SCIENTIFIC CULTURE
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SCIENTIFIC CULTURE, Vol. 12, No. 2.1, (2026), pp. 6813-6826
Open Access. Online & Print

DOI: 10.5281/zenodo.19595994

REINTERPRETING THE PHANOM RUNG LANDSCAPE: GEOARCHAEOLOGICAL EVIDENCE OF FIRED CLAY AND HUMAN ACTIVITY BEYOND MONUMENTAL ARCHITECTURE

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Received: 26/01/2026
Accepted: 11/02/2026

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ABSTRACT

This study investigates the Phanom Rung Historical Park in northeastern Thailand, expanding our understanding of the site's cultural and geological landscape. Traditionally viewed as a ceremonial center dominated by its sandstone temple, this research shifts focus to the surrounding volcanic slopes, revealing a more complex landscape where human activity, geology, and material technology intersect. Using a combination of geological surveys, X-ray diffraction (XRD), and scanning electron microscopy (SEM), the study identifies anomalous kaolinite-rich clay that was intentionally fired at high temperatures, indicating the presence of fired-clay technology previously overlooked in PNR. This clay is locally sourced, and its production process reflects a chaîne opératoire in which raw geological materials are transformed into durable architectural elements. The findings challenge traditional monument-centric views, supporting a relational understanding of Khmer construction in which monumental centers were sustained by ancillary structures embedded within a complex natural environment. The study emphasizes the value of geoarchaeology and material-based approaches in interpreting ancient construction, showing that the archaeological significance of Khmer-period sites extends beyond monumental structures. This research contributes to a broader understanding of settlement systems, material technologies, and human-environment interaction, highlighting the importance of reconsidering how archaeological heritage is defined and conserved, particularly in forested landscapes often seen as peripheral to monumental heritage. The study provides a nuanced view of Phanom Rung, emphasizing its role as a palimpsest landscape shaped by volcanic formation, human intervention, and

ongoing material practices.

KEYWORDS: Geoarchaeology, Cultural Landscape, Ancient Construction Materials, Fired Clay Technology, Phanom Rung, Buriram Province, Northeast Thailand.

1. INTRODUCTION

The Phanom Rung (PNR) Historical Park, located in Chalerm Phra Kiat District, Buriram Province, in northeastern Thailand (Figure 1), stands as one of the most remarkable Khmer monuments in mainland Southeast Asia. It is renowned not only for its architectural complexity and cosmological significance but also for its strategic position atop an extinct volcanic hill, i.e., PNR mountain. Traditionally, the site has been recognized primarily as a ceremonial and religious center, with much of the scholarly attention directed towards the sandstone temple situated at the summit. Research has long focused on the temple's alignment with celestial events, such as the movement of the sun, and its commanding visibility over the surrounding plains, which served both ritualistic and defensive functions. Consequently, PNR has predominantly been studied as a monumental sanctuary, often detached from the broader socio-economic and environmental context in which it existed (Stark, 2006; Narasaj, 2013; Higham, 2014; Poshyanandana, 2022). However, this narrow focus on the hilltop temple has led to viewing PNR as an isolated site, disconnected from the daily lives of the local community. Archaeological studies have historically overlooked the surrounding forested slopes and lower elevations of the volcanic massif. These areas may have played vital roles in supporting both the temple and its inhabitants. The marginalization of these areas has contributed to a limited understanding of how the temple functioned within its broader landscape and how the local community interacted with it. This represents a significant gap in research, especially considering the growing body of present-day studies emphasizing the interconnectedness of monumental centers with their surrounding environments.

Recent archaeological studies have challenged the previous view, implying that Khmer monumental centers, including PNR, were part of larger cultural landscapes that integrated settlements, production zones, transportation routes, and resource procurement systems (Uchida and Shimoda, 2010; Evans et al., 2013; Stark and Bong, 2016; Khamsiri et al., 2023). These findings highlight the importance of considering the broader context in which monumental structures were built and used. From a landscape archaeology perspective, monuments should not be studied in isolation but rather as integral components of the surrounding environment, which played a crucial role in supporting the activities that took place within the monument itself. The surrounding landscape, with its natural resources, settlement areas, and transportation networks, was just as vital to the monument's functioning as the monument itself (Ingold, 1993; Tilley, 1994; Ashmore and Knapp, 1999). Thus, this study aims to expand our understanding of PNR by exploring human activity beyond the summit temple and investigating the surrounding forested slopes of the PNR (Figure 1). The research seeks to identify how human activity influenced the geological landscape and distinguish between natural geological materials and those altered or shaped by human intervention. To achieve this, the study integrates a combination of i) systematic field surveys, ii) geological assessments, and iii) geochemical analysis of anomalous materials found in the area. The goal of this study is to provide a comprehensive understanding of the human-made features within the landscape, offering valuable insights into construction materials, land-use practices, and the socio-economic systems that supported the monumental architecture at PNR.

In addition, this research also has broader implications for regional studies and heritage management, particularly in tropical forest environments (Figure 1a). It highlights the importance of adopting an integrated approach to archaeological research, one that considers both monumental structures and the landscapes that support them. This perspective can provide valuable insights into the sustainability of ancient settlements and inform the conservation and management of archaeological sites today. By expanding the scope of archaeological inquiry to include the broader landscape, the study of PNR offers a more nuanced and holistic understanding of Khmer-period cultural practices, landscape use, and the interconnectedness of human activity with the natural world.

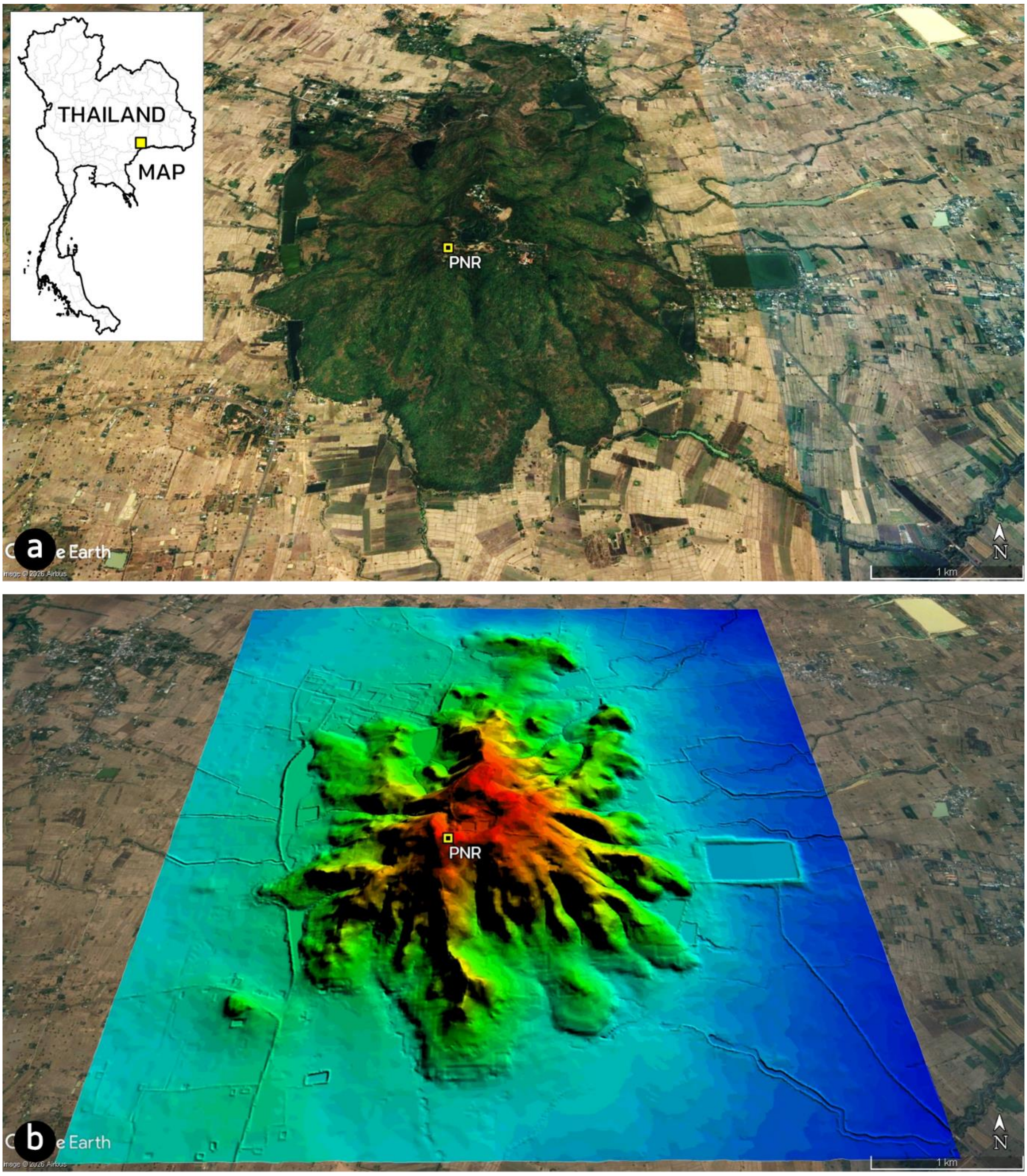

Figure 1: (A) Satellite Image Showing the Dense Forest Of PNR, Buriram Province, Northeastern Thailand, Where the Local Population Currently Resides and Practices Agriculture on the Lowland Plains Surrounding PNR. (B) Detailed Topography Of PNR, Highlighting Its Isolated Volcanic Morphology as a Solitary Basaltic Volcanic Hill (Inselberg) Rising Prominently from the Surrounding Lowland Plain, Emphasizing Its Geomorphological Distinction and Strategic Position Within the Landscape.

2. GEOLOGY OF PHANOM RUNG

The volcanic edifice of PNR is geographically isolated, with an estimated basal diameter of approximately 4–6 km and a relative relief of roughly 180 m above the surrounding alluvial landscape (Figure 1b). Such topographic prominence renders PNR highly visible across the regional plain and has likely contributed to its long-standing cultural, symbolic, and strategic significance, a pattern widely documented in landscape archaeological studies of monument placement and visibility (Tilley, 1994; Bell and Lock, 2000; Llobera, 2001). At the summit of the hill lies a well-defined volcanic crater, which currently functions as a water-retaining basin and continues to play a practical role in sustaining activities on the hilltop. Summit craters functioning as natural water reservoirs are a common feature of basaltic volcanic edifices and have been noted as important ecological and cultural resources in archaeological landscapes (Ingold, 1993; Ashmore and Knapp, 1999). The geomorphology of PNR is therefore characterized by steep slopes, a centralized summit depression, and a sharply defined boundary between the volcanic massif and the surrounding sedimentary lowlands (Figure 1). This pronounced geomorphological and geological contrast is particularly significant for geoarchaeological investigations, as it creates a clearly bounded geological "island" whose lithological composition differs markedly from the regional background, enhancing the detectability of anthropogenic material signatures (Butzer, 1982; Goldberg and Macphail, 2006).

In geological terms, PNR is a relatively young volcano formed during the Quaternary Period, with eruptive activity dated to around one million years ago (Charusiri et al., 2005; Racey et al., 2012). The volcanic activity involved magma rising through sedimentary strata of the Khorat Group, primarily sandstone formations deposited during the Mesozoic Era, which are widely exposed across the Khorat Plateau (Hite and Japakasetr, 1979; Racey et al., 2012). Quaternary magma penetrated these older units, depositing volcanic materials on a regional foundation of fluvial and aeolian sandstones. Geoarchaeological survey and petrographic analyses indicate that PNR was built primarily by effusive lava flows, creating extensive basaltic lava sheets (Charusiri et al., 2005; Migon, 2006). These flows, originating from mafic magma, crystallized into basalt, which dominates the hill's geology (Winter, 2010).

As a result, basalt serves as both the bedrock and primary surface material, providing a uniform geological substrate that aids archaeological interpretation by making non-local or anomalous materials easier to detect (Butzer, 1982; Dreesen and Dusar, 2014). Any stone types or sediments inconsistent with basalt suggest human activity, such as transportation, technological modification, or construction (Bloxam, 2011; Goldberg and Macphail, 2006). In addition, the contrast between the basaltic hill and the surrounding Khorat Group sandstones also provides a natural setting for studying material selection and resource procurement in past societies (Uchida and Shimoda, 2013; Bloxam, 2011). The volcano's youth imply minimal post-eruptive tectonic disturbance, preserving volcanic landforms and enhancing the reliability of geomorphological and geochemical signatures used to differentiate between natural and anthropogenic processes (Migon, 2006; Charusiri et al., 2005). Overall, the Quaternary age, basaltic composition, isolation from surrounding terrains, and well-preserved volcanic features create a solid framework for geoarchaeological investigations, linking material anomalies to past human activity within a constrained geological context.

3. NATURAL-MANMADE MATERIALS

3.1. Natural Material

In volcanological classification, eruptive styles are commonly divided into two broad categories: i) effusive eruptions characterized by the sustained outpouring of lava, and ii) explosive eruptions dominated by violent fragmentation and widespread pyroclastic dispersal (Winter, 2010; Sigurdsson et al., 2015). The morphology of both PNR (Figure 1) and petrographic observations during the field survey (Figure 2) strongly supports an effusive eruptive regime rather than an explosive one. The absence of extensive pyroclastic deposits and the dominance of coherent lava-derived lithologies are consistent with eruption styles analogous to Hawaiian and Strombolian volcanism (Sigurdsson et al., 2015; Francis and Oppenheimer, 2004). Hawaiian-style eruptions typically produce extensive lava flows that cool into dense, massive basalt. In contrast, Strombolian activity generates vesicular basalt (Figure 2) and scoriaceous material through gas-driven fragmentation of magma (Winter, 2010). Consistent with these models, field survey documented two principals basaltic lithologies across PNR: i) massive basalt, and ii) vesicular basalt, occurring in a range of clast sizes from large blocks exceeding one meter in diameter to smaller fragments comparable to cobbles or pebbles.

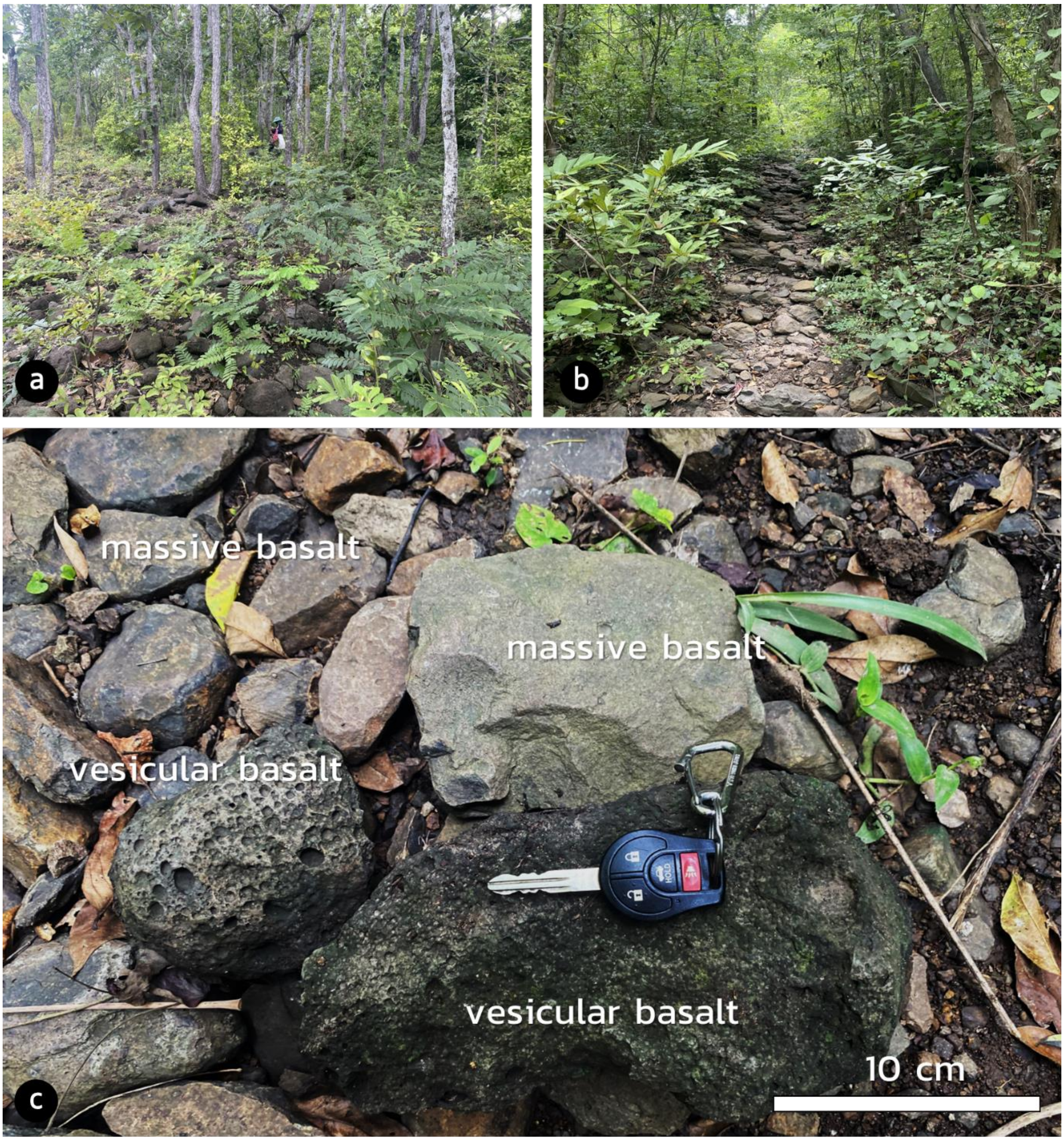

Figure 2: (A-B) Naturally Occurring Basalt Outcrops, Including Large, Dense Blocks and Areas Displaying Systematic Jointing Patterns Attributable to Geological Processes. (B) Hand-Sized Basalt Blocks Are Deliberately Arranged in a Linear Alignment That Deviates from Natural Geomorphological Patterning. (B) Basalt Lithologies Found At PNR, I.E., Massive Basalt and Vesicular Basalt, Which Naturally Formed Through Volcanic Eruption Processes.

3.2. Manmade Material

Systematic pedestrian survey across the forested slopes of PNR demonstrates that the lithological environment is overwhelmingly dominated by locally derived basalt. Extensive transects covering multiple elevations and slope aspects consistently revealed basalt as the sole naturally occurring rock type, present as bedrock outcrops, angular blocks, and weathered clasts distributed across the forest floor. This dominance reflects the volcanic origin of the hill and confirms that basalt constitutes the primary geological substrate of the study area (Charusiri et al., 2005; Migon, 2006). Such lithological uniformity creates a highly consistent material background, against which any deviation becomes immediately conspicuous during field inspection, a condition long recognized as advantageous for geoarchaeological detection of anthropogenic materials (Butzer, 1982; Goldberg and Macphail, 2006).

Within this basalt-dominated setting, the survey documented a visually and texturally distinct material characterized by pale whitish coloration, fine-grained texture, and friable surfaces (Figures 3a-b). This material contrasts sharply with the dark color, crystalline fabric, and mechanical durability of basalt, and cannot readily be attributed to volcanic lithologies associated with PNR. Initial field assessment suggests closer resemblance to degraded cementitious or lime-based substances than to any known basaltic rocks occurring naturally on the hill. Importantly, this material was not observed as an isolated anomaly; it was repeatedly observed across multiple survey sectors, frequently intermingled with basalt blocks and, in several cases, partially coating basalt clasts (Figure 3). Such associations are difficult to reconcile with natural weathering processes, as basalt alteration typically produces iron-rich soils and reddish-brown residues rather than pale, fine-grained surface materials.

Figure 3: (A) Representative Sample of Anomalous Material Identified During Field Survey, Preliminarily Interpreted as Non-Basaltic in Origin and Visually Resembling Heavily Weathered Cementitious Material Resulting from Prolonged Exposure and Degradation. (B) General Condition of the Forested Surface Environment on PNR During the Rainy Season, Showing Anomalous Pale Material Recurrently Intermixed with Naturally Occurring Basalt Blocks Across the Forest Floor. (C-D) Flattened and Stepped Anomalous Surface Features Displaying Planar Morphologies Inconsistent with Natural Volcanic Landforms,

Tentatively Interpreted as Degraded Anthropogenic Surfaces Resembling Terraced or Stair-Like Constructions When Viewed in Spatial Context.

A more detailed examination of the spatial distribution and surface morphology further supports the idea that the anomalous material is not natural. In several locations, the white substance forms flat, smooth surfaces with sharp breaks in slope, arranged in stepped or terraced patterns descending the hillside (Figures 3c-d). The regularity and repetition of these stepped surfaces go beyond what we would expect from natural geomorphological processes. These flat features often cover or incorporate basalt blocks, suggesting that the white material served as a binding or surfacing medium rather than as naturally deposited sediment. The consistent association of the white material, flattened surfaces, and basalt fragments indicates that these features are likely degraded remnants of constructed platforms, pavements, or architectural elements that have undergone prolonged weathering and biological disturbance. These findings show that the forested areas of PNR contain material evidence that is clearly different from the natural basaltic landscape. This highlights the importance of material-focused survey strategies in densely vegetated environments, where architectural forms may survive as altered surface materials rather than intact structures (Goldberg and Macphail, 2006; Evans et al., 2013).

4. GEOCHEMISTRY

4.1. XRD Analysis of Anomalous Material

To determine the mineralogical composition of the anomalous material identified during the field survey, representative samples were analyzed by X-ray diffraction (XRD). XRD is a widely applied technique that enables identification of crystalline phases based on characteristic diffraction patterns produced by ordered atomic lattices (Moore and Reynolds, 1997; Bish and Post, 1989). Contrary to initial field expectations, the XRD results do not indicate dominance of calcium carbonate phases typically associated with lime plaster, mortar, or cementitious materials. Instead, the diffraction patterns consistently reveal a mineral assemblage dominated by clay minerals with subordinate quartz (Figure 4).

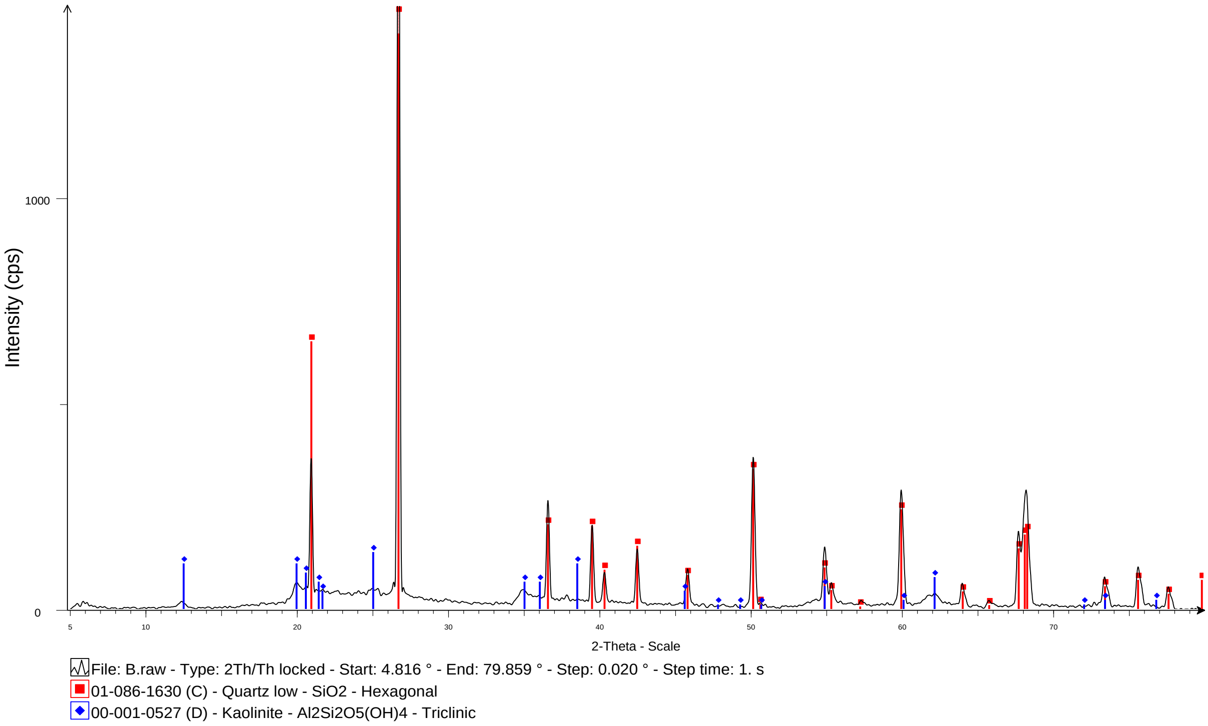

Figure 4: X-Ray Diffraction (XRD) Pattern of the Anomalous Material Collected from the Forested Slopes Of PNR, Showing Diagnostic Peaks Corresponding to Kaolinite with Subordinate Quartz, Supporting the Interpretation of the Material as a Clay-Rich, Non-Basaltic or Carbonate Substance.

More specifically, kaolinite ($Al_2Si_2O_5(OH)_4$) is identified as the principal clay phase, while quartz (SiO_2) occurs as a secondary component. The absence of calcite, dolomite, or other carbonate minerals effectively excludes conventional lime-based construction materials as the primary constituent of the anomalous white substance. From a mineralogical perspective, this assemblage corresponds to a fine-grained sedimentary material rather than an igneous or carbonate lithology (Moore and Reynolds, 1997). Quartz represents detrital sand-sized particles commonly preserved during sedimentation, whereas kaolinite is a well-known product of intense chemical weathering, i.e., the hydrolysis process, of feldspar-rich parent rocks under warm and humid conditions (Wilson, 1999; Deer et al., 2013). In both practical and historical contexts, kaolinite-rich clays, often referred to as kaolin or white clay, have been widely used in ceramic production, brickmaking, and earthen construction materials across tropical and subtropical regions (Rice, 2015; Shepard, 1956). The XRD results, therefore, establish that the anomalous material consists predominantly of a kaolinite-rich clay matrix rather than altered basalt or carbonate cement, providing a crucial mineralogical baseline for subsequent interpretation (Figure 4).

4.2. Geological Context and Provenance of Kaolinite-Rich Material

Following the identification of the mineralogical composition, the investigation focused on determining the potential geological provenance of the kaolinite-rich material. Regional geological studies indicate that the area extending from the Phanom Dong Rak Range (Thailand-Caombodia border) to the vicinity of PNR is dominated by sedimentary units of the Khorat Group, deposited during the Mesozoic Era (Hite and Japakasetr, 1979; Department of Mineral Resources, 2010; Racey et al., 2012). Within this sequence, two formations are particularly relevant: The Phu Phan Formation, primarily composed of sandstone, exhibits variegated colors, including gray, brown, orange, and pink. It is characterized by cross-bedding and thick-bedded units, with interspersed siltstone and conglomeratic sandstone layers, and by the Kok Kruat Formation, consisting of fine-grained sandstone, gray to pale red siltstone, and conglomerate with calcrete horizons (Department of Mineral Resources, 2010). The Phu Phan Formation is well documented as the primary source of sandstone used in Khmer monumental construction, including the PNR temple complex itself (Uchida and Shimoda, 2013; Bloxam, 2011). In contrast, the Kok Kruat Formation represents a significant source of feldspar-rich clastic sediments (Figure 5).

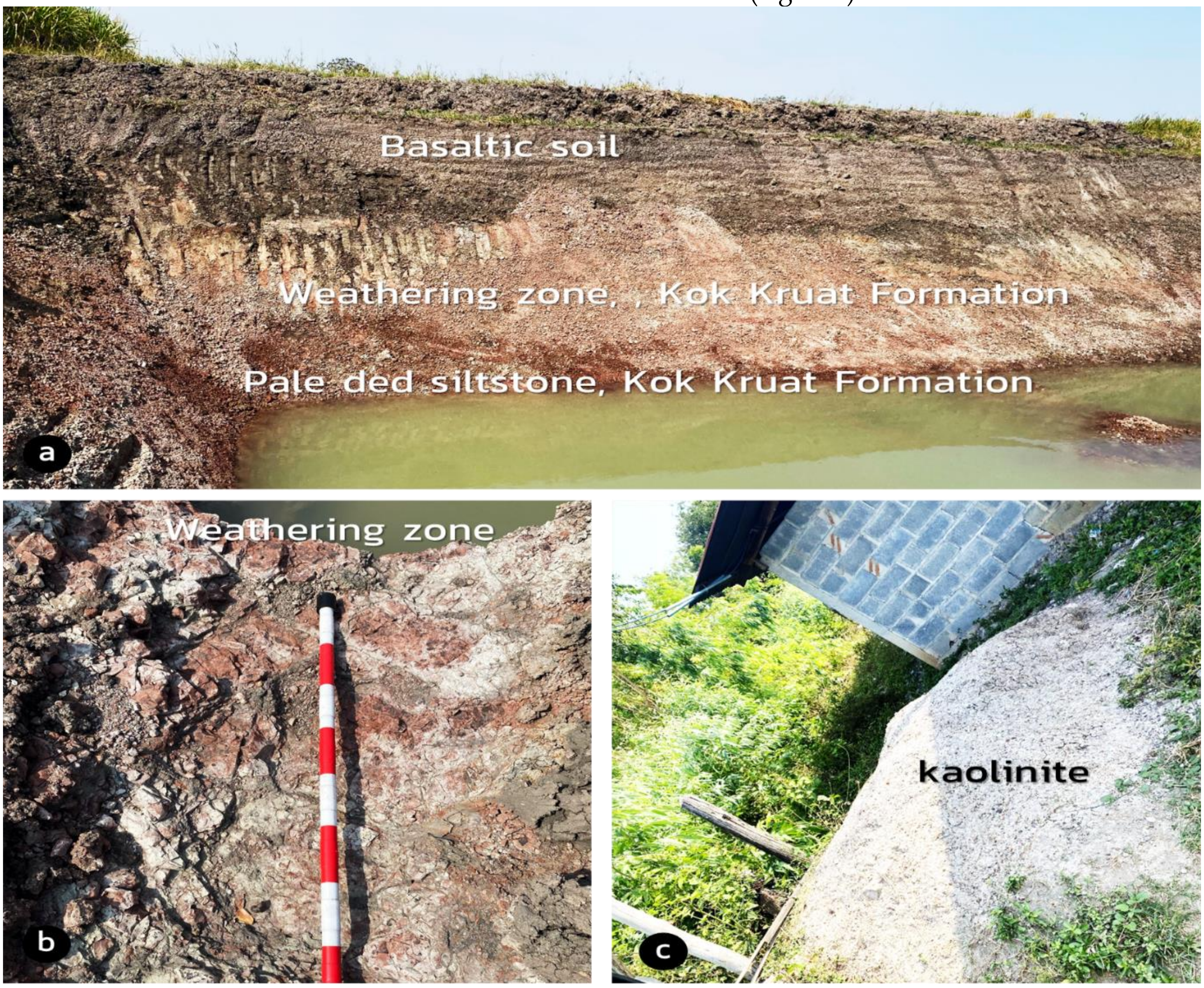

Figure 5: (A) Stratigraphic Sequence Exposed Along the Wall of a Water Well, Illustrating the Vertical

Arrangement of Geological Units in The Lowland Plains Surrounding PNR. (B) Weathered Exposures of the Kok Kruat Formation, Showing in Situ Alteration of Feldspar-Rich Sedimentary Rocks into Kaolinite-Rich Clay Through Chemical Weathering Processes. (C) Stockpiled Kaolinite Clay Excavated by Residents at the Foot Of PNR, Reflecting the Availability of Kaolinite as a Shallow, Locally Accessible Sedimentary Resource Utilized for Various Domestic and Practical Purposes.

Geochemical weathering theory provides a well-established mechanism linking these lithologies to the formation of kaolinite. Under warm, humid climatic conditions, potassium feldspar ($KAlSi_3O_8$) undergoes hydrolytic alteration upon interaction with carbonic acid, producing kaolinite while releasing potassium ions, silica, and bicarbonate into solution (Nesbitt and Young, 1984; Wilson, 1999). Field observations in lowland areas surrounding PNR provide direct stratigraphic evidence supporting this process. Recently excavated village wells expose vertical sequences in which unweathered pale red siltstone of the Kok Kruat Formation occurs at depth (Figures 5a-b), overlain by distinct layers of white kaolinite clay and capped by darker soils derived from basaltic material eroded from the PNR volcanic hill. This stratigraphy demonstrates that kaolinite forms naturally in the region as a weathering product of Kok Kruat lithologies and accumulates as a discrete sedimentary layer accessible at shallow depths. Additional surface observations confirm that kaolinite deposits are locally extracted and stockpiled for utilitarian purposes (Figure 5c).

Taken together, the compositional correspondence between the analyzed samples and locally derived kaolinite deposits strongly supports a local provenance for the anomalous material. Its occurrence within architectural contexts on a basalt-dominated volcanic hill, therefore, reflects deliberate selection and transport of a readily available sedimentary resource rather than incidental geological contamination. This geochemical and stratigraphic evidence provides a robust foundation for interpreting the material as a purposeful component of human activity within the PNR landscape.

5. MATERIAL PRODUCTION

A key unresolved issue regarding the anomalous kaolinite-rich material identified on the forested slopes of PNR concerns its original physical state and production process. If the material had been applied or deposited in its original condition, prolonged exposure to tropical rainfall and surface runoff would be expected to result in rapid disaggregation and erosion (Butzer, 1982; Goldberg and Macphail, 2006). The persistence of coherent fragments and planar surfaces, therefore, raises the hypothesis that the material underwent thermal treatment before use. At present, several studies have utilized Scanning Electron Microscopy (SEM) to investigate ancient materials, offering valuable insights into their production and properties. For example, Min Dai et al. (2019) analyzed ancient mortar from a Qing Dynasty tomb using SEM and other techniques. They found that the mortar, composed of calcium silicate hydrate, quartz, and calcite, exhibited high water resistance and stability, indicating thermal treatment. Wongsawan (2002) also used SEM to study lime from freshwater shells at the Wang Phai archaeological site in Lopburi. SEM revealed that lime from shells had larger, angular crystals compared to the smaller, sharper crystals in limestone, indicating differences in production processes. Additionally, Bordeepong et al. (2019) examined clay from Ban Aang in Pattani, finding that heating the clay at various temperatures (700, 800, 900°C) caused fusion of illite and kaolinite, enhancing quartz crystals and revealing temperature-dependent changes. These studies demonstrate SEM's effectiveness in analyzing ancient materials and understanding how they were intentionally modified for specific purposes.

To evaluate this possibility, selected samples were examined using scanning electron microscopy (SEM), a technique widely used in research on archaeological materials to identify microstructural indicators of firing and mineral transformation (Maniatis and Tite, 1981; Rice, 2015). SEM imaging reveals a heterogeneous microfabric characterized by coarse quartz grains embedded within a fine-grained clay matrix (Figure 6). The quartz particles exhibit angular-to-subrounded morphologies and remain structurally intact, while the surrounding clay matrix displays collapsed, wrinkled, and irregular surface textures. Such textures are inconsistent with untreated kaolinite, which typically exhibits well-defined platy crystals with smooth surfaces at the micrometer scale (Wilson, 1999; Deer et al., 2013). Instead, the observed morphology closely corresponds to thermally altered kaolinite, in which dehydroxylation and structural reorganization during heating lead to surface contraction, microfracturing, and loss of original crystalline order (Brindley and Brown, 1980; Moore and Reynolds, 1997).

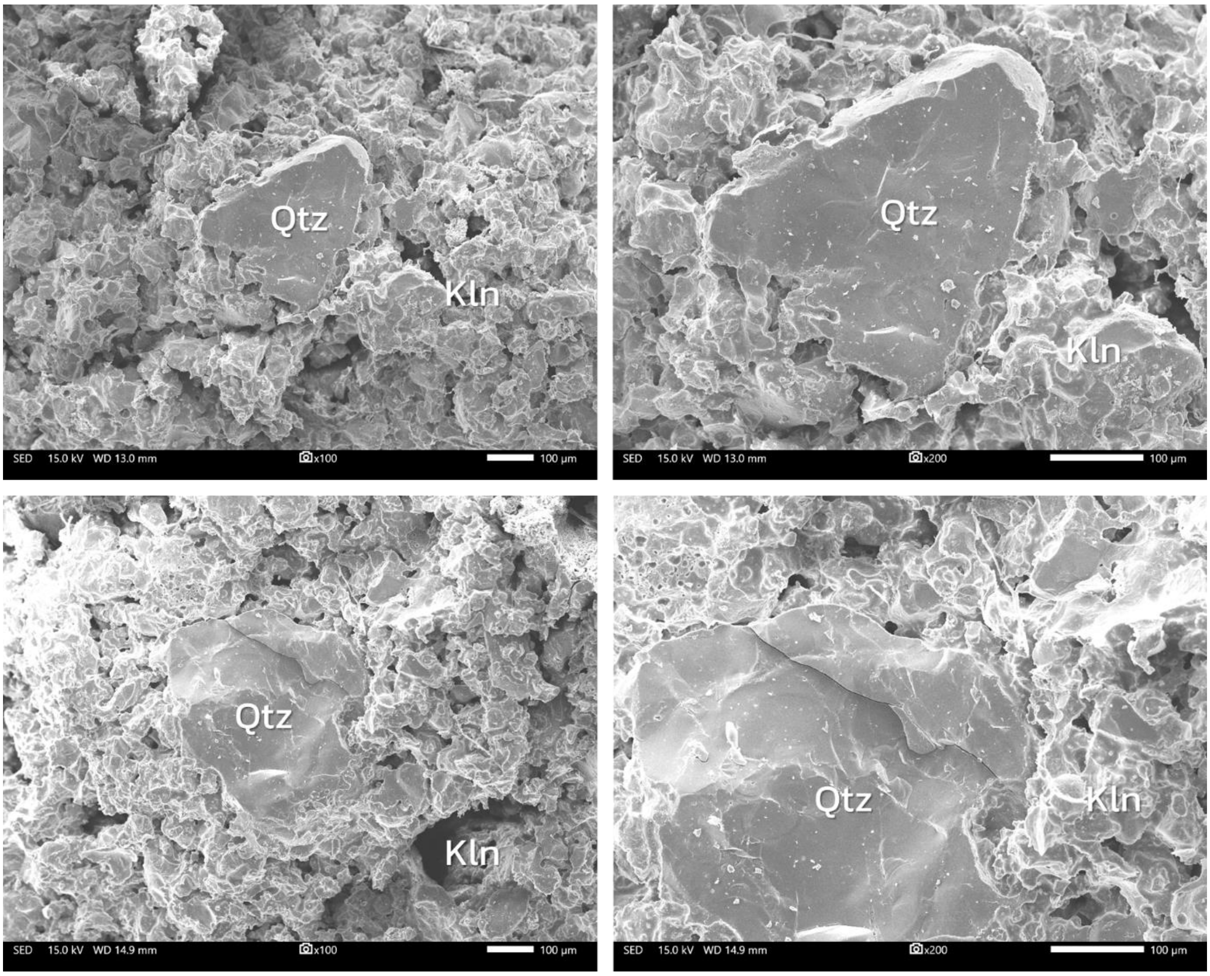

Figure 6: High-Resolution Scanning Electron Microscope (SEM) Image of the Anomalous Material Collected From PNR, Showing Surface Microstructures That Indicate Thermal Alteration. Note: The Symbols Kln Represent Kaolinite, And Qtz Represents Quartz.

Comparative analysis with experimental studies documenting kaolinite microstructures subjected to controlled firing temperatures suggests that the PNR samples most closely resemble kaolinite heated to approximately 800–900 °C. This is consistent with the findings of Bordeepong et al. (2019), who conducted experiments by firing clay at temperatures of 700, 800, and 900 °C. SEM analysis revealed that quartz exhibited large, clearly defined crystals, while surrounding minerals such as kaolinite and illite displayed sheet-like structures. Following heating, kaolinite and illite fused, resulting in more distinct quartz crystals due to the lack of fusion with other minerals. These variations in mineral structure were temperature-dependent. At lower firing temperatures (~700 °C), kaolinite generally retained recognizable plate-like structures, whereas at temperatures approaching 900 °C, the clay matrix became increasingly amorphous, exhibiting significant surface collapse (Maniatis and Tite, 1981; Rice, 2015; Bordeepong et al., 2019). The SEM textures observed in the analyzed samples fall within this higher-temperature range, indicating that the material underwent controlled heating sufficient to induce irreversible mineralogical transformation.

In addition, macroscopic field observations provide further evidence corroborating the SEM-based interpretation of a fired construction material. Fragments recovered during follow-up surveys exhibit pronounced internal heterogeneity, with pale, friable zones indicative of advanced weathering adjacent to compact, orange-brown areas that closely resemble fired clay bricks documented in archaeological and ethnographic contexts (Figure 7; Shepard, 1956; Rice, 2015). This variability suggests differential post-depositional alteration of an originally homogeneous fired material rather than the juxtaposition of separate substances. Moreover, less weathered portions preserve elongated voids and filamentous impressions penetrating the clay matrix, morphologically consistent with vegetal temper inclusions such as straw or grass fibers deliberately added to clay to reduce shrinkage and improve firing performance (Shepard, 1956; Rice, 2015). The resulting tubular pores cannot be explained by natural sedimentary or pedogenic processes (Figure 7; Goldberg and Macphail, 2006). Taken together, the SEM microstructural data and macroscopic observations provide convergent evidence that the kaolinite-rich material was intentionally shaped, tempered, and fired at high temperatures before deployment. These findings constitute direct empirical evidence of brick-based construction activities within the forested landscape of PNR, confirming that the archaeological footprint of the site extends beyond the sandstone temple complex and includes additional built features employing fired-clay technology.

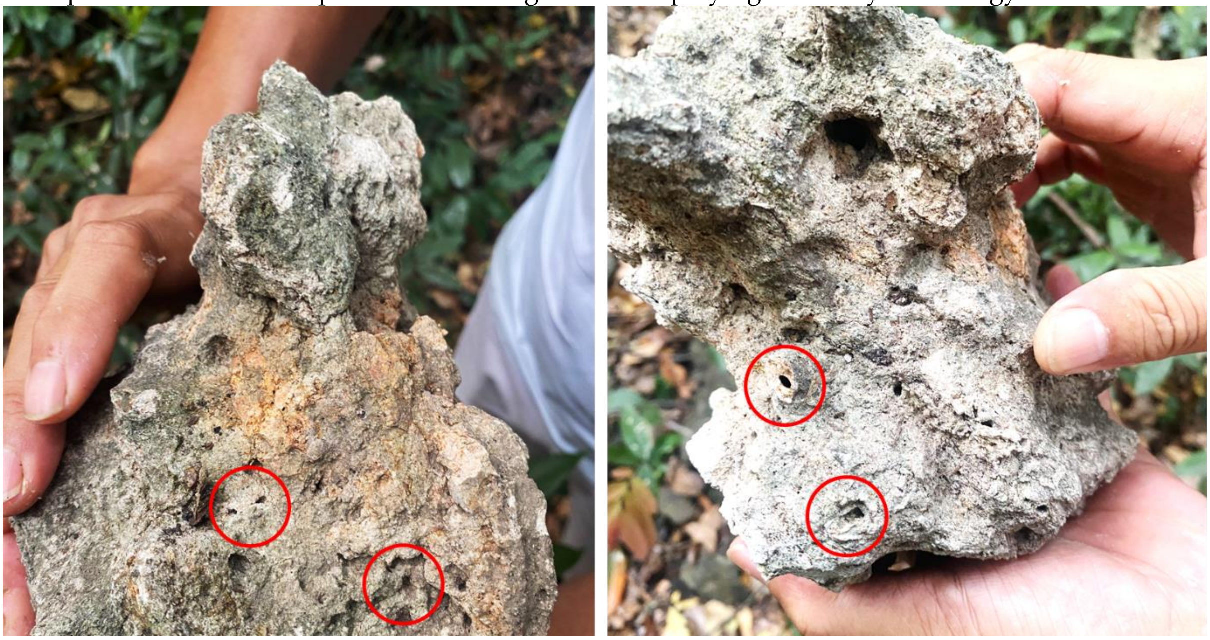

***Figure 7:** Representative Sample Fragment Recovered During Subsequent Field Survey, Showing Contrasting Zones of Weathered and Relatively Intact Fired Clay Material Within a Single Specimen. The Less Weathered Portions Preserve Elongated Voids, Tubular Pores, And Fibrous Impressions Penetrating the Clay Matrix (Red Circles), Preliminarily Interpreted as Traces of Vegetal Temper, Such As Straw or Grass Fibers, Incorporated During Clay Preparation and Subsequently Combusted During Firing.*

6. CONCLUSION REMARKS

This study reinterprets Phanom Rung (PNR) not as an isolated temple on a passive volcanic hill, but as a culturally shaped landscape where geology, material technology, and human activity are closely interconnected. Mineralogical and microstructural analyses support this view, showing that the anomalous white material at the site is primarily kaolinite with some quartz, indicating it originates from a sedimentary, weathering-derived context rather than carbonate or igneous sources. SEM analysis further reveals that this kaolinite-rich clay was intentionally fired at high temperatures, a process consistent with brick or brick-like construction materials. The combination of locally sourced clay, vegetal temper, and controlled firing processes demonstrates a chaîne opératoire in which raw materials were transformed into durable building elements. This highlights how technological choices in construction are influenced by cultural practices, environmental constraints, and social organization, rather than technological determinism alone.

These findings challenge monument-centric models that separate monumental temples from their surrounding environments. Instead, they support a relational understanding of Khmer construction, in which monumental centers like PNR were supported by extensive yet often subtle surrounding architecture embedded in complex landscapes. The study underscores the value of geoarchaeology and material-based approaches in uncovering architectural practices that survive as altered sediments, fired fragments, and reconstructed stone features. It emphasizes the importance of viewing ancient construction as a continuous process, shaped over time by geological, material, and human factors. PNR emerges as a palimpsest landscape, where volcanic, sedimentary, and human activities intersect to form a complex built environment that extends far beyond the hilltop sanctuary. This perspective enriches our understanding of Khmer settlement systems and calls for a reassessment of archaeological significance in forested zones, which have often been seen as marginal to monumental heritage.

Author Contributions: Santi Pailoplee: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review and editing. **Nopphamat Ritthanonta:** XRD and SEM analysis, Data curation. **Sutthikan Khamsiri:** Investigation, Writing – original draft, Formal analysis. **Kangvol Khatshima:** Supervision, Writing, review and editing, Conceptualization, Discussion, and conclusion.

Acknowledgments: This research was funded by the Thailand Science Research and Innovation Fund, Chulalongkorn University (SOC_FF_69_045_2300_013). The authors sincerely thank Mr. Pakphum Yuphol, Head of Phanom Rung Historical Park, and all staff members of the Phanom Rung Historical Park Fine Arts Department for their kind cooperation, logistical support, and valuable advice during the field investigations. We also gratefully acknowledge the thoughtful comments and constructive suggestions provided by the editors and anonymous reviewers, which significantly enhanced the quality and clarity of this manuscript.

REFERENCES

Ashmore, W. and Knapp, A. B. (1999) Archaeological landscapes: Constructed, conceptualized, ideational. In Ashmore, W. and Knapp, A. B. (eds.), *Archaeologies of landscape: Contemporary perspectives.* Oxford, Blackwell, pp. 1–30.

Bell, A. and Lock, G. (2000) *Geographical perspectives on landscape archaeology*. Cambridge University Press.

Bish, D. L. and Post, J. E. (1989) X-ray diffraction and the analysis of clays. *American Mineralogist,* 74(1-2), 171–177.

Bloxam, E. (2011) The organization, transportation, and logistics of hard stone quarrying in the Khmer world. In Bloxam, E., Heldal, T. (eds.), *Quarrying and stoneworking in the ancient world*. London, Geological Society, Special Publications 333, pp. 73–95.

Bordeepong, S., Phansuke, P. and Sukolrat, A. (2019) Study of Mineralogy, Chemical Composition and Physical Properties of Clays from Local Pottery Areas, Rongang Community Pattani Province. *UTK Research Journal, Rajamalaklong, Bangkok,* 13(1), 1–13.

Brindley, G. W. and Brown, G. (1980) *Crystal structures of clay minerals and their X-ray identification*. London, Mineralogical Society.

Butzer, K. W. (1982) *Archaeology as human ecology: Method and theory for a contextual approach*. Cambridge, Cambridge University Press.

Charusiri, P., Clark, A. H., Farrar, E., Archibald, D. and Charusiri, B. (2005) Granite belts in Thailand: Evidence from geochronological and geochemical studies. *Journal of Asian Earth Sciences,* 24, 49–64.

Dai, M., Peng, C., Liu, H., Wang, J., Ali, I. and Naz, I. (2019) Analysis and imitation of organic Sanhetu concrete discovered in an ancient Chinese tomb of the Qing Dynasty. *Materials Science Forum,* 954, 53–58.

Deer, W. A., Howie, R. A. and Zussman, J. (2013) *An Introduction to the Rock-Forming Minerals*. London, Mineralogical Society.

Department of Mineral Resources (2010) *Geological and resource management zoning for Buriram Province*. Department of Mineral Resources, Ministry of Natural Resources and Environment, Thailand. 104p.

Dreesen, R. and Dusar, M. (2014) Geological and mineralogical considerations in archaeological contexts. In Smith, C. (ed.), *Encyclopedia of Global Archaeology*. New York, Springer, pp. 2976–2986.

Evans, D., Pottier, C., Fletcher, R., Hensley, S., Tapley, I., Milne, A. and Barbetti, M. (2013) Uncovering archaeological landscapes at Angkor using LiDAR. *Proceedings of the National Academy of Sciences,* 110, 12595–12600.

Francis, P. and Oppenheimer, C. (2004) *Volcanoes*. Oxford, Oxford University Press.

Goldberg, P. and Macphail, R. I. (2006) *Practical and theoretical geoarchaeology*. Oxford, Blackwell.

Hite, D. M. and Japakasetr, T. (1979) *Geology of Thailand*. Bangkok, Department of Mineral Resources.

Ingold, T. (1993) The temporality of the landscape. *World Archaeology,* 25(2), 152–174.

Khamsiri, S., Venunan, P., Khaokheiw, C., Silapanth, P. and Pailoplee, S. (2023) Reconstructing the ancient route network in the Thailand–Cambodia borders: A case study of the Angkorian Royal Road. *Archaeological Prospection,* 30, 357–368.

Llobera, M. (2001) Building past landscape perception with GIS: Understanding topographic prominence.

Journal of Archaeological Science, 28, 1005–1014.
Maniatis, Y. and Tite, M. S. (1981) Technological examination of Neolithic–Bronze Age pottery from central and southeast Europe and from the Near East. *Journal of Archaeological Science,* 8, 59–76.
Moore, D. M. and Reynolds, R .C. (1997) *X-ray Diffraction and the Identification and Analysis of Clay Minerals*. Oxford, Oxford University Press.
Narasaj, B. (2013) Representations of Phanom Rung Sanctuary in the View of Local People. *Journal of Mekong Societies,* 8(2), 1–25.
Nesbitt, H. W. and Young, G. M. (1984) Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. *Geochimica et Cosmochimica Acta,* 48, 1523–1534.
Poshyanandana, S. (2022) Ensemble of Phanom Rung, Mueang Tam, Plai Bat Sanctuaries and the Phimai Cultural Route: Comparative Study and Future Expectation in World Heritage Context. *Manusya: Journal of Humanities,* 25(1), 1–18.
Racey, A., Love, M. A., Canham, A. C., Goodall, J. G. S., Polachan, S. and Jones, P. D. (2012) Mesozoic and Cenozoic sedimentary basins of Thailand. *Journal of Asian Earth Sciences,* 61, 1–17.
Rice, P. M. (2015) *Pottery Analysis: A Sourcebook*. Chicago, University of Chicago Press.
Shepard, A. O. (1956. *Ceramics for the Archaeologist*. Washington, DC, Carnegie Institution of Washington.
Sigurdsson, H., Houghton, B., McNutt, S. R., Rymer, H. and Stix, J. (2015) *The Encyclopedia of Volcanoes*. Academic Press.
Stark, M. T. (2006) Landscape and monumentality: Case studies from Southeast Asia. *Journal of Southeast Asian Archaeology,* 19(1), 25–45.
Stark, M. T. and Bong, S. (2016) Political economy and settlement systems in the Lower Mekong Basin. *Asian Perspectives,* 55(1), 3–26.
Tilley, C. (1994) *A Phenomenology of Landscape: Places, Paths, and Monuments*. Oxford, Berg.
Uchida, E., and Shimoda, I. (2013) Quarries and transportation routes of Angkor monument sandstone blocks. *Journal of Archaeological Science,* 40, 1158–1164.
Wilson, M. J. (1999) Kaolinite and its significance in clay mineralogy. *Journal of Clay Science,* 17(1), 45–58.
Winter, T. (2010) *Volcanic Eruptions and Landscape Formations: A Global View*. Oxford, Oxford University Press.
Wongsawan, S. (2002) *Analysis of lime from clams unearthed at Wang Phai archaeological site, Ban Mi District, Lop Buri Province*. Master's thesis, Department of Archaeology, Silpakorn University, Thailand. 236p.