://doi.org/10.1016/0168-583X\(94\)95661-8](https://doi.org/10.1016/0168-583X(94)95661-8)
- Elghareb, W.K. (2021). Analysis and restoration of pottery artefacts from tell El-hir, North Sinai, Egypt: A case study. *International Journal of Conservation Science*, 12(4): 1327-1342.
- Harriët, van E., (2008). Thermoluminescence dating of sediments using mineral zircon, [Thesis fully internal (DIV)]. University of Groningen, Netherlands, 13p.
- Hossain, S.M. (2003). A critical comparison and evaluation of methods for the annual radiation dose determination in the luminescence dating of sediments, [Ph.D., Thesis]. Institute for Nuclear Sciences, Laboratory of Analytical Chemistry, 209p.
- Janz, L., Feathers, J.K., and Burr, G.S. (2015). Dating surface assemblages using pottery and eggshell: Assessing radiocarbon and luminescence techniques in Northeast Asia. *Journal of Archaeological Science*, 57:119-129. <https://doi.org/10.1016/j.jas.2015.02.006>
- Kim, J.C., Eum, C.H., Yi, S., Kim, J.Y., Hong, S.S., and Lee, J.Y. (2012). Optically stimulated luminescence dating of coastal sediments from southwestern Korea. *Quaternary Geochronology*, 10:218-223. <https://doi.org/10.1016/j.quageo.2012.03.008>
- Mahan, S., Wood, J.R., Lovelace, D.M., Laden, J., McGuire, J.L., and Meachen, J.A. (2023). Luminescence ages and new interpretations of the timing and deposition of Quaternary sediments at Natural Trap Cave, Wyoming. *Quaternary International*, 647-648:22-35. <https://doi.org/10.1016/j.quaint.2022.01.005>
- Margariti, C., Sava, G., Sava, T., Boudin, M., and Nosch, M.L. (2023). Radiocarbon dating of archaeological textiles at different states of preservation. *Heritage Science*, 11(1):44. <https://doi.org/10.1186/s40494-023-00867-x>
- Moreno, D., Richard, M., Bahain, J.J., Duval, M., Falguères, C., Tissoux, H., and Voinchet, P. (2017). ESR dating of sedimentary quartz grains: Some basic guidelines to ensure optimal sampling conditions. *Quaternaire*, 28(2):161-166. <https://doi.org/10.4000/quaternaire.8008>
- Murphy, S.A. (2010). The buddhist boundary markers of northeast Thailand and central Laos, 7th-12th centuries CE: Towards an understanding of the archaeological, religious and artistic landscapes of the Khorat Plateau, [Ph.D., Thesis]. School of Oriental and African Studies, University of London, 479p.
- Murray, A.S. and Olley, J.M. (2002). Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz: a status review. *Journal on Methods and Applications of Absolute Chronology*, 21:1-16.
- Murray, A.S. and Wintle, A.G. (2003). The single aliquot regenerative dose protocol: Potential for improvements in reliability. *Radiation Measurements*, 37(4-5):377-381. [https://doi.org/10.1016/S1350-4487\(03\)00053-2](https://doi.org/10.1016/S1350-4487(03)00053-2)
- Pacompiá, Y., Supo-Ramos, J.G., Gonzales-Lorenzo, C.D., Callo-Escobar, D.J., Rocca, R.R., Pastrana, E.C., Gomes, M.B., Silva-Carrera, B.N., Watanabe, S., Ayca-Gallegos, O., and Ayala-Arenas, J.S. (2023). Luminescence dating and firing temperature determination of ancient ceramics fragments from the Tunata-hill site in the Churajon archaeological complex in Arequipa, Peru. *Radiation Physics and Chemistry*, 204:110725. <https://doi.org/10.1016/j.radphyschem.2022.110725>
- Pailoplee, S., Chaisuwannand, B., Takashima, I., Won-In, K., and Charusiri, P. (2005). Dating Ancient Remains by Thermoluminescence: The Case of Bricks from Thung Tuk Archaeological Site, Phang Nga Province, Southern Thailand. In: International Conference on Geology, Geotechnology and Mineral Resources of Indochina (GEOINDO 2005), 28-30 November 2005, Khon Kaen, Thailand, 9p.
- Peng, J., Li, B., Jacobs, Z., and Gliganic, L.A. (2023). Optical dating of sediments affected by post-depositional mixing: Modelling, synthesizing and implications. *Catena*, 232:107383. <https://doi.org/10.1016/j.catena.2023.107383>
- Preusser, F., Degering, D., Fuchs, M., Hilgers, A., Kadereit, A., Klasen, N., Krbetschek, M., Richter, D., and Spencer, J.Q.G. (2008). Luminescence dating: basics, methods and applications. *Eiszeitalter und Gegenwart Quaternary Science Journal*, 57(1-2):95-149.
- Punpate, N., Pailoplee, S., Takashima, I., and Charusiri, P. (2005). Ages of layered Tektites and tektites bearing sediments in Buntharik area, Ubonrathchathani, Northeast Thailand. *Proc. of the Int. Conference on Geology, Geotechnology and Mineral Resources of 102 Sangad Bunopas / Thai Geoscience Journal* 2(1), 2021, p. 16-109 Indochina. GEOINDO 2005, Kosa Hotel, Khon Kaen, 28-30 Nov. 2005.
- Puttagan, T., Chawchai, S., Surakiatchai, P., Chalorsantisakul, S., and Preusser, F. (2019). Luminescence dating of brick constructions being part of Songkhla City Wall, Southern Thailand. *Archaeological and Anthropological Sciences*, 11(10):5393-5403. <https://doi.org/10.1007/s12520-019-00878-5>
- Rhodes, E.J. (2011). Optically stimulated luminescence dating of sediments over the past 200,000 years. *Annual Review of Earth and Planetary Sciences*, 39:461-488. <https://doi.org/10.1146/annurev-earth-040610-133425>
- Richter, D., Richter, A., and Dornich, K. (2013). Lexsyg - A new system for luminescence research. *Geochronometria*, 40(4):220-228. <https://doi.org/10.2478/s13386-013-0110-0>

- Sanjurjo-Sánchez, J., Arce-Chamorro, C., Vidal-Romaní, J.R., and Matin, N. (2024). OSL dating of very young aeolian sediments of NW Spain to assess dune erosion and accretion periods. *Quaternary Geochronology*, 82:101537. <https://doi.org/10.1016/j.quageo.2024.101537>
- Spencer, J.Q. and Owen, L.A. (2004). Optically stimulated luminescence dating of Late Quaternary glaciogenic sediments in the upper Hunza valley: Validating the timing of glaciation and assessing dating methods. *Quaternary Science Reviews*, 23(1-2):175-191. [https://doi.org/10.1016/S0277-3791\(03\)00220-8](https://doi.org/10.1016/S0277-3791(03)00220-8)
- Tatumi, S.H., Martins, G.R., Kashimoto, E.M., Ayta, W.E.F., and Watanabe, S. (1998). Thermoluminescence dating of archaeological ceramics collected from state of Mato Grosso Do Sul, Brazil. *Radiation Effects and Defects in Solids*, 146(1-4):297-302. <https://doi.org/10.1080/10420159808220301>
- Thamó-Bozsó, E., Magyari, Á., Nagy, A., Unger, Z., and Kercksmár, Z. (2007). Osl dates and heavy mineral analysis of upper quaternary sediments from the valleys of the Er and Berettyó rivers. *Geochronometria*, 28(1):17-23. <https://doi.org/10.2478/v10003-007-0026-x>
- Tudela, D.R.G., Tatumi, S.H., Yee, M., Brito, S.L.M., Morais, J.L., De Morais, D., Piedade, S.C., Munita, C.S.P., and Hazenfratz, R. (2012). TL, OSL and C-14 Dating Results of the Sediments and Bricks from Mummified Nuns' Grave. *Annals of the Brazilian Academy of Sciences*, 84(2):237-244. <https://doi.org/10.1590/S0001-37652012005000031>
- Vichaidid, T. and Danworaphong, S. (2021). Dating the historical old city walls of Songkhla Thailand using thermoluminescence technique. *Heliyon*, 7(2):e06166. <https://doi.org/10.1016/j.heliyon.2021.e06166>
- Wakadoun, P. (2024). The dvaravati footprints from the study of paleogeography. *Global Interactive Journal of World Religions and Cultures*, 4(1):63-77.
- Wallinga, J., Murray, A.S., Wintle, A.G., and Bøtter-Jensen, L. (2002). Electron-trapping probability in natural dosimeters as a function of irradiation temperature. *Radiation Protection Dosimetry*, 101(1-4):339-344. <https://doi.org/10.1093/oxfordjournals.rpd.a005997>
- Wang, W. (2009). Study and progress of the thermoluminescence dating of the ancient pottery and porcelain. *Science in China, Series E: Technological Sciences*, 52(6):1613-1640. <https://doi.org/10.1007/s11431-009-0106-4>
- Wei, J., Jin, J., Fu, L., Zuo, X., Qiu, J., Hou, C., and Xu, D. (2024). New chronology evidence of prehistoric human activities indicated by pottery luminescence dating in the humid subtropical mountains of South China. *Journal of Archaeological Science*, 171:106072. <https://doi.org/10.1016/j.jas.2024.106072>
- Zarie, K.A., El-Fiki, S.A., A1-Saleh, F.S., A1-Harbi, A.A., and A1-Hammad, N.A. (2001). Dating of ancient pottery in Najran (Al-ukhdud) using the thermoluminescence technique. *Isotope & Radiation Research*, 33(3):331-337.