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Classification of geologic materials used in the Sukhothai Historical Park of Thailand using a portable X-ray fluorescence analyzer and petrographic analysis

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Abstract
The Sukhothai Historical Park, designated as a world heritage site in Thailand, encompasses the remnants of the Sukhothai Kingdom and serves as a valuable locus for geological and geoarchaeological investigations. Situated in the Sukhothai province, the region is characterized by diverse lithologies, including slate, phyllite, and laterite, as well as red bricks (synthetic materials), utilized in the construction of various ancient structures. Petrographic analysis using polarized light microscopy reveals the phyllites as the primary dimension stones, exhibiting foliated and mylonitic textures with small quartz augen. A portable X-ray fluorescence analyzer was employed for geochemical analysis and the analysis of major oxides and trace elements. The resulting data facilitated the classification of protoliths and comparison with rocks from an abandoned quarry near Saritphong Dam in the western part of the historical park. Notably, phyllites utilized in several prominent structures within the park; Wat Saphan Hin, Wat Pa Daeng 2, Wat Thap Sakae, Wat Chetuphon, Wat Sri Chum, and Wat Mangkorn Temples, exhibited similar characteristics to those in the Wat Khao Noi old quarry, as confirmed by Rubidium (Rb) and Strontium (Sr) values. The SiO_2/Al_2O_3 and FeO/K_2O ratios were pivotal in identifying the protoliths of the studied phyllites as shales. In summary, the primary dimension stones for Sukhothai Historical Park originated from the western mountain within the park, with laterites sourced from foothill areas. The presence of quartz pebbles in red bricks suggests local sediment utilization, and quartz additions were employed to enhance structural strength. This comprehensive geoarchaeological study sheds light on the geological composition of the Sukhothai Historical Park, providing valuable insights into the selection and utilization of construction materials in this historically significant site.

Keywords Sukhothai Historical Park, Phyllite, Laterite, Geochemistry, Petrography, Geoarcheology

Introduction

The analysis of stones and rocks stands as an enduring and integral facet of human history, with its roots extending to the early periods when individuals sought refuge in natural formations like escarpments, caves, inverted slopes, and rock shelters for protection against inclement weather conditions [1]. Across the annals of civilization, the profound exploration and utilization of building stones have persisted, with these materials often serving as enduring canvases for the engraving of human activities [2, 3]. The study of heritage stones emerges as

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a linchpin in advancing our comprehension of ancient civilizations, offering invaluable insights into their cultures and practices [4]. Many stones now designated as heritage stones were originally employed for construction purposes, occasionally assuming functions beyond their initial utilitarian roles [5].

Within the scholarly exploration of megalithic monuments, the investigation of construction materials assumes paramount importance. A myriad of studies is dedicated to unraveling the lithologies and origins of expansive stone supports, a foundational pursuit crucial for comprehending site selection, operational sequences (including transport), levels of architectural specialization, the symbolic significance of stones, and even the dynamics of mobility and territorial interactions among social groups [6]. The selection and procurement of materials for megalithic structures are influenced by numerous factors, including accessibility, physical properties, visual characteristics, symbolic attributes, cultural significance, and adherence to technical traditions [6]. Notable instances, such as the use of local rocks in western European megaliths as detached blocks or the incorporation of sandstone blocks from quarries located kilometers away in the Stones of Stenness and Ring of Brodgar, exemplify the diverse and intricate processes involved in the construction of these monumental structures [7, 8, 9]. Moreover, the remarkable case of Stonehenge, with its 'bluestones' traced back to distant quarries in the Preseli Hills of western Wales, underscores the complexity and extensive scope of ancient megalithic endeavors [10, 11].

The selection of construction materials for megalithic structures was a nuanced process, influenced not only by the physical attributes of rocks, such as hardness and strength, but also by their visual and aesthetic properties, including color, light, lustre, and texture [12, 13]. Quartz, for example, was intentionally employed in external areas of megaliths to enhance their visual impact [14–16]. Further instances exemplify deliberate choices, such as the use of limestone with ichnofossils for dolmen headstones in the Lisbon region [17] and the incorporation of sedimentary rocks with bioturbation and sedimentary structures resembling megalithic art in tholos tombs like La Pastora and Matarrubilla [18]. Symbolic considerations played a significant role in the site and material selection process, as evidenced by the spatial association between rocky outcrops, with or without rock art, and megaliths, contributing to the creation of monumental landscapes with a pronounced territorial imprint [19–22]. Additionally, practices like the reuse and recycling of standing-stones and steles in tombs across diverse regions, including Brittany, the British Isles, and the Iberian Peninsula, were driven by symbolic reasons [23–27]. This dual consideration of both functional and symbolic aspects sheds light on the complexity and intentionality underlying megalithic construction practices.

The utilization of specific materials in megalithic monuments may carry cosmogonic and cultural significance, reflecting the lithologies and geological formations of the surrounding environment [12, 24]. This significance extends to considering the geographical origins of rocks [28] or the provenance of monument builders [8]. Understanding these aspects necessitates a consideration of the technical traditions of megalithic groups, where correlations between architectural styles and lithotypes are observed, such as the use of volcanic rocks from the Iberian Pyrite Belt in the construction of the eastern Andévalo region [29].

Provenance area analysis assumes a critical role in research, providing insights into the criteria for material selection, strategies of exploitation, and conditions of transport. The comprehensive study of Stonehenge serves as a notable example [10, 11, 30–36]. Similarly, significant research has been undertaken at various sites in the Iberian Peninsula, including the dolmens of Menga and Viera, the tholos tomb of La Pastora in the necropolis of Valencina de la Concepción, the dolmen of La Chabola de la Hechicera in the Basque Country, and the megalithic necropolis of Panoría in the Guadix Depression [18, 37–41]. These investigations collectively contribute to a deeper understanding of the symbolic and practical dimensions associated with the use of specific materials in megalithic constructions.

In recent decades, significant strides in archaeological knowledge regarding the prehistory and early history, particularly the Dvaravati period, of Thailand have been achieved through extensive and enduring research initiatives. These investigations have systematically addressed a range of issues, including changes in subsistence practices, settlement patterns, technological advancements, socio-political structures, trade dynamics, and external influences [42–55]. This surge in archaeological efforts has notably enriched our understanding of Thailand's historical evolution during this era. However, despite existing research on the categorization of materials within Dvaravati archaeological sites in central Thailand [56], a discernible gap remains in comprehensive studies concerning the materials utilized in megalithic structures across Thailand's historical landscape.

This research project delves into the geological characteristics of ornamental stones, serving as construction materials in Sukhothai Historical Park, situated in Mueang Kao Subdistrict (Mueang Kao Subdistrict Municipality), Mueang Sukhothai District, Sukhothai Province. The study involves the analysis of rock samples' geochemistry using portable X-ray fluorescence spectrometry (XRF) and the examination of rock formations under a polarized light microscope. This comprehensive approach includes a comparison of the physical characteristics of the materials to establish their origins.

Sukhothai Historical Park is situated in the Mueang Kao Subdistrict Municipality, Mueang District, Sukhothai Province, within the upper central region of Thailand. It is located 12 km to the west of Sukhothai City and 447 km from Bangkok. The Fine Arts Department has officially registered the ancient city of Sukhothai, encompassing an area of 43,750 rai or ~ 70 km^2, inclusive of each historical site. Evidence of human settlement dating back to prehistoric times has been discovered, particularly in Sri Nakhon, Ban Dan Lan Hoi, and Kirimat Districts, revealing the existence of a prehistoric community. These communities endured over time, ultimately forming a colony around the 12th Buddhist century. During this period, interactions occurred between this community and other regions in the central and northeastern areas influenced by Dvaravati culture.

Sukhothai Historical Park was initially designated as a protected site through a Royal Gazette announcement (Volume 92, Section 112, dated 2 August 1961). Subsequently, in 1976, a restoration project for the park received approval and officially commenced in July 1988. On December 12, 1991, UNESCO declared Sukhothai Historical Park a world heritage site, along with the historical parks at Kamphaeng Phet and Si Satchanalai, under the designation "Historic Town of Sukhothai and Associated Historic Towns" [57].

The city plan of Sukhothai is rectangular, spanning ~ 2 km in length and 1.6 km in width. Each side of the city wall features a city gate, with traces of the palace and 26 temples, including the prominent Wat Mahathat Temple, located within. The park has undergone restoration by the Fine Arts Department, aided by UNESCO, and attracts hundreds of thousands of visitors annually, accessible by foot or bicycle (Fig. 1).

Sukhothai Historical Park comprises a total of 193 historical sites, with 58 officially designated as registered historical sites [59]. The majority of these historical sites were constructed using slate, laterite, and red bricks, expected to originate from sources proximate to the old city. However, no empirical research has substantiated this historical or archaeological hypothesis. Consequently, this study investigates the stone characteristics of slate, laterite,

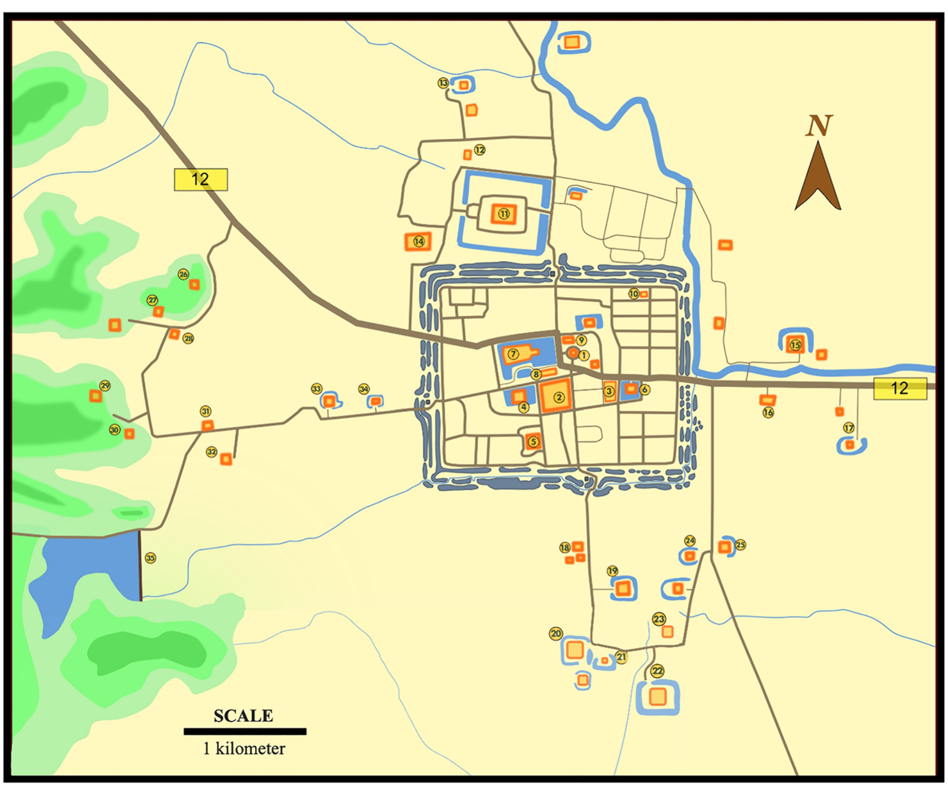

Fig. 1 Map of Sukhothai Historical Park, Sukhothai Province, northern Thailand (modified from Map of Sukhothai Historical Park [58])

and red bricks from sources near Sukhothai Old City, aiming to connect geographic and geological features to the creation of Sukhothai in a more scientifically informed manner.

Geologic setting

Geological features in the Sukhothai Province encompass sediments of the Quaternary age, influenced by the Yom River's flow, covering the central and eastern regions. The northern section and parts of the western coast exhibit karst topography characterized by Permian limestone. Moving southwards, a prominent high mountain range known as Khao Luang Sukhothai emerges, composed of Carboniferous rocks, including metatuff, quartzite, schist, quartz schist, chlorite schist, and limestone lenses. This formation dates back ~ 286–360 ma. In addition to these formations, there are faint occurrences of Triassic intrusive rocks and Permo-Triassic volcanic rocks scattered to the west. This geological configuration is illustrated in Fig. 2 [60]. The various rock types and formations contribute to the diverse geological landscape of Sukhothai Province, offering insights into the region's geological history and evolution over millions of years.

Methods

The study commenced with the compilation of information pertaining to Sukhothai Historical Park, encompassing topographical conditions, the geographic environment, geological aspects, and the historical construction of both Sukhothai Historical Park and its surrounding areas. This initial phase was grounded in academic reports concerning lithology and the geochemistry of rocks in the study area as well as geologic maps, drawing on prior research, relevant theories, and established principles. Following the literature review, the research design incorporated plans for field data collection specifically focused on geological field observation of 8 study points, consisting of Wat Saphan Hin, Wat Pa Daeng 2, Wat Thap Sakae, Wat Chetuphon, Wat Sri Chum, and Wat Mangkorn Temples as well as Wat Khao Noi old quarry, and lateritic resources (Table 1).

This stage involved the characterization of construction materials and the conduct of geochemical studies on rock samples. Samples of rocks sourced from the Sukhothai Historical Park and an antiquated quarry, exhibiting smooth surfaces devoid of moss and humidity, and showcasing minimal variation, were meticulously selected for X-ray analysis with the instrument to ensure the derivation of highly accurate analytical outcomes. X-ray Fluorescence Spectrometry (XRF) was employed in geochemical mode, with quantification expressed in parts per million (ppm), see Additional file 1. To mitigate the effects of non-homogeneous texture in the studied rocks, each sample was analyzed thrice, and the resulting averages were calculated. A portable X-ray fluorescence spectrometry (Olympus Vanta XRF analyser) was utilized to measure major oxides and trace elements. The standard C series (VCR) is outfitted with a silicon drift detector, a 40 kV X-ray tube, and a rhodium (Rh) anode. Conversely, the M series (VMR) is equipped with a large-area silicon drift detector and a 50 kV X-ray tube, also with a Rh anode.

In instances where objects had been lost at old mining areas and ancient sites, rock samples were systematically collected for additional petrography studies, conducted under the supervision of archaeologists. To facilitate comprehensive analysis, 11 samples of thin sections, were created from the collected rock samples. These thin sections served as representative specimens for petrographic analysis under the Nikon polarized light microscope, connecting with Zeiss Light Microscopes and ZEN core free Imaging Software, enabling the classification of textures and rock names. This multi-faceted approach ensured a robust investigation into the geological and petrographic characteristics of the Sukhothai Historical Park area, incorporating both existing academic knowledge and original field data.

Results

Specific architectural applications of these phyllite materials were observed in various structures within Sukhothai Historical Park (Fig. 3). Wat Saphan Hin Temple, for instance, utilized phyllites as construction material for the stairs leading to the top of Wat Saphan Hin Temple courtyard. Wat Chetuphon Temple employed phyllites for the construction of stairs, floors, door frames, window frames, walls, and Semas. Similarly, Wat Pa Daeng 2 and Wat Thap Sakae Temples used phyllites for the construction of floors, monastic seats, and Semas. Wat Sri Chum Temple utilized phyllites for constructing floors and door frames, whereas Wat Mangkorn Temple employed them for constructing SEMAs.

Furthermore, the construction materials varied across different structures. Laterite was predominantly used for large walls, floors, pillars, and the bases of pagodas. Red bricks, on the other hand, were primarily utilized in the construction of walls and pagodas. These detailed observations contribute to a comprehensive understanding of the geological materials employed in diverse architectural elements within Sukhothai Historical Park.

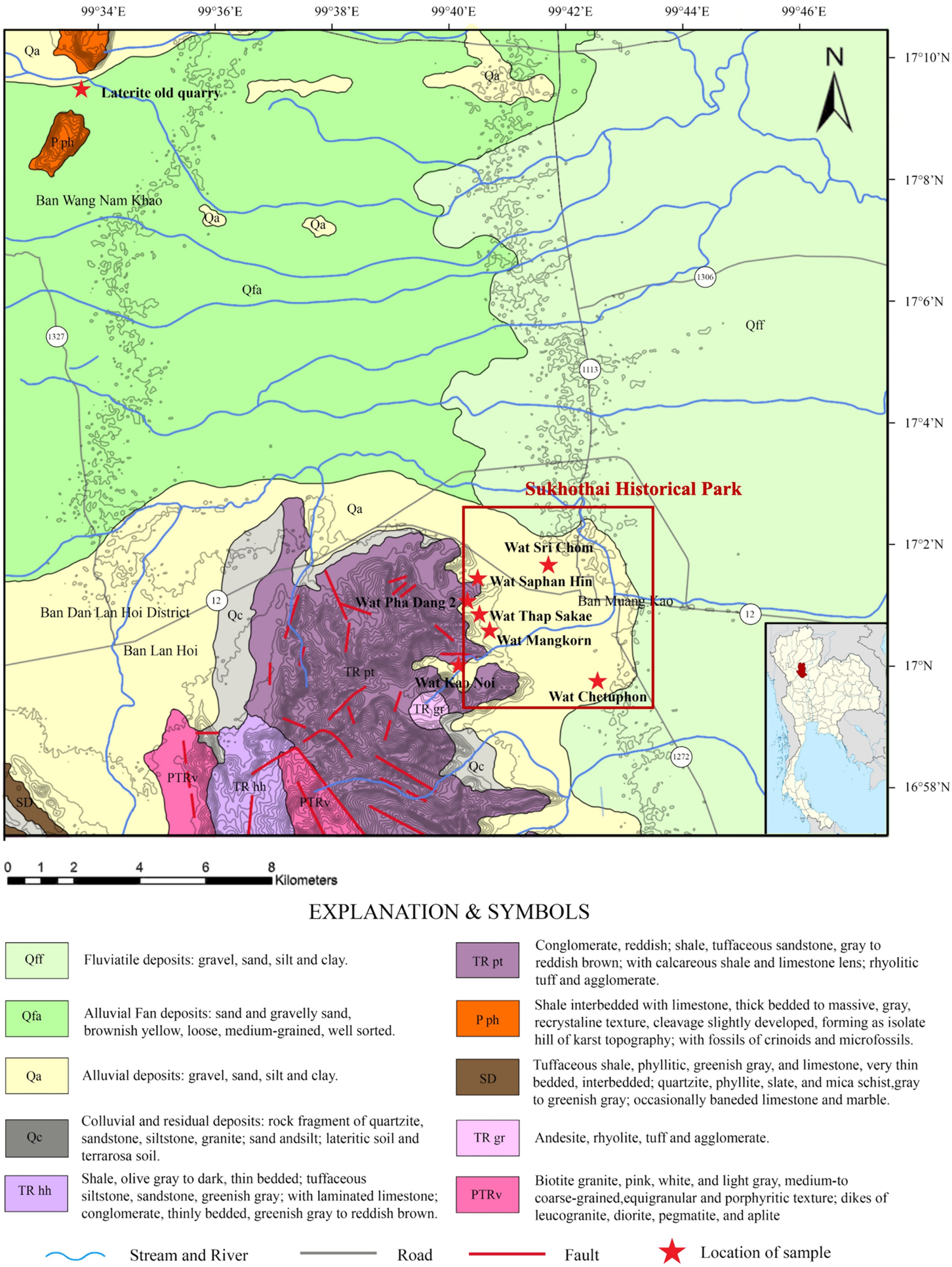

Fig. 2 Geologic map of Sukhothai Historical Park, Sukhothai Province, northern Thailand (Geologic data modified from department of mineral resources [60])

Table 1 Location and sample number for geochemical and lithological studies

No	Location (47Q)	Sites	Geochemical samples	Lithologic samples
1	1882216N 572049E	Wat Saphan Hin Temple	ST-1-1, ST-1-2, ST1-3, ST-1-4, ST-1-5	SK1-1, SK1-2, SK1-3, SK1-4, SK1-5, SK1-6
2	1881418N 571690E	Wat Pa Daeng 2 Temple	ST-2-1, ST-2-2	–
3	1881418N 571904E	Wat Thap Sakae Temple	ST-3-1, ST-3-2	–
4	1880043N 571318E	Wat Chetuphon Temple	ST-1-1, ST-4-2, ST-4-3, ST-4-4, ST-4-5, ST-4-6	SK4-1
5	1881250N 572113E	Wat Mangkorn Temple	ST-6-1, ST-6-2, ST-6-3, ST-6-4	–
6	1882664N 573821E	Wat Sri Chum Temple	ST-5-1, ST-5-2, ST-5-3	–
7	1897863N 558464E	Wat Khao Noi old quarry	ST-8-1, ST-8-2, ST-8-3, ST-8-4, ST-8-5, ST-8-6, ST-8-7, ST-8-8, ST-8-9, ST-8-10	SK8-1, SK8-2 SK8-3, SK8-4
8	1880029N 571328E	Lateritic resources	ST-7-1, ST-7-2, ST-7-3, ST-7-4, ST-7-5	–

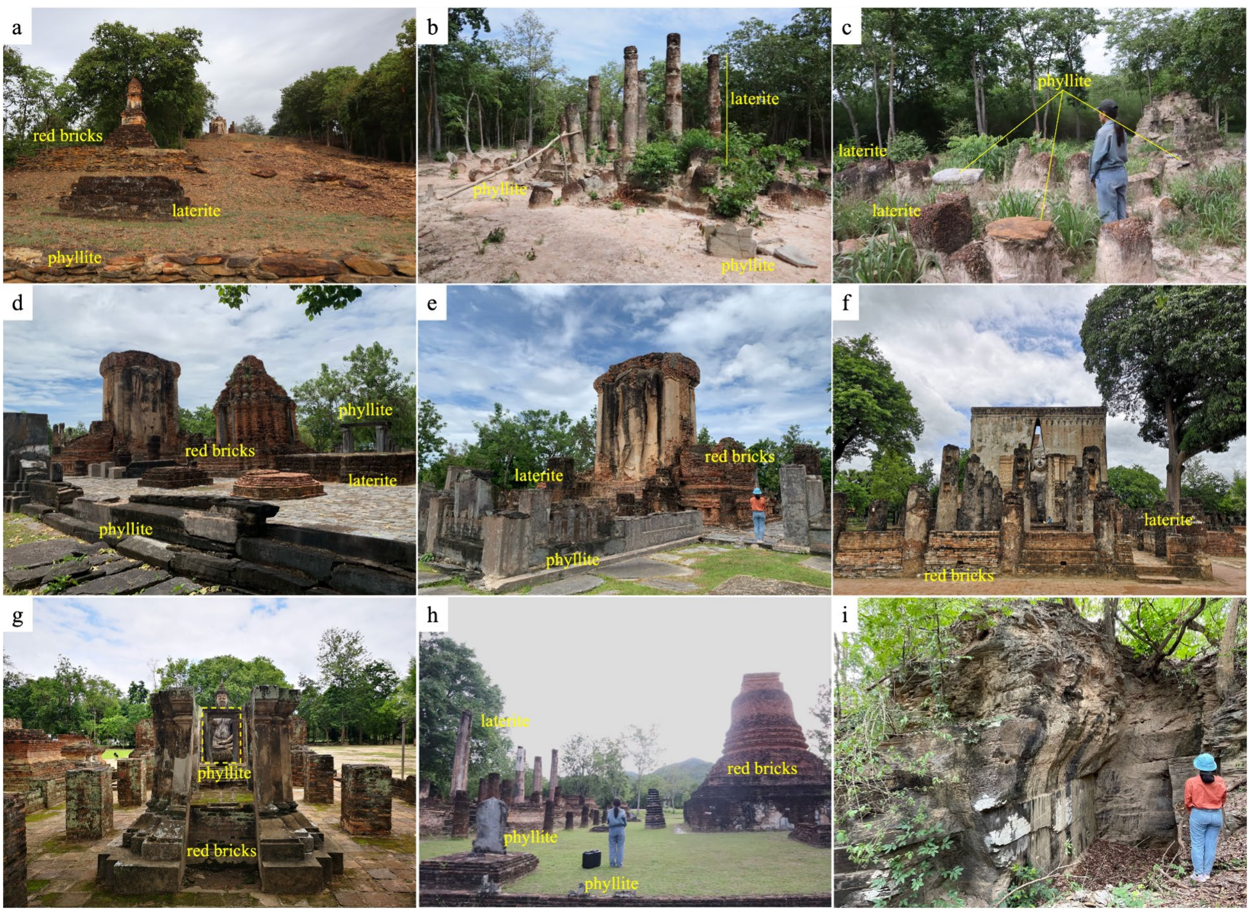

Fig. 3 Photographs of dimension stone used in the Sukhothai Historical Park and quarries of phyllite in Sukhothai Province. **a** Wat Saphan Hin Temple, **b** Wat Pa Daeng 2 Temple, **c** Wat Thap Sakae Temple, **d**, **e** Wat Chetuphon Temple, **f**, **g** Wat Sri Chum Temple, (**h**) Wat Mangkorn Temple, and (**i**) phyllite quarry at Wat Khao Noi Temple

Lithology

The lithologic characteristics of dimension stones in Sukhothai Historical Park indicate that geological materials such as phyllite, laterite, and clay bricks were utilized in the construction of ancient cities during the Sukhothai period. The phyllite exhibits a foliated texture, and certain sections display a mylonitic texture with small quartz augen.

The laterite employed as a construction material is poorly graded and contains phyllite fragments ranging from 5 mm to 10 cm in width. This stands in contrast to the laterite found in cutting rocks or lateritic resource sites, as the laterite in this area has been meticulously selected for construction purposes. Additionally, the clay bricks employed in construction feature quartz gravel measuring 1 mm to 5 cm in size. These distinctive lithologic characteristics provide valuable insights into the geological composition of the construction materials used in the Sukhothai period, shedding light on the careful selection and utilization of specific rocks and minerals in the building processes of ancient cities within Sukhothai Historical Park.

Petrographic data

The examination of thin sections under a polarized light microscope from phyllite specimens sourced from Sukhothai Historical Park yielded noteworthy findings. The mineral composition was identified to include quartz, muscovite, biotite, and opaque minerals, each exhibiting a fine size ranging from approximately 0.5 to 0.75 mm (Fig. 4).

Quartz minerals manifested subhedral crystals, characterized by undulose extinction features. Muscovite displayed anhedral crystals with moderate alteration to clay minerals, while biotite exhibited anhedral crystals undergoing moderate alteration to chlorite. Opaque minerals showcased anhedral crystals without signs

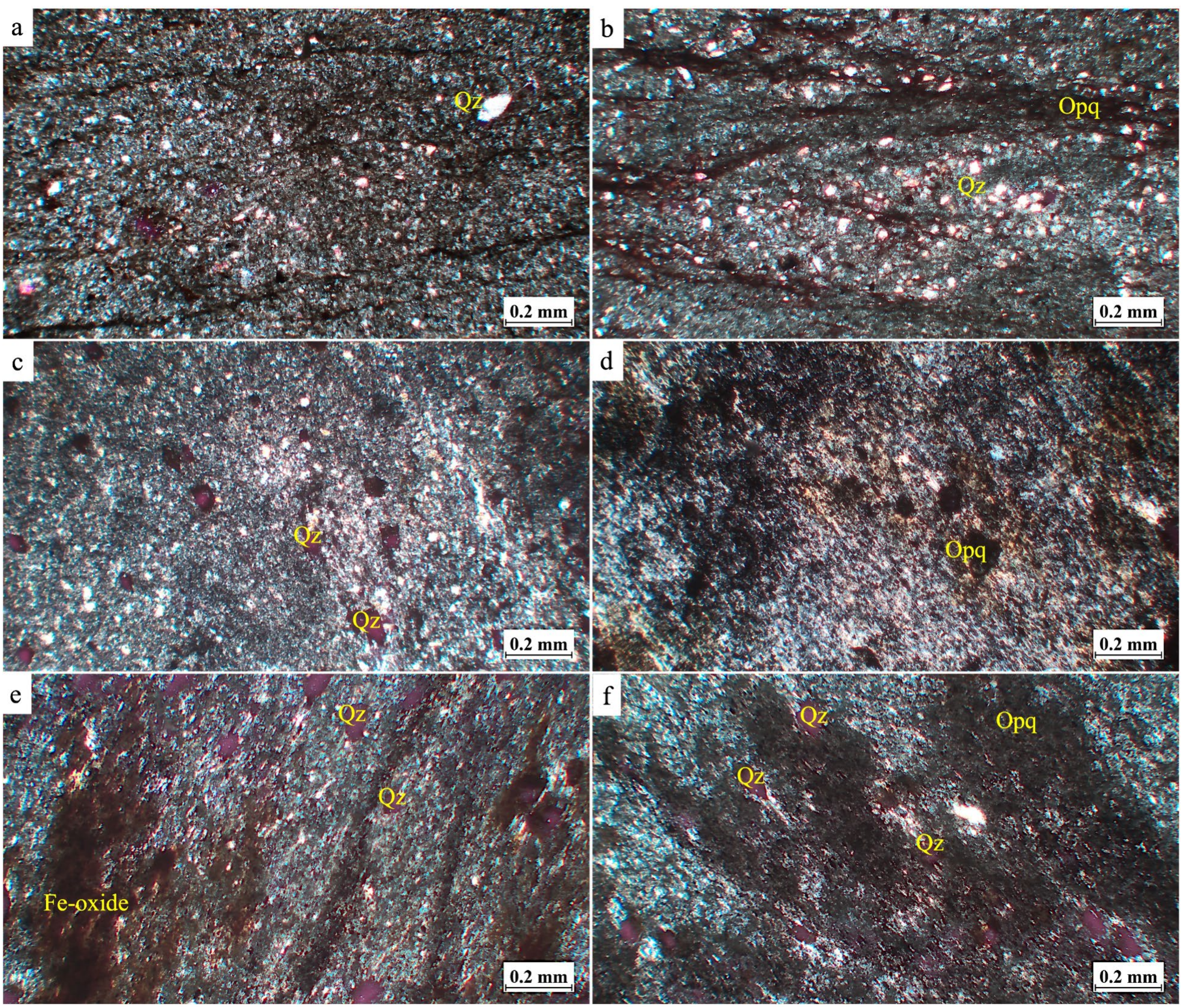

Fig. 4 Photomicrographs of phyllite in the Sukhothai Historical Park and quarries in Sukhothai Province. **a** Wat Chetuphon Temple, **b**–**d** Wat Saphan Hin Temple, **e**, **f** phyllite quarry at Wat Khao Noi Temple. *Qz* quartz, *Opq* opaque minerals, *Fe-Oxide* Fe-rich oxide minerals

of alteration but rather displayed a parallel striated arrangement indicative of foliation (Fig. 4).

Geochemical characteristics

This study utilized X-ray fluorescence spectrometry to conduct testing on phyllite rocks at all eight designated study points within Sukhothai Historical Park, see in Additional file 1. The objective was to analyze the geochemistry of the rocks, specifically focusing on the classification of trace elements.

The geochemical analysis aimed to classify the major oxides, including iron oxide (Fe_2O_3), potassium oxide (K_2O), silicon dioxide (SiO_2), and aluminium oxide (Al_2O_3), in order to categorize the protolith or original rocks of the phyllite within Sukhothai Historical Park. This investigation employed a portable X-ray fluorescence analysis for chemical classification, utilizing the criteria for sandstones outlined by Herron [61], as illustrated in Fig. 5.

The protoliths of rocks at all study sites within Sukhothai Historical Park and the Wat Khao Noi rock quarry site, which were subjects of study, exhibited similarities classified as shale. These metamorphic rocks originated from sedimentary rocks, specifically interbedded shale and sandstone, comparable to the Phrathat Formation within the Lampang Group, as indicated on the geological map [61], and underwent metamorphism due to a shear zone.

In addition, the study analyzed trace elements, specifically rubidium (Rb) and strontium (Sr), to compare the sources of stones used as construction materials in Sukhothai Historical Park with those assumed to be derived from the old quarry. Based on the mineral framework, Rb has the potential to replace K^+ ions in alkaline feldspars, biotite, muscovite, and similar minerals, while Sr can substitute Ca^{2+} ions in plagioclase, calcite, epidote, and related mineral species. Hence, the Rb/Sr ratio serves as a pivotal parameter for discerning the composition of various rock types, including sedimentary grains and cementitious materials, as well as gauging the extent of alteration. Similar Rb/Sr ratios among rocks may indicate shared lithological characteristics and possibly a comparable depositional age.

The observed phenomenon is attributable to the genesis of the studied phyllite, wherein its parent material likely comprises sedimentary formations like shale, which might not have existed as a singular entity and underwent metamorphic processes. Consequently, the distribution of minerals within the resultant phyllite may exhibit

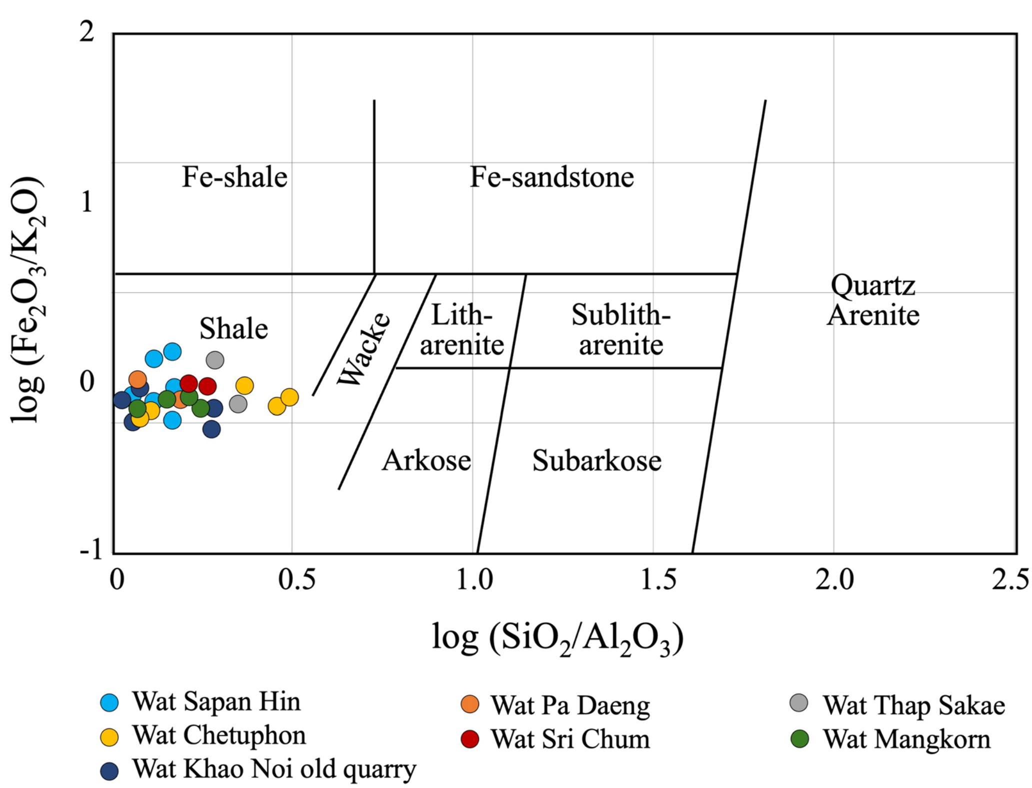

Fig. 5 Protolith classification diagram of metamorphic rocks by log (SiO_2/Al_2O_3) vs. log(Fe_2O_3/K_2O) (diagram outline modified from Herron [61])

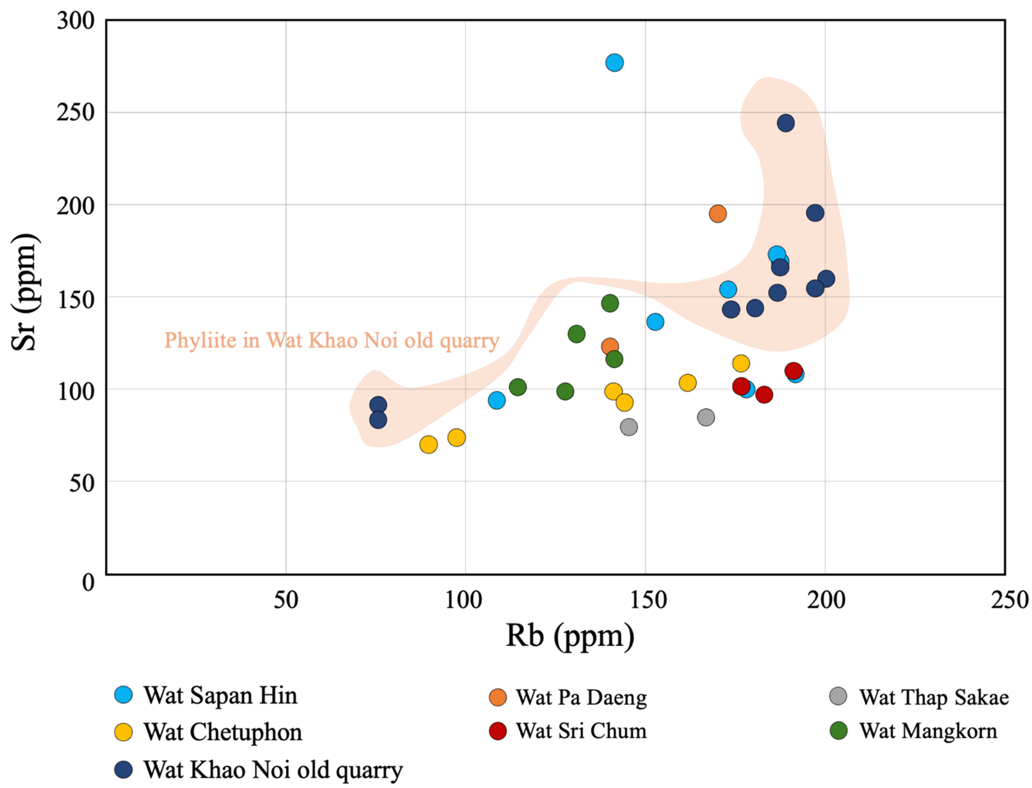

Fig. 6 Rubidium (Rb) versus Strontium (Sr) content for phyllite used in the Sukhothai Historical Park and Wat Khao Noi old quarry. The shaded region delineates the spectrum of Rb vs. Sr concentrations observed within the phyllite samples sourced from the historical quarry site at Wat Khao Noi

irregularity across its mass. Consequently, localized zones enriched with potassium and calcium-bearing minerals manifest elevated concentrations of Rubidium (Rb) and Strontium (Sr). This geological scenario thus delineates two discernible categories within the Wat Khao Noi old quarry: one characterized by lower Rb–Sr data, and the other occupying a broader Rb–Sr spectrum.

Figure 6 illustrates the relationship between the quantities of rubidium and strontium, where Rb ranges from 78 to 198 ppm, and Sr ranges from 41 to 272 ppm. The distribution of rocks sourced from the quarry at Wat Khao Noi Temple may vary considerably; nevertheless, it spans the entire range of phyllite rocks utilized in the construction of the Sukhothai Historical Park, encompassing both the lowest and highest values. These findings provide significant insights into the geological characteristics, including mineral compositions, cementation processes, and alteration patterns, as well as the provenance of the construction materials utilized in the historical park, aligning with those of the Wat Khao Noi Quarry.

Discussion

Petrographic and geochemical analyses were conducted on phyllitic rocks within the Sukhothai Historical Park, encompassing a total of eight study points, including Wat Saphan Hin Temple, Wat Pa Daeng Temple 2, Wat Thap Sakae Temple, Wat Chetuphon Temple, Wat Sri Chum Temple, Wat Mangkorn Temple, laterite resources sites, and old quarry at Wat Khao Noi. The findings indicated that ancient cities during the Sukhothai period utilized geological materials such as phyllite, laterite, and clay bricks. Phyllite exhibited a foliated texture, with certain sections displaying mylonite. Laterite used as construction material exhibited poor sorting and contained various sizes of phyllite fragments (Figs. 7a, b), distinguishing it from laterite found in the laterite resources sites (Figs. 7d, e), as the laterite in this region was carefully selected. Clay bricks utilized in construction contained quartz gravel (Fig. 7f).

Quartz, a hard and durable mineral, adds structural integrity to the bricks, making them more resistant to wear, weathering, and other environmental factors as well as showing more strength than normal brick [62].

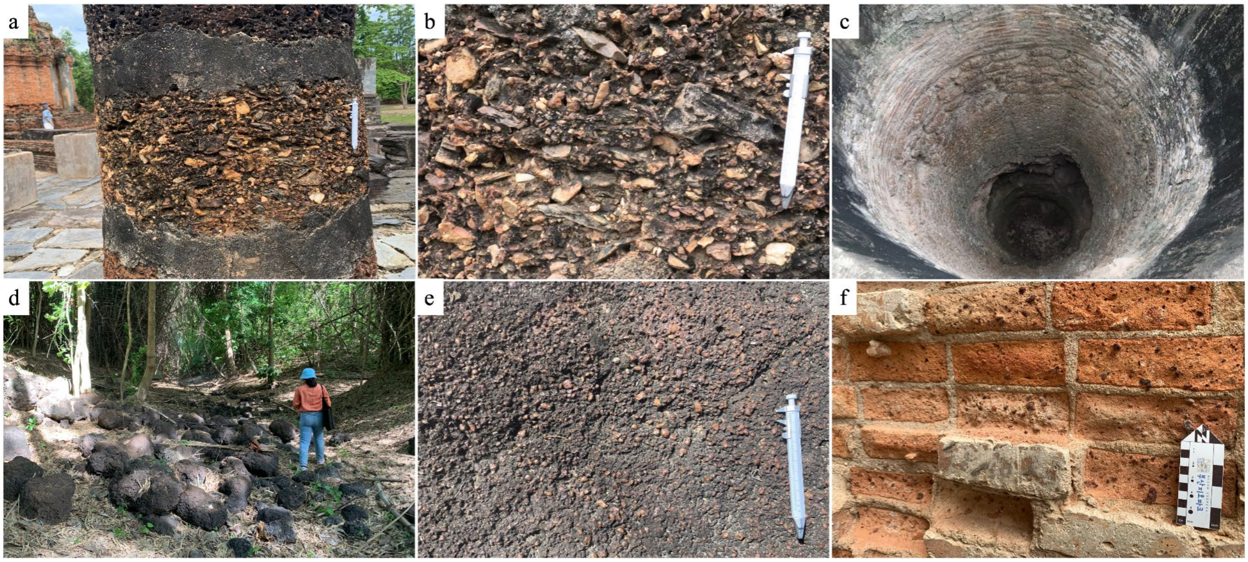

Fig. 7 Photographs of laterite and red bricks used in the Sukhothai Historical Park and laterite resources. **a** Pillar at Wat Chetuphon Temple, **b** pillar at Wat Pa Daeng 2 Temple, **c** pond at Wat Pa Daeng 2 Temple, **d** lateritic boulders at laterite resources, **e** well-sorted laterite at laterite resources, and (**f**) red bricks with gravels

The examination of the representative samples under a polarized light microscope in the Sukhothai Historical Park area revealed a mineral composition including quartz, muscovite, biotite, and opaque minerals with a fine size of ~ 0.5 to 0.75 mm, arranged in parallel lines as foliations. Quartz exhibited a semi-perfect crystal shape, and some displayed characteristics reminiscent of augen by fault movement consistent with the geologic setting of the area [60].

Additionally, results from the geochemical analysis ($\log(SiO_2/Al_2O_3)$ vs. $\log(Fe_2O_3/K_2O)$) were used to classify the major oxides, specifically iron oxide, potassium oxide, silicon dioxide, and aluminium oxide, to classify the protolith of all studied phyllites as shale.

A geochemical analysis was conducted to identify trace elements, specifically using the ratio of rubidium (Rb) and strontium (Sr) quantities. This comparison aimed to discern the sources of phyllite used as decorative and construction materials in Sukhothai Historical Park with those from the old quarry at Wat Khao Noi. The results demonstrated that phyllite used in decorative stones and construction materials in the study area, including Wat Saphan Hin and Wat Pa Daeng 2, Wat Thap Sakae, Wat Chetuphon, Wat Sri Chum, and Wat Mangkon Temples, were of the same type as the source of that old quarry. This conclusion was drawn based on the proportional relationship between rubidium and strontium elements within the corresponding range, confirming that phyllite originated from the old quarry at Wat Khao Noi.

Through a comparative analysis of the chemical composition of stones utilized in construction and those sourced from antiquated quarries, it was discerned that both major and trace elements exhibited notable similarities, indicating cohesive groupings. This finding aligns with established theories within rock-forming mineral geochemistry, suggesting a congruence in rock type, protolith, cementation processes, and potentially age, given the uniform alteration rates observed, particularly in the transformation of feldspars and mica groups into clay minerals. These observations are further substantiated by the lithological attributes and petrographic examinations conducted across all investigated rock specimens.

Further evidence was uncovered, revealing the use of chisels or sharp tools to shape rocks, resulting in the transformation of the mountain into a wide alcove scattered across the area. Geochemical analyses of rocks within the old quarry at Wat Khao Noi and the surrounding ancient sites support the conclusion that the stones used in constructing the ancient city were sourced from the phyllite mountains on the west side of Sukhothai Historical Park.

The Wat Saphan Hin Temple extensively employed phyllite sourced from the adjacent mountain to construct the bridge leading to the primary temple structure. This practice aligns with architectural principles advocating for the utilization of materials readily available at the construction site to mitigate transportation costs. In

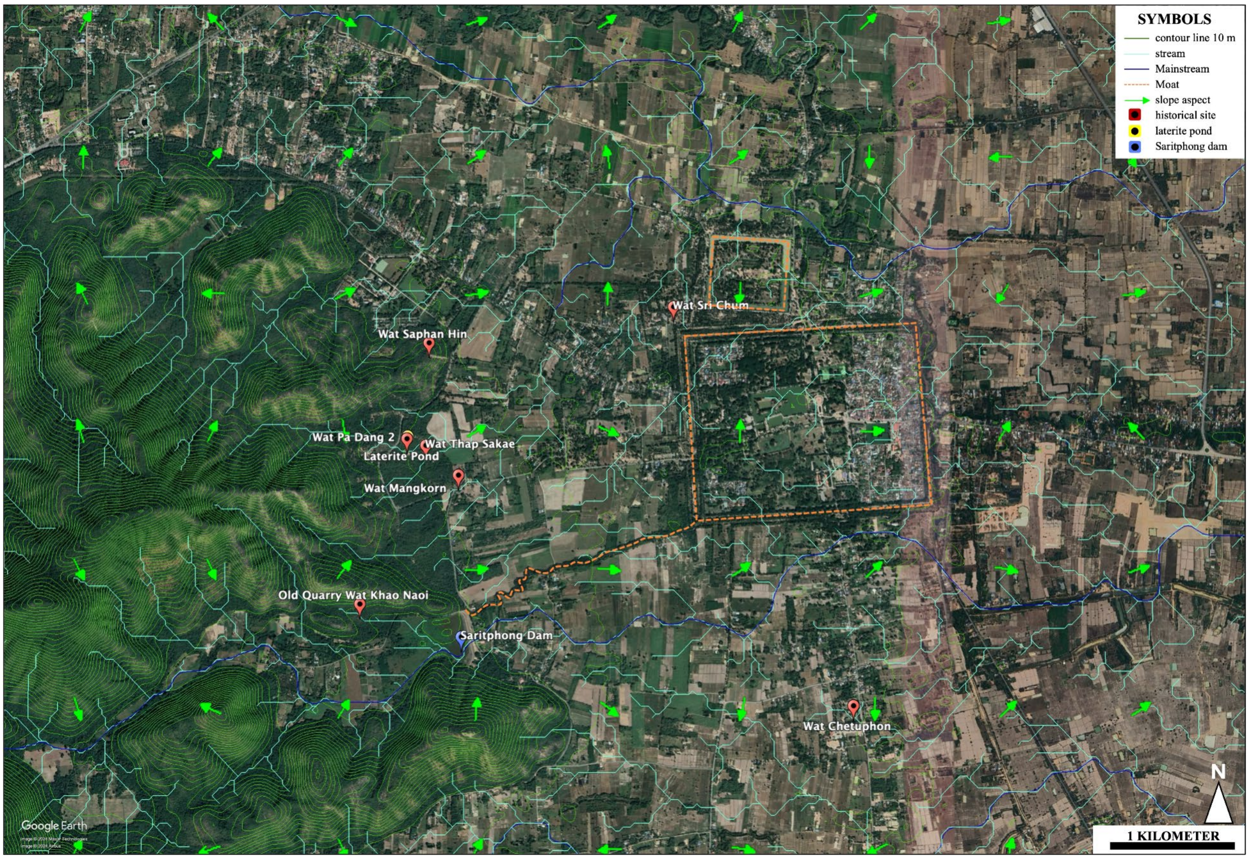

Fig. 8 Satellite image of the Sukhothai Historical Park presented studied points (analyzed by Google Earth Pro [63])

a similar vein, the Wat Chetuphon Temple stands out as a noteworthy example of a temple that extensively incorporates phyllite in its construction, encompassing various elements such as floors, walls, door frames, window frames, and skylights. This geographical region appears to serve as a significant production hub for phyllite, facilitating its distribution for the construction of diverse temples situated at the base of the mountains. It is hypothesized that the transportation of these rocks likely occurred through the primary waterway originating from an antiquated quarry near Saritphong Dam (Fig. 8) similar to the transportation of sandstones used in the Angkor monuments of Cambodia [68].

In the vicinity of the various temples examined, deep ponds were discovered, suggesting a potential source for rock or laterite utilized in construction (Fig. 7c). The study focused on assessing the dimensions of laterite and the size of phyllite fragments within the laterite blocks employed in the construction of the ancient city of Sukhothai. As a result, it is inferred that the laterite used in construction originated from the foothills on the west side of Sukhothai, indicating that the rock fragments were transported from a relatively short distance.

Additional evidence supports the proposition that the laterite in the Sukhothai Historical Park did not originate from the extensive laterite source in the northern part in the discernibly distinct well-sorted. The laterite resource from the north lacks substantial rock fragments but is abundant in metallic ore nodules resembling iron. This observation potentially supports the hypothesis that it served as a historic source of iron ore. Subsequent research will delve into a comprehensive examination of the significant mineral resources of the Sukhothai Kingdom, providing valuable insights for future investigations.

The selection of lithologies for the construction of temples within the immediate environment likely influenced the choice of megalithic group location, easing procurement and allowing restricted use, particularly of mylonitic phyllite outcrops confined to this sacralized space located on the top of the mountain at the western flank of the city.

This preference for mylonitic phyllite can be attributed to both its material properties and symbolic significance. As the sole stone in the local geological environment available in large blocks within a 2 km radius, it possesses favorable conditions for procurement and physical properties suitable for megalithic support [6]. The deliberate acquisition and utilization of this material indicate a planned approach, considering the scarcity of detached blocks on the surface and the necessity for stones with specific morphological and structural characteristics ensuring architectural stability. The intensive exploitation of this resource necessitated strategic planning, manifested in systematic block selection, efficient quarrying practices, and technical expertise in stone placement [6].

The construction process likely followed a linear and continuous sequence, involving concatenated and spatially segmented operations such as acquisition, transport, transformation, and placement of blocks. The magnitude of these architectural projects required collective organization, with the participation of a group of builders, potentially including individuals with high levels of experience and technical specialization, a trend observed in numerous Neolithic monuments in Western Europe [64], Dvaravati archaeological sites in central Thailand [61], historical sites in northeastern Thailand [65], and Khmer Temples in Angkor monument [66–69]. Considering the scale and complexity of these tasks, it is plausible that the workforce from the Sukhothai Kingdom community might have been insufficient. Consequently, individuals from other settlements associated with the Sukhothai Kingdom, communities in central Thailand (i.e. Lopburi) sharing similar architectural styles, or even those from more distant geographical areas might have contributed to the construction (i.e. Cambodia). This mobility of people for megalithic construction could have been a common practice in Southeastern Asia during the Late Neolithic, akin to the alliances between social groups observed in the Swedish region of Falbygden for the construction of gallery dolmens [70].

Conclusion

Various structures (stairs, floors, door frames, walls, monastic seats, and SEMAs) in Sukhothai Historical Park, including Wat Saphan Hin, Wat Chetuphon, Wat Pa Daeng 2, Wat Thap Sakae, Wat Sri Chum, and Wat Mangkorn Temples, employed phyllite materials for a range of construction purposes, contributing to a diverse architectural landscape. The petrographic analysis of phyllite revealed minerals like quartz, muscovite, biotite, and opaque minerals, displaying fine-sized particles and organized foliations. Additionally, SiO_2/Al_2O_3 and FeO/K_2O ratios identified the protolith as shale and the Rb/Sr ratio confirmed that the phyllite originated from the old quarry at Wat Khao Noi, offering insights into the geological and historical aspects of construction practices in the park. The petrographic and geochemical analyses revealed analogous compositions and alteration patterns among the materials and rocks extracted from the former quarry site. The study also assessed the sorting and sizes of phyllite fragments in the construction blocks (large pillars and floors), indicating that laterite used in Sukhothai's ancient city originated from the west side foothills, providing valuable information about the transportation of rock fragments over a short distance. Further evidence suggests that the laterite used in the park, distinctively poorly sorted and containing substantial rock fragments, differs from the extensive laterite source in the northern part, potentially indicating its historical use as a source of iron ore. Meanwhile, red bricks utilized for walls and pagodas contain numerous quartz pebbles, which could have been produced from nearby sediments, and quartzes might have been incorporated to enhance strength.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-024-01259-5.

Additional file 1: S1. Chemical analysis of phyllitic rocks in Sukhothai Historical Park and Wat Khao Noi old quarry.

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Author contributions

V.S. and B.P. conceptualization; V.S., S.J., N.P., B.P. field observation, data curation, resources, and materials; V.S. and S.J. methodology, formal analysis, and prepared figures; V.S. writing (original draft preparation – review and editing). All authors reviewed the manuscript.

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Data availability

The data that support the current study are available in the article.

Declarations

Ethics approval and consent to participate
This study excludes investigations involving both human and/or animal subjects.

Competing interests
The authors assert the absence of any identified conflicting financial interests or personal affiliations that might have presented perceived influence on the findings reported in this manuscript.

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References
1. Gori S, Falcucci E, Galadini F, Moro M, Saroli M, Ceccaroni E. Geoarchaeology and paleoseismology blend to define the Fucino active normal fault slip history, central Italy. Quat Int. 2017;451:114–28. https://doi.org/10.1016/j.quaint.2017.01.028.
2. Smith BD, Zeder MA. The onset of the Anthropocene. Anthropocene. 2013;4:8–13. https://doi.org/10.1016/j.ancene.2013.05.001.
3. Finney SC. The 'Anthropocene' as a ratified unit in the ICS International Chronostratigraphic Chart: fundamental issues that must be addressed by the Task Group. In: Waters CN, Zalasiewic JA, Williams M, Ellis MA, Snelling AM, editors. A stratigraphical basis for the anthropocene. London: Geological Society; 2014. p. 23–8. https://doi.org/10.1144/sp395.9.
4. Ruddiman WF, Ellis EC, Kaplan JO, Fuller DQ. Defining the epoch we live in. Science. 2015;348:38–9. https://doi.org/10.1126/science.aaa7297.
5. Freire-Lista DM. The forerunners on heritage stones investigation: historical synthesis and evolution. Heritage. 2021;4:1228–68. https://doi.org/10.3390/heritage4030068.
6. Linares-Catela JA, Donaire Romero T, Mora Molina C, Cáceres PL. Choosing the site, getting the stones, building the dolmens: local sourcing of andesites at the El Pozuelo megalithic complex (Huelva, Spain). Archaeol Anthropol Sci. 2023;15:101. https://doi.org/10.1007/s12520-023-01799-0.
7. Scarre C. Stony ground: outcrops, rocks and quarries in the creation of megalithic monuments. In: Scarre C, editor. Megalithic quarrying. Source, extracting and manipulating the stones. BAR International Series 1923. Oxford: Archaeopress Oxford; 2009. p. 3–20.
8. Richards C. Building the great stone circles of the north. London: Oxbow Books; 2013.
9. Cooney G. Landscape of neolithic Ireland. London: Routledge; 2000.
10. Parker Pearson M, Pollard J, Richards C, Welham K, Casswell C, French C, Schlee D, Shaw D, Simmons E, Stanford A, Bevins R, Ixer R. Megalith quarries for Stonehenge's bluestones. Antiquity. 2019;93(367):45–62. https://doi.org/10.15184/aqy.2018.111.
11 Parker Pearson M, Bevins R, Ixer R, Pollard J, Richards C, Welham K. Long-distance landscapes: from quarries to monument at Stonehenge. In: Boaventura R, Mataloto R, Pereira A, editors. Megaliths and geology. Oxford: Archaeopress Oxford; 2020. p. 151–70.
12. Scarre C. Choosing stones, remembering places. Geology and intention in the megalithic monuments of western Europe. In: Boivin N, Owoc MA, editors. Soils, stones and symbols. Cultural perceptions of the mineral world. London: UCL Press; 2004. p. 187–202.
13. Darvill T. Megaliths, monuments and materiality. In: Furholt M, Lüth F, Müller J, editors. Megaliths and identities. Early monuments and neolithic societies from the Atlantic to the Baltic. Bonn: Dr Rudolf Habelt GmbH; 2011. p. 35–46.
14. Jones A. Local colour: megalithic architecture and colour symbolism in Neolithic Arran. Oxf J Archaeol. 1999;18:339–50. https://doi.org/10.1111/1468-0092.00088.
15. Trevarthen D. Illuminating the monuments: observation and speculation on the structure and function of the cairns at Balnuaran of Clava. Camb Archaeol J. 2000;10(2):295–315. https://doi.org/10.1017/S0959774300000111.
16. Cummings V. Experiencing texture and transformation in the British Neolithic. Oxf J Archaeol. 2002;21(3):249–61. https://doi.org/10.1111/1468-0092.00161.
17. Cardoso JA, Boaventura R. The megalithic tombs in the region of Belas (Sintra, Portugal) and their aesthetic manifestations. Trab Prehist. 2011;68(2):297–312. https://doi.org/10.3989/tp.2011.11071.
18. Cáceres LM, Vargas JM, Muñiz F, Donaire T, GarcíaSanjuán L, Odriozola C, Rodríguez-Vidal J. Natural, "megalithic art" at Valencina (Seville): a geoarchaeological approach to stone, architecture, and cultural choice in Copper Age Iberia. Archaeol Anthropol Sci. 2019;11:4621–41. https://doi.org/10.1007/s12520-019-00870-z.
19. Tilley C. A phenomenology of landscape. Places, paths and monuments. Oxford: Berg; 1994.
20 Tilley C. The powers of rocks. Topography and monument construction on Bodmir Moor. World Archaeol. 1996;28(2):161–78. https://doi.org/10.1080/00438243.1996.9980338.
21 Bradley R. The significance of monuments. On the shaping of human experience in Neolithic and Bronze Age Europe. London: Routledge; 1998.
22. Bradley R. An archaeology of natural places. London: Routledge; 2000.
23. Le Roux CT. New excavations at Gavrinis. Antiquity. 1985;59(227):183–7. https://doi.org/10.1017/S0003598X00057240.
24. Richards C. Monuments as landscape: creating the centre of the world in late neolithic Orkney. World Archaeol. 1996;28(2):190–208. https://doi.org/10.1080/00438243.1996.9980340.
25. Robin G. Spatial structures and symbolic systems in Irish and British passage tombs: the organization of architectural elements, parietal carved signs and funerary deposits. Camb Archaeol J. 2010;20(3):373–418. https://doi.org/10.1017/S0959774310000478.
26. Bueno Ramírez P, BalbínBerhmann R, Barroso BR. Chronologie de l'art Mégalithique ibérique: C14 et contextes archéologiques. L'Anthropologie. 2007;111(4):590–654. https://doi.org/10.1016/j.anthro.2007.07.006.
27. Bueno Ramírez P, BalbínBerhmann R, Barroso BR. Custodian bones: human images in the megalithism of the Southern Iberian Peninsula. In: Cruz A, Cerrillo-Cuenca E, Bueno P, Caninas JC, Batata C, editors. Rendering death: ideological an archaeological narrative from recent prehistory (Iberia). BAR International Series 2648. Oxford: Archaeopress; 2014. p. 3–12.
28. Giot PR. Barnenez, Carn, Guennoc. Travaux du Laboratoire "Anthropologie-Prehistoire-Protohistoire-Quaternaire Armoricans", Equipe de Recherche no. 27. CNRS. Rennes: Université de Rennes; 1987.
29 LinaresCatela JA. The megalithic architecture of Huelva (Spain): typology, construction and technical traditions in eastern Andévalo. In: Laporte L, Scarre C, editors. The megalithic architectures of Europe. Oxford: Oxbow Books; 2016. p. 111–26.
30. Thorpe RS, Williams TO. The myth of long-distance megalithic transport. Antiquity. 1991;65(246):64–73. https://doi.org/10.1017/S0003598X00079308.
31. Patton M. Megalithic transport and territorial markers: evidence from the Channel Islands. Antiquity. 1992;66(251):392–5. https://doi.org/10.1017/S0003598X00081503.
32. Darvill T, Wainwright G. Beyond Stonehenge: Carn Menyn Quarry and the origin and date of bluestone extraction in the Preseli Hills of south-west Wales. Antiquity. 2014;88(342):1099–114. https://doi.org/10.1017/S0003598X00115340.
33. Bevins RE, Pearce NJG, Ixer RA. Revisiting the provenance of the Stonehenge bluestones: refining the provenance of the Group 2 non-spotted dolerites using rare earth element geochemistry. J Archaeol Sci Rep. 2021;38: 103083. https://doi.org/10.1016/j.jasrep.2021.103083.
34. Bevins RE, Pearce NJG, Parker Pearson M, Ixer RA. Identification of the source of dolerites used at the Waun Mawn stone circle in the Mynydd Preseli, west Wales and implications for the proposed link with Stonehenge. J Archaeol Sci Rep. 2022;45: 103556. https://doi.org/10.1016/j.jasrep.2022.103556.
35. Parker Pearson M, Bevins R, Ixer R, Pollard J, Richards C, Welham K, Chan B, Edinborough K, Hamilton D, Macphail R, Schlee D, Schwenninger JL, Simmons E, Smith M. Craig Rhos-y-felin: a Welsh bluestone megalith quarry for Stonehenge. Antiquity. 2015;89(348):1331–52. https://doi.org/10.15184/aqy.2015.177.

36. Ixer R, Bevins R. The bluestones of Stonehenge. Geol Today. 2017;33:180–4. https://doi.org/10.1111/gto.12198.
37. Carrión F, Lozano JA, García D, Muñiz T, Félix P, López CF, Esquivel JA, Mellado I. Estudio geoarqueológico del conjunto de los Dólmenes de Antequera (Málaga, España). In: Calado D, Baldia M, Boulanger M, editors. Monumental questions: prehistoric megaliths, mounds and enclousures. BAR International Series 2122. Oxford: Archaeopress; 2010. p. 57–69.
38 Lozano JA, Ruiz G, Hódar M, Pérez-Valera F, Morgado A. Prehistoric engineering and astronomy of the great Menga Dolmen (Málaga, Spain). A geometric and geoarchaeological analysis. J Archaeol Sci. 2014;41:759–71. https://doi.org/10.1016/j.jas.2013.10.010.
39. Cáceres LM, Muñiz F, Rodríguez-Vidal J, Vargas JM, Donaire T. Marine bioerosion in rocks of the prehistoric tholos of La Pastora (Valencina de la Concepción, Seville, Spain): archaeological palaeoenvironmetal implications. J Archaeol Sci. 2014;41:435–46. https://doi.org/10.1016/j.jas.2013.09.001.
40. Martínez Torres LM, FernádezEraso J, Mujika JA, Rodríguez Miranda A, Valle Melón JM. Geoarchaeology and construction of the La Chabola de la Hechicera Megalithic Tomb, Elvillar. Northern Spain Geoarchaeol An Int J. 2014;29:300–11. https://doi.org/10.1002/gea.21479.
41. Aranda Jiménez G, Lozano JA, Pérez VF. The megalithic necropolis of Panoria, Granada, Spain: geoarchaeological characterization and provenance studies. Geoarchaeol Int J. 2018;33:260–70. https://doi.org/10.1002/gea.21643.
42. Anderson DD. A Pleistocene-early holocene rockshelter in peninsular Thailand. Nat Geo Res. 1987;3:184–98.
43. Bayard D. Excavations at Non Nok Tha, Northeast Thailand 1968: an interim report. Asian Perspect. 1972;13:109–43.
44. Bhumadhon P. The development of towns and communities in the proto-historical period of the Maenam Bangkham Basin, Banmee District, Lopburi Province. Bangkok: Thammasat University; 1999.
45. Bronson B. The late prehistory and early history of Central Thailand, with special reference to Chansen. In: Smith RB, Watson W, editors. Early South East Asia. New York: Oxford University Press; 1979. p. 315–36.
46. Gorman CF. The hoabinhian and after subsistence patterns in Southeast Asia during the late pleistocene and early recent periods. World Archaeol. 1971;2(3):300–20.
47. Higham CFW. The transition from prehistory to the historic period in the Upper Mun Valley. Int J His Archaeol. 1998;2(3):235–60.
48. Higham CF, Kijngam A. Prehistoric investigations in Northeast Thailand. Oxford: British Archaeological Reports; 1984. p. 321.
49. Mudar KM. Prehistoric and early historic settlement patterns on the central plain: analysis of archaeological survey in Lopburi Province, Thailand. Ph.D. dissertation, Department of Anthropology. Ann Arbor: University of Michigan; 1993.
50. Natapintu S. Current research on ancient copper-base metallurgy in Thailand. In: Charoenwongsa P, Bronson B, editors. Prehistoric studies: the stone and metal ages in Thailand. Bangkok: Thai Antiquity Working Group; 1988. p. 107–24.
51. Nitta E. Archaeological study on the ancient iron-smelting and salt-making industries in the Northeast of Thailand: preliminary report on the excavations of Non Yang and Ban Don Phlong. J Southeast Asian Archaeol. 1991;11:1–46.
52. Santoni M, Pautreau JP, Prishanchit S. Excavations at Obluang, Chiang Mai (Thailand). In: Glover IC, Glover EA, editors. Southeast Asian Archaeology. Oxford: British Archaeological Research; 1990. p. 37–54.
53. Shoocongdej R. Forager mobility organization in seasonal tropical environments of Western Thailand. World Archaeol. 2000;32(1):14–40.
54. White J, Pigott V. From Community Craft to Regional Specialization: Intensification of Copper Production in Pre-state Thailand. In: Wailes B, editor. Craft specialization and social evolution: In Memory of V. Gordon Childe. Philadelphia: The University Museum of Archaeology and Anthropology, University of Pennsylvania; 1996. p. 151–175.
55. Wilen R. Excavation and site survey in the Huay Sai Khao Basin, Northeastern Thailand. IPPA Bull. 1986;9:94–117.
56. Singtuen V, Phajuy B. Archaeological distribution of geoheritage for geotourism development in Nakhon Sawan Province, Thailand. Quaest Geogr. 2020;39(3):57–68. https://doi.org/10.2478/quageo-2020-0023.
57. Tourism Authority of Thailand, 2023. เมืองเก่าสุโขทัย Sukhothai Muang Kao (Old Town). 2023. https://thai.tourismthailand.org. Accessed 20 June 2023.
58. Damm, H., 2008. Sukhothai Historical Park, Sukhothai Province, northern Thailand. https://upload.wikimedia.org. Accessed 22 July 2023.
59. Fine Arts Department, 2020. อุทยานประวัติศาสตร์สุโขทัย Sukhothai Historical Park. http://virtualhistoricalpark.finearts.go.th. 20 June 2023.
60. Department of Mineral Resources. แผนที่ธรณีวิทยาจังหวัดสุโขทัย Geologic map of Sukhothai Province. Bangkok: Department of Mineral Resources; 2008.
61. Herron MM. Geochemical classification of terrigenous sands and shales from core or log data. J Sed Petrol. 1988;58(5):820–9.
62 Shirgire A, Deepak M, Thenmozhi S, Sharma A, Pawar SH, Prakash Arul Jose J. Experimental study on brick performance using quartz material and woods ash. Mater Today Proc. 2023. https://doi.org/10.1016/j.matpr.2023.11.054.
63. Google Earth Pro (2024). Accessed 20 Jan 2024.
64. Laporte L, Cousseau F, Gouezin P, Linares-Catela JA, Piofett H. Chapter 1. Stonemasons, and even engineers, for megalithic building in Neolithic Europe? Des maçons, voire quelques ingénieurs, pour le bâti mégalithique du Néolithique européen? In: Laporte L, Cousseau F, editor. Pre and Protohistoric stone architectures Comparisons of the social and their technical contexts associated to building. UISPP Proceedings Series vol. 1. Oxford: Archaeopress; 2020. p. 1–26.
65. Singtuen V, Won-In K. Preliminary geotourism study in ancient Khmer civilization area, Buriram province, northeastern Thailand. TOJDACISSN. 2018; Special Edition: 1538–1544. https://doi.org/10.7456/1080SSE/206.
66 Carò F, Sokrithy IM. Khmer sandstone quarries of Kulen Mountain and Koh Ker: a petrographic and geochemical study. J Archaeo Sci. 2012;39(5):1455–66. https://doi.org/10.1016/j.jas.2012.01.007.
67. Uchida E, Shimoda I, Shimoda M. Consideration of the construction period of the khmer temples along the East Royal Road to Preah Khan of Kompong Svay and the provenance of sandstone blocks based on their magnetic susceptibility. Archaeol Discov. 2013;1:37–48. https://doi.org/10.4236/ad.2013.12004.
68. Uchida E, Watanabe R, Cheng R, Nakamura Y, Takeyama T. Non-destructive in-situ classification of sandstones used in the Angkor monuments of Cambodia using a portable X-ray fluorescence analyzer and magnetic susceptibility meter. J Archaeol Sci Rep. 2021;39: 103137. https://doi.org/10.1016/j.jasrep.2021.103137.
69. Uchida E, Kobayashi Y. Siliceous sandstones used in local Khmer temples in Battambang, Ta Keo, and Kampong Cham Provinces, Cambodia. Heritage. 2024;7:608–20. https://doi.org/10.3390/heritage7020029.
70. Sjögren KJ. Raw material and work force in Falbygden passage graves. Identity, competition and social dynamic. In: Boaventura R, Mataloto R, Pereira A, editors. Megaliths and geology. Oxford: Archaeopress; 2020. p. 171–86.

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