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GEORESOURCE DISTRIBUTION IMPACTS THE PROSPERITY OF THE SUKHOThai KINGDOM AND ANTHROPOLOGICAL CIVILIZATION IN THAILAND

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ABSTRACT

The Sukhothai Kingdom, which emerged in the Yom River valley around the 13th-14th century AD, functioned as a trading post between the Gulf of Martaban and the central Mekong River basin and is now recognized as a UNESCO World Heritage site. The reasons behind the establishment of Sukhothai remain unclear, with limited research on the topic. This study explores significant geological resources within Sukhothai and its surrounding areas using field surveys, macroscopic analysis, geochemical analyses via portable X-ray fluorescence (pXRF), and Least Cost Path (LCP) analysis to hypothesize the factors contributing to Sukhothai's prosperity. Archaeological evidence from the northern part of Sukhothai indicates that metal smelting dates back to prehistoric times, continuing through the Dvaravati period and possibly extending into the Sukhothai era. Field surveys have identified two types of ore deposits associated with archaeometallurgical slags: hydrothermal vein-type deposits related to volcanic rocks, and lateritic deposits accompanied by ancient kilns. Macroscopic analysis reveals that most archaeometallurgical slags are dark gray to black with a metallic luster and structures indicative of high-temperature smelting. Geochemical analyses show significant variations in FeO content, categorized into three levels: low, moderate, and high as well as contain notable concentrations of TiO₂, MgO, Bi, Pb, As, Sn, Sb, Zn, and Cu. These findings align with ore sources, including quartz-metal veins in rhyolite, dacite, andesite, basaltic andesite, and absarokite, all rich in FeO and Zn. Lateritic deposits, dense and black, also contain high FeO levels suitable for iron production. Moreover, Sukhothai is rich in rhyolite exhibiting extensive kaolinization and illitization due to hydrothermal processes, making it a potential hub for kaolinite-based ceramics. The area also contains red sedimentary rocks that weather into red clay suitable for pottery. The strategic establishment of Sukhothai enabled control over valuable resources and facilitated trade and communication with other regions, as indicated by LCP analysis. This approach is vital for regional development, enhancing public understanding of geoarchaeology, and ensuring the sustainability of the Sukhothai Historical Park as a World Heritage Site.

KEYWORDS: Sukhothai Kingdom, geoarchaeology, archaeometallurgy, georesources, geochemistry, geo-information, iron, kaolinite, laterite

1. INTRODUCTION

The Sukhothai Kingdom, also referred to as the Northern Cities, was a post-classical Siamese mandala in Mainland Southeast Asia, centered around the ancient capital of Sukhothai in present-day north-central Thailand (Figure 1a). The capital's ruins, located 12 km (7.5 mi) from the modern town of Sukhothai Thani in Sukhothai Province, are preserved as the Sukhothai Historical Park, a designated World Heritage Site. The Sukhothai Historical Park comprises a total of 193 archaeological sites (Figure 1b), of which 58 have been officially registered as historical sites by the Fine Arts Department (2020). This park has undergone extensive restoration efforts by the Fine Arts Department with assistance from UNESCO and has been declared a protected area for the first time under the Royal Gazette announcement on December 12, 1991. UNESCO designated this park as a joint World Heritage Site with the historical parks of Kamphaeng Phet and Si Satchanalai, collectively known as the "Historic Town of Sukhothai and Associated Historic Towns." Research conducted in this area contributes significantly to the global heritage, with potential wide-ranging societal impacts. The Sukhothai Historical Park is located in Sukhothai Province, in the northern central region of Thailand, renowned for its geological diversity, as illustrated in Figure 1c.

The Sukhothai Kingdom, also known as the Northern Kingdom, was a state established in the Yom River valley around the 13th -14th century AD as a trading post of the Lawa state (Fine Arts Department, 2020). In approximately 1782, Phra Khlang Haew and Phra Khlang Pha Mueang successfully seized power from the Khmer, establishing the Sukhothai Kingdom as an independent state (Fine Arts Department, 2020). The kingdom flourished progressively, reaching its zenith during the reign of King Ramkhamhaeng the Great before gradually declining due to both internal and external challenges, eventually being absorbed into the Ayutthaya Kingdom.

The Sukhothai Kingdom was strategically positioned along trade routes between the Gulf of Martaban and the central Mekong River basin. Its governance structure was characterized by the decentralization of administrative power from the capital city to various provincial centers. The capital city, Sukhothai, served as the royal seat of the monarch.

The kingdom consisted of four hierarchical levels of administrative centers:

- 1) The Royal Capital (Rajathani) was Sukhothai, serving as the center of royal authority.
- 2) The Provincial Capitals (Inner Provincial Capitals) were frontier cities surrounding the royal

capital in all four cardinal directions. These included Si Satchanalai (Sawankhalok) to the north, Si Satchanalai (Phitsanulok) to the south, Songkhwaeng (Phitsanulok) to the east, and Nakhon Chum (Kamphaeng Phet) to the west.

- 3) The Provincial Sub-Capitals (Outer Provincial Capitals) were located further away from the royal capital. The king appointed high-ranking officials or capable individuals to govern these cities. Examples include Phra Bang, Chiang Thong, Bang Phan, and Bang Chang.
- 4) Border Towns (Upcountry Towns) were located beyond the kingdom's borders. Indigenous inhabitants governed these towns themselves. Examples include Malaka and Yarhor to the north, Saow (Lung Phrabang), and Wiang Chan to the northeast, and Thawai and Hongswadi to the west.

Historical evidence suggests abundant geological resources in this area capable of producing exquisite Buddhist sculptures, ceramics, and various artifacts including coins, ornaments, and tools. Moreover, the construction of the city utilized a variety of locally sourced geological materials, predominantly limestone, laterite, and kiln-fired bricks, likely manufactured from sources near the ancient city. However, there is still a lack of comprehensive historical or archaeological research supported by rigorous investigation and collaboration with officials from the Sukhothai Historical Park and the Department of Fine Arts seeking to investigate hypotheses or archaeological evidence. This study aims to analyze the geological characteristics of slags, ore-related rocks, and laterite integrating with geography and archaeological evidence from nearby the ancient city of Sukhothai. It also seeks to establish connections between geographical and geological features and the scientific aspects of Sukhothai city transportation. Furthermore, the study investigates metal ore deposits, particularly iron ore, crucial for the growth and prosperity of Sukhothai, in relation to local resources.

Regarding the prehistoric traces of communities preceding the emergence of Sukhothai, it is evident that the surrounding areas of Sukhothai exhibit clear evidence of human settlement before the 19th century AD. Since prehistoric times, significant archaeological sites have been discovered around the source of the Mae Ramphan Stream, such as the Ban Wang Hat archaeological site in Taling Chan sub-district, Ban Dan Lan Hoi district. This archaeological site dates back to prehistoric times and extends through the Sukhothai period. It contains traces of iron smelting and various iron tools and pottery, as well as gold and silver items like bracelets, jewelry, and figurines made of gold and

silver. In the Sri Satchanalai district, standing Buddha images from the Sukhothai and Sri Satchanalai periods have been uncovered. Excavations at the Chom Chuen Temple reveal the distribution of artifacts da-

ting back to the Sukhothai period in the Mae Ramphan Basin, indicating their relationship with the water routes of each community, with the main route being the Mae Ramphan Stream and the Yom River.

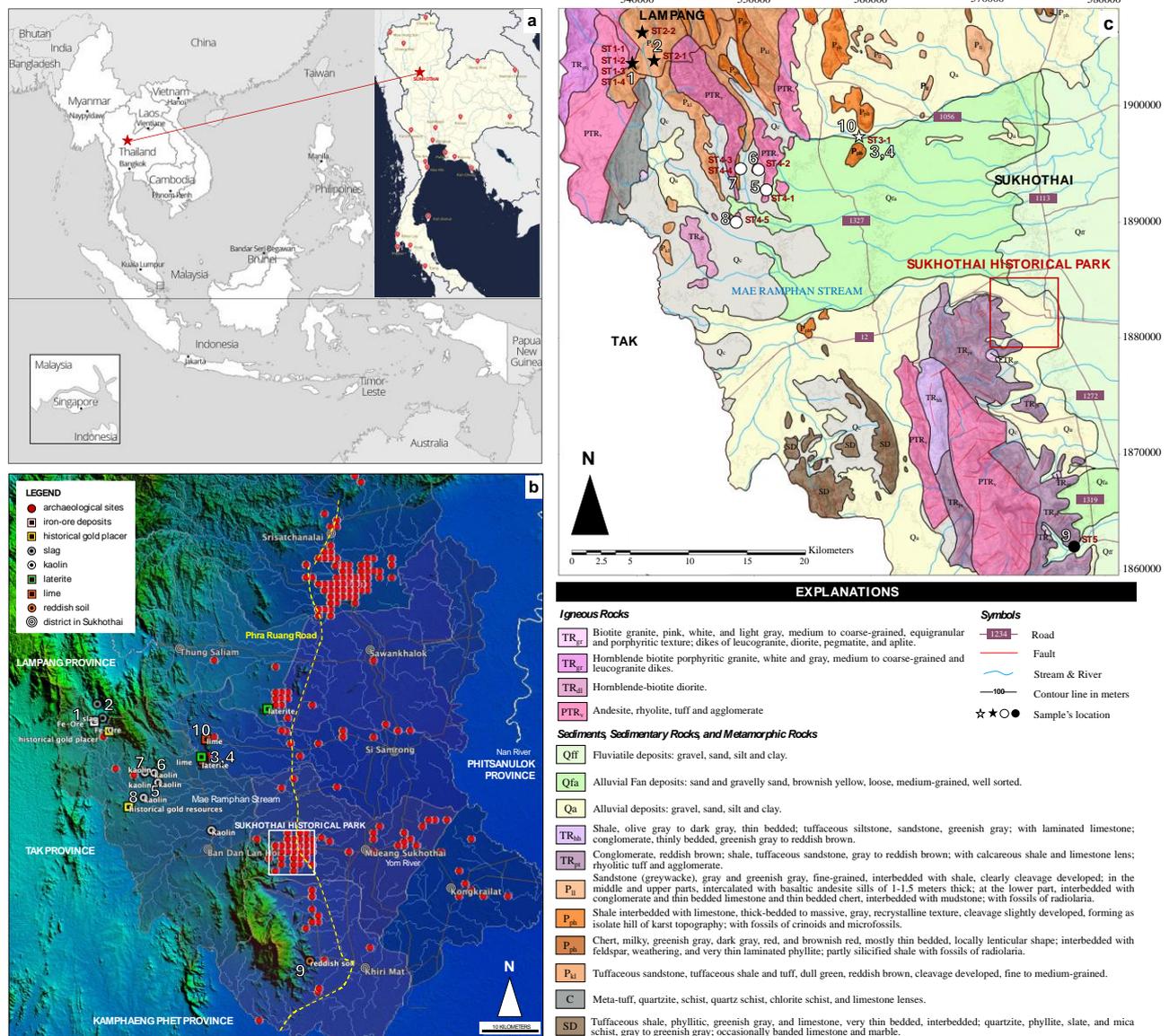


Figure 1. Cartographic representation of the Sukhothai Area. (a) location of Sukhothai Province (red star) in southeastern Asia and Thailand. (b) distribution of archaeological and georesources sites analyzed in Google Earth Pro®. Symbols including rectangles (white, green, and orange), circles (gray, white, and orange), and several red spots were also sampled for measurements. (c) geologic map of Sukhothai Province (data modified from the Department of Mineral Resources, 2008a). The white star is slags, kilns, and laterites. Black star is archaeometallurgical slag with hydrothermal deposits. The white circle is the source rocks of kaolinite and the black circle is the source rocks of reddish soil deposits. The numerical symbols represent the point of study sites outlined in Table 1.

The vast archaeological site of Ban Wang Hat extends across a wide area within the expansive landscape of Tambon Taling Chan, Amphoe Thoen, Lamphang Province. This archaeological site reveals a community with specialized industrial capabilities, particularly in iron smelting technology. Abundant metal artifacts, including various iron tools and utensils, were discovered throughout the site, indicating a fully integrated production process rarely found in

other archaeological sites, except for some sites in the Lopburi-Pasak River Basin (Pigott and Natapintu, 1988; Mudar, 1993; Bhumadhon, 1999; Gale, 2001; Pollard, 2009; Higham et al., 2011; Higham and Higham, 2009; White, 2008; White and Hamilton, 2009; Singtuen and Phajuy, 2020).

Valuable resources were a crucial factor in human settlement, aimed at controlling and managing these

assets. Consequently, it can be inferred that this region is rich in significant mineral resource management. It served as a center for the ancient metal industry from prehistoric times until the establishment of the Sukhothai Kingdom as its capital. Additionally, the renowned Sangkhalok or Sukhothai ceramics, crafted from kaolin or kaolinite, significantly contributed to the kingdom's prosperity. Although it has been established for several decades that the large iron smelting site located in the mountainous region between the northern and central parts of Thailand is in the Ban Dan Lan Hoi district or the Wang Hat area, which is believed to be one of the primary reasons for establishing the Sukhothai community or city, there is still no research that thoroughly supports this historical or archaeological hypothesis. Additionally, consultations with officials from the Sukhothai Historical Park and the Department of Archaeology, who seek collaborative research in geological studies, have motivated this study. Consequently, this research investigates the distribution of valuable geological resources in Sukhothai, particularly focusing on metal ore deposits and significant clay sources, which are essential to the growth and prosperity of Sukhothai, in relation to local resources.

2. GEOLOGIC SETTING

Sukhothai Province, situated in the lower northern region of Thailand, lies approximately 440 kilometers away from Bangkok, encompassing an area of roughly 6,596,092 square kilometers. This city shares borders with neighboring provinces: to the north are Phrae and Uttaradit provinces, while to the south are Kamphaeng Phet and Phitsanulok provinces (Figure 1a). Additionally, it is connected to Phitsanulok and Uttaradit provinces to the east, and Tak and Lampang provinces to the west (Figure 1a).

The terrain of Sukhothai Province is predominantly lowland, with the northern part comprising a plateau flanked by mountains to the west. In the central region lies a plain, while the southern area is characterized by another plateau. The Yom River traverses the province from north to south over a distance of approximately 170 kilometers (Figure 1a). Sukhothai Province boasts Khao Luang (Triassic Khao Luang Pyroclasts) as its highest peak, reaching 1,200 meters above sea level.

The general topography of Sukhothai Province features high mountains in the northern part and scattered mountains in the western region. The central and eastern areas consist of hilly terrain, hillside plains, sloping plains, and river basins. The geological composition of the province comprises a variety of rocks ranging from 438 ma sedimentary rocks, metamorphic rocks, igneous rocks, and recent sediments (Department of Mineral Resources, 2008a), all contributing to its diverse landscape (Figure 1b). The primary urban area of Sukhothai Historical Park is situated on the western bank of the Yom River, within Muang District, Sukhothai Province, covering the area near the confluence of the Mae Ramphan Stream and the eastern bank of the low-grade rock foothills (Figure 1c). Sukhothai Province is rich in various significant mineral and rock resources, including gold, antimony, manganese, fluoride, gemstones (blue sapphire), limestone, marble, and decorative granite (Department of Mineral Resources, 2008b).

Although the Sukhothai Kingdom was situated between the Ping River (number 1 in Figure 2a) and Yom River (number 2 in Figure 2a), two major rivers in Thailand, the terrain around the city of Sukhothai was sloped, preventing natural water retention. Consequently, the area adjacent to the mountains required the development of water storage facilities for use during the dry season. The people of Sukhothai developed various water retention methods, including the construction of reservoirs, embankments, irrigation canals, and water pipes to channel water into the city, where it was stored in multiple large and small ponds. Notably, the Phra Ruang Canal, running parallel to the present-day Phra Ruang Road, provides clear evidence of this irrigation system. The Phra Ruang Canal was utilized as part of the water diversion system, directing water from the Ping River to the Yom River during the dry season when the Yom River experienced extremely low water levels, almost drying up. However, no embankments were found to the west due to the proximity to the mountains and the presence of the Mae Ramphan Stream, the city's main waterway, which received water from the northwest (Figure 2b). In addition, during the rainy season, when the Mae Ramphan Stream and the Yom River have a high volume of water, causing overflow, the aforementioned irrigation system is also utilized to retain water to prevent flooding to some extent.

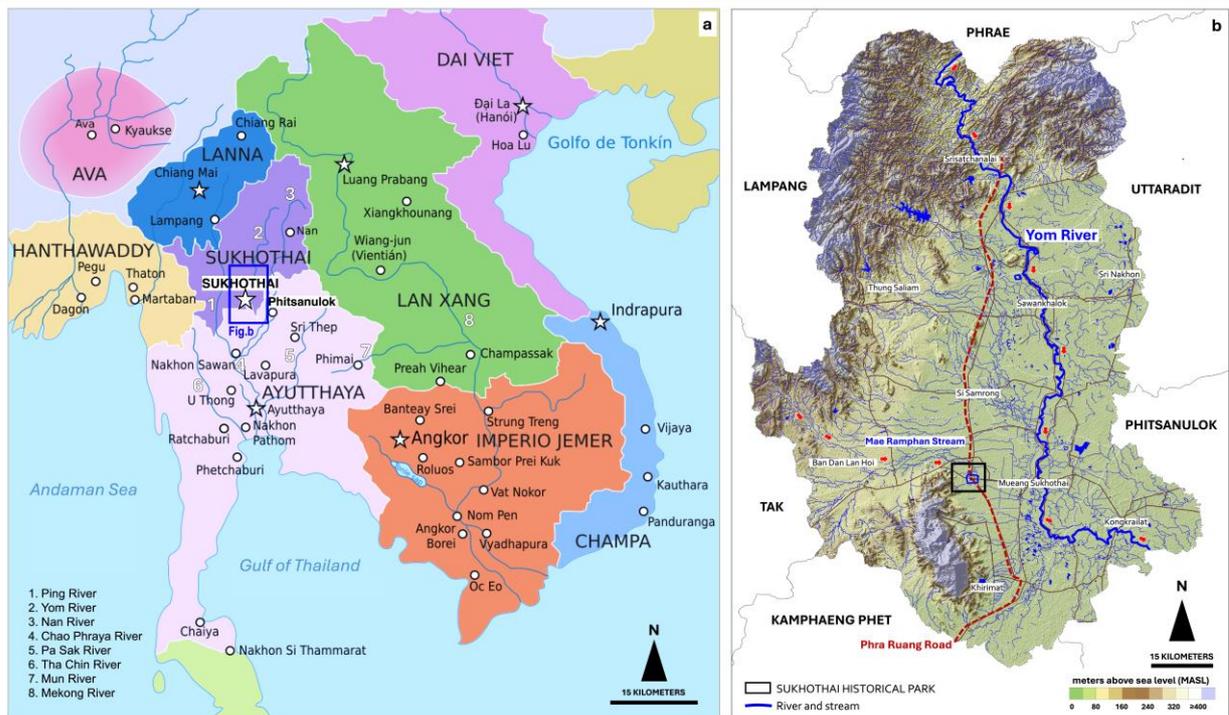


Figure 2. The river and stream distribution map of Sukhothai includes two key elements: (a) A historical map of Southeast Asia circa 1400 AD, highlighting the main rivers and showing the Sukhothai Kingdom in purple, Ayutthaya Kingdom in pale pink, Khmer Empire in orange, Lan Xang Kingdom in green, Champa in pale blue, Kingdom of Lanna in dark blue, and surrounding states; (b) A satellite analysis of modern Sukhothai Province's stream distribution, with the red dotted line indicating Phra Ruang Road, which is the remnant of an ancient canal renowned for its water management in the Sukhothai Kingdom.

3. METHODOLOGY

The study was initiated by gathering data on Sukhothai Historical Park, covering topographical, geographical, and geological features, along with inventorying nearby historical sites within the region, as well as in another area within Thailand. This initial phase drew upon academic reports, geological maps, and existing research to establish a foundational understanding.

Following the literature review, the research design was developed, outlining plans for field data collection, with a specific emphasis on geological observations related to six resource schemes. These schemes included archaeometallurgical sites linked to iron and gold deposits as well as laterite, kaolin, reddish soils, and lime. The samples under investigation included 21 archaeometallurgical slags, 15 rock and ore specimens, 4 laterites, 10 rhyolites, and 1 limestone, all subjected to macroscopic studies and geochemical analysis.

In the subsequent phase, samples including slags, rocks, ores, and laterites were characterized through macroscopic and geochemical analyses, with selected samples undergoing detailed X-ray analysis for precise results. X-ray Fluorescence Spectrometry (XRF)

was employed in geochemical mode, quantified in parts per million (ppm), and applied to the archaeometallurgical study of bronze artifacts, as demonstrated by Çakaj et al. (2023). A portable X-ray fluorescence spectrometry or p-XRF (Olympus Vanta XRF analyzer) was used to measure major oxides and trace elements. The standard C series (VCR) is equipped 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. Pre-calibrated with certified reference materials (CRMs) for excellent accuracy, p-XRF analyzers can store multiple calibration models for different minerals and withstand temperatures from $-10\text{ }^{\circ}\text{C}$ to $50\text{ }^{\circ}\text{C}$, ensuring continuous operation. Featuring a protective detector shutter and IP55 rating, Vanta handheld XRF analyzers are rugged and reliable, meeting U.S. Department of Defense standards for durability. Furthermore, sample selection involved scrutinizing for smooth, uncontaminated surfaces devoid of foreign substances (dirt, soil, moss, or other stains) for subsequent geochemical analysis. To address the non-homogeneous texture in the studied rocks, each sample was analyzed thrice, and the resulting averages were calculated.

This study employed Google Earth Pro and ArcGIS 10.4 software for least cost path (LCP) analysis to investigate the ancient waterways of the Sukhothai Kingdom. Secondary data sources, including Landsat satellite images, aerial photographs from 1976, current river and stream data, locations of the Sukhothai Historical Park and archaeological evidence, as well as Digital Elevation Models (DEM) with a spatial resolution of up to 5 meters, were utilized. These methodologies align with similar approaches employed in previous studies (Cortegoso *et al.*, 2016; Byrd *et al.*, 2016; Gustas and Supernant, 2019; Aşınmaz and Özcan, 2023; Waiyasusr *et al.*, 2024). The analysis included collecting locations of ancient cities, geological resources, and historical cart paths (by using toponymy), which, combined with high-resolution DEM data, generated a slope database for LCP analysis. This process identified efficient travel routes linking ancient cities and explored associations between rural site distribution and various environmental and anthropogenic factors, such as elevation, slope, resource distribution, and proximity to hydrologic units and ancient roads. The study provides new spatial insights into the georesource distribution in the Sukhothai Kingdom, representing a significant advance in mapping and analyzing the cultural sphere's regional georesources.

4. RESULTS

4.1. Field investigation

The Sukhothai Historical Park, a designated UNESCO World Heritage Site, showcases a rich amalgamation of geologic materials, including slate, phyllite, laterite, and synthetic red bricks (Singtuen *et al.*,

2024), as depicted in Figures 3a-3b. Field investigations have been concentrated on regions proximal to the Sukhothai Historical Park in Sukhothai Province, particularly areas featuring ancient kilns and archaeometallurgical slags, alongside significant non-metallic resources such as kaolinite, lime, and laterite (refer to Figure 1 and detailed in Table 1).

Notably, two sites hosting archaeometallurgical slags, coupled with hydrothermal iron deposits, are situated in the upper reaches of the Mae Ramphan Stream (coordinates: 47Q 1903365N 540104E and 47Q 1903267N 539929E), within the Ban Dan Lan Hoi District, in the northwestern quadrant of Sukhothai Province, as delineated in Figure 3c. These locales are characterized by the presence of Permian tuffaceous rocks and Permo-Triassic volcanic formations located near the boundary of Sukhothai and Lampang Provinces, illustrated in Figure 3d. Both study sites can be accessed via the Mae Ramphan reservoir, followed by traversing through the forest and small streams. The specimens are distributed along the streams and foothills within the dense, rugged forest.

Concurrently, archaeometallurgical slags and ancient kilns (Figure 3e), correlated with laterite deposits (Figure 3f), are situated amidst karst topography typified by Permian limestone, located in the Si Samrong District (coordinates: 47Q 1880029N 571328E). The study site is conveniently accessible and situated within a community area. A prominent feature is the presence of laterite clearings exhibiting evidence of cut or excavated grooves. Ancient kilns are scattered throughout small, relatively undisturbed forested areas. While metallic slags are not as widely distributed in this area compared to the two previously mentioned sites, they can still be observed within the kilns.

Table 1. Location of studied areas for field observation about six resource schemes

Site	Location			Resource	Sample for geochemistry
	UTM	Latitude	Longitude		
1	47Q	1903365N	540104E	archaeometallurgy	ST1-F1, ST1-F2, ST1-F3, ST1-F4, ST1-F5, ST1-F6, ST1-F7, ST1-F8, ST1-F9, ST1-F10, ST1-F11, ST1-R1, ST1-R2, ST1-R3, ST1-R4, ST1-R5, ST1-R6, ST1-R7, ST1-R8, ST1-R9
2	47Q	1903267N	539929E	archaeometallurgy	ST2-F1, ST2-F2, ST2-F3, ST2-F4, ST2-F5, ST2-R1, ST2-R2, ST2-R3, ST2-R4, ST2-R5, ST2-R6
3	47Q	1880029N	571328E	archaeometallurgy	ST3-F1-1, ST3-F1-2, ST3-F2-1, ST3-F2-2, ST3-F3-1
4	47Q	1880029N	571328E	Laterite deposit	LT1-1, LT1-2, LT2-1, LT2-2
5	47Q	1892802N	551022E	Kaolinite 1	WNK 1-2, WNK 1-3, WNK 1-4,
6	47Q	1894461N	550318E	Kaolinite 2	WNK 2-1
7	47Q	1894530N	548726E	Kaolinite 3	WNK 3-1, WNK 3-2, WNK 3-5
8	47Q	1890168N	548533E	Kaolinite 4	WNK 4-1, WNK 4-4, WNK 4-6
9	47Q	1861916N	577481E	Reddish soil	-
10	47Q	1880029N	571328E	Lime	LS1

Furthermore, kaolinite deposits are distributed within the Ban Wang Nam Khao area of the Ban Dan Lan Hoi District (Figure 3f), underlain by rhyolite and rhyolitic tuff formations (Figure 3g). According to

Thai language principles, "Wang Nam Khao" translates to an area with white water sources, indicating the geographical characteristics of the area. This region comprises white volcanic rocks, indicative of

both high and low elevations around the headwaters. It exhibits a relatively high weathering and alteration, resulting in the presence of white clays or kaolinite when washed by water. These minor watercourses convey the clays into the Mae Ramphan watershed, flowing towards Sukhothai Town situated on the southeastern flank. Additionally, the Tha Din Daeng Reservoir (coordinates: 47Q 1861916N 577481E) serves as a pivotal location for the extraction of reddish soil utilized in brick and pottery production in

the Khiri Mat District (Figure 3h), overlaying Triassic reddish brown sedimentary rocks and rhyolitic tuff (Figure 3i). According to Thai linguistic conventions, the term "Tha Din Daeng" signifies a region rich in red soil, reflecting the geographical features of the area. Consequently, when the reddish-brown sedimentary and pyroclastic rocks within the region undergo weathering, they primarily yield red soils and clays.



Figure 3. Field investigations were conducted in Sukhothai Historical Park and adjacent archaeological sites: (a) Wat Mahathat and (b) Wat Chetuphon within Sukhothai Historical Park; (c) archaeometallurgical slags and (d) volcanic rocks in the Mae Ramphan Upstream; (e) ancient kilns and (f) laterite resources in Si Samrong District, Sukhothai Province; (g) rhyolite and its weathered soil and (h) volcanic rocks in Wang Nam Khao, situated in the Mae Ramphan Upstream; (i) Tha Din Daeng Reservoir; and (j) sandstone in Khiri Mat District, Sukhothai Province

4.2. Macroscopic studies

The studied samples were examined macroscopically to elucidate their physical characteristics using naked-eye observation, magnifying lenses, and magnets (Table 2). The magnet used to test the magnetic properties of materials shows strong attraction if the material contains magnetite and weak attraction if it contains hematite.

The archaeometallurgical slags predominantly exhibit shades of black, reddish-brown, and yellow-brown, occasionally featuring white, orange, and red hues interspersed (Figures 4a-4g). The fresh surface of these slags reveals a distinct metallic luster or iridescence, sometimes exhibiting adherence to the magnetism to a certain extent. However, some specimens do not undergo a magnetic reaction.

Table 2. Macroscopic characteristics of archaeometallurgical slags near hydrothermal iron deposits in the upper part of Mae Ramphan Stream, Ban Dan Lan Hoi District, Sukhothai Province.

Sample	Type	Colour	Details	Magnetic properties		
				high	med	none
ST1-F1	slag	black, brown	metal and slag exhibit flow patterns, air bubbles, and fragments (brown, orange, grey) 1- 5 mm.	✓		
ST1-F2	slag	black	metal exhibit flow patterns and air bubbles			✓
ST1-F3	slag	black, brown	slag exhibit air bubbles			✓

ST1-F4	slag	black, brown	slag exhibits adamantine luster	✓
ST1-F5	slag	black, red	high density metal exhibits metallic luster	✓
ST1-F6	slag	black, brown	slag exhibit air bubbles and fragments (white, orange, grey) 1- 4 mm.	✓
ST1-F7	slag	black, brown	high density metal exhibits metallic luster and air bubbles	✓
ST1-F8	slag	brown	slag exhibit exhibits metallic luster, air bubbles, and fragments (white, grey) 1- 6 mm.	✓
ST1-F9	slag	black, brown	low density slag exhibits metallic and fragments (white) 0.5- 4 mm.	✓
ST1-F10	slag	black, orange, brown	low density slag exhibits air bubbles and orange stain surface	✓
ST1-F11	slag	brown	slag exhibit air bubbles and fragments (grey, white) 1- 6 mm.	✓
ST2-F1	slag	black	slag exhibit air bubbles and fragments (brown, orange, white) 0.5- 1 mm.	✓
ST2-F2	slag	black	metal and slag exhibit air bubbles, and fragments (brown, orange, white) 1- 5 mm.	✓
ST2-F3	slag	black, grey	moderate density slag exhibits red stain surface	✓
ST2-F4	slag	black, red	slag exhibit air bubbles, metallic luster, quartz, orange fragments 1-4 mm., goethite	✓
ST2-F5	ore	black	low density slag exhibit air bubbles and white fragments 1-3 mm.	✓
ST1-R1	ore	grey, brown, red	plagioclase rich andesite with quartz-metal veins	✓
ST1-R3	ore	black, grey, red	plagioclase rich andesite with quartz-metal veins	✓
ST2-R1	ore	grey, brown	quartz veins/stockworks with metal	✓
ST3-F1-1	slag	black, brown, grey, white	slag exhibit flow patterns, vitreous luster, air bubbles, and white fragments 1- 5 mm.	✓
ST3-F1-2	slag	black, grey, white		✓
ST3-F2-1	slag	black, grey, white		✓
ST3-F2-2	slag	black, brown, grey, white		✓
ST3-F3-1	slag	black, brown, grey, white		✓

Variations in density are observed among different slag samples, ranging from markedly high to considerably low, correlating with the presence of cavities or voids. Typically, small pores are dispersed throughout the specimens, with pore sizes approximately 0.1 centimeters in diameter (Figures 4a-4h). Some slag specimens manifest characteristics reminiscent of opaque black glass, indicative of exposure to heat during the smelting process. Certain samples display metal particles embedded within the slag, contributing to a smooth texture and exhibiting black, gray, and white colors akin to glassy flow marks (Figure 4h). At specific locations, fragments of white, gray, orange, and brown colors ranging from 0.5 to 6

millimeters in size are evident of fluxes (Figures 4a-4h).

The accompanying rocks found alongside the slag near Mae Ramphan Upstream comprise volcanic rocks with porphyritic textures, containing feldspars phenocrysts in crystal sizes ranging from 0.5 to 2 millimeters. These rocks exhibit green, reddish-purple, and gray colors, with most specimens displaying numerous quartz veins and interspersed dark gray ores with metallic lusters (Figures 4i-4j). Additionally, large quartz chunks with associated dark gray metallic inclusions are also encountered within the rocks (Figure 4k).

Regarding the laterite samples, they exhibit black coloration with a surface patina ranging from dark

brown to reddish-brown. The laterites within the study area consist of iron oxide compounds as oxidized iron constituents. The laterites typically possess a relatively spherical shape with a high degree of roundness and are well-sorted, ranging from approximately 0.5 to 5 centimeters in diameter (Figure 4l).

The metal nodules are densely interconnected to form laterites but do not undergo a magnetic reaction.

In addition, limestone displays a coloration ranging from white to pale-yellow, exhibiting numerous calcite veins traversing in diverse orientations. Additionally, weathering has imparted pink, brown, and black hues on the surface of the limestone.

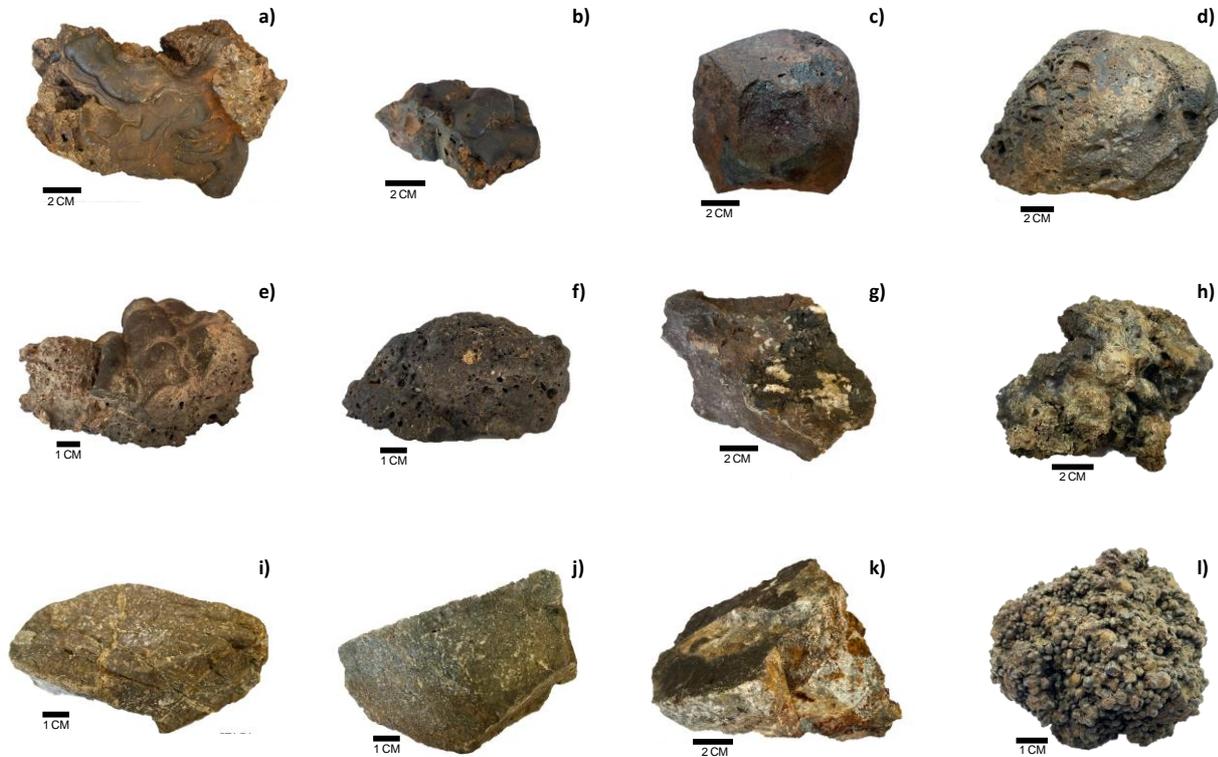


Figure 4. Archaeometallurgical slags and ore resources in Sukhothai Province. (a) slag sample no. ST1-F1, (b) slag sample no. ST1-F2, (c) slag sample no. ST1-F5, (d) slag sample no. ST1-F7, (e) slag sample no. ST2-F1, (f) slag sample no. ST2-F5, (g) slag sample no. ST2-F4, (h) slag sample no. ST3-F1, (i) rock sample no. ST1-R1, (j) rock sample no. ST1-R3, (k) quartz stockwork sample no. ST2-R1, and (l) laterite sample no. LT1-1.

4.3. Geochemical characteristic

In the points where archaeometallurgical slags display black-gray hues, characterized by metallic luster and smooth, clean surfaces, they are subjected to analysis using p-XRF to determine their significant chemical composition. This study aims to focus on the oxides of metallic groups and metallic elements economically valuable and capable of smelting metals for weaponry. The archaeometallurgical slags exhibit total FeO concentrations within three ranges: low (10.4641-16.9137 wt%), moderate (48.6875-61.7968 wt%), and high (72.6560-81.7732 wt%) as shown in Figure 5a. Additionally, some specimens also contain trace amounts of MgO, MnO, and TiO₂, ranging from 0.0282 to 3.4484 wt%. Regarding the concentrations of trace elements in the archaeometallurgical slag samples, which are important metals, they comprise Bi, Pb, As, Sn, Sb, Zn, and Cu, ranging from 0 to 921 ppm.

Notably, zinc (Zn) or trace amounts of zinc can be found in all slag samples (Figure 5b).

Furthermore, the geochemical analysis of the volcanic rocks discovered in proximity to the area where archaeometallurgical slags were found, exhibiting the accumulation of hydrothermal iron ore deposits as noted in field surveys, revealed notably high FeO concentrations ranging from 5.0943 to 16.8088 wt% (Figure 5c). Additionally, moderate levels of MgO and TiO₂ were observed, spanning from 1.2477 to 10.7517 wt%, except in rhyolite rocks where they were absent. Furthermore, traces of MnO were consistently present in all samples in minor quantities ranging from 0.0128 to 0.4768 wt% (Figure 5d). As for trace elements, zinc (Zn) was prominent and detected in all rock samples, with concentrations ranging from 13 to 511 ppm, mirroring those found in the archaeometallurgical slag samples.

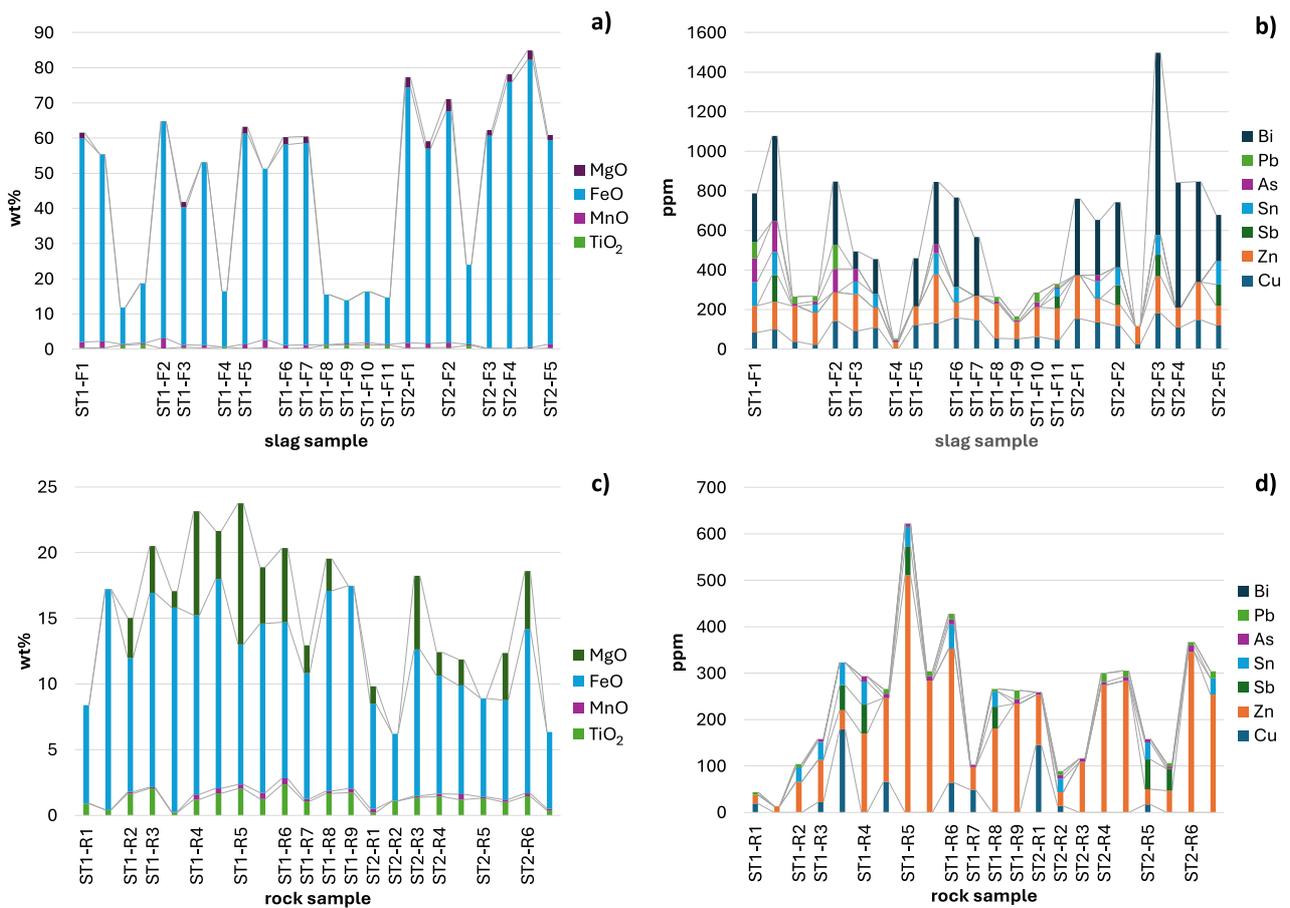


Figure 5. Quantitative geochemical analysis of archaeometallurgical slags and rocks from ore resources in Sukhothai Province by using *p*-XRF. (a) major oxides of slags, (b) trace elements of slags, (c) major oxides of rocks, and (d) trace elements of rocks.

In study sites 1 and 2, where the accumulation of iron ore deposits is observed in volcanic rocks, the rocks can be classified based on their geochemical composition using the SiO₂ and K₂O ratio (Figure 6a). This classification reveals a variety of rock types such as rhyolite, dacite, andesite, basaltic andesite, and ab-sarokite/basaltic-trachyandesite, originating from different types of magma (alkaline, high-k calc-alkaline, calc-alkaline, and low-k calc-alkaline series) and possibly erupted at different times (Phajuy and Singtuen, 2019). The subsequent mineral accumulation occurs after these volcanic rocks have been deposited and amalgamated. Tectonic processes lead to fracturing and void formation within the rocks, facilitating

the ingress of hydrothermal fluids carrying metallic minerals. The parent rocks originating from the kaolinite deposits can be categorized based on their geochemical composition using the SiO₂ and K₂O ratio, leading to their classification as rhyolite (Figure 6a). The rock samples exhibit a very high SI (sericitization index) and moderate CCPI (chlorite-carbonate-pyrite index) values, indicating a process where these rocks have gained K⁺ while losing Na⁺ and Ca²⁺ during feldspar alteration, illitization, and kaolinization (Figure 6b). These alterations are influenced by hydrothermal processes (Figure 6c), akin to numerous felsic rocks found in Lampang, Tak, and Sukhothai Provinces (Singtuen and Phajuy, 2022).

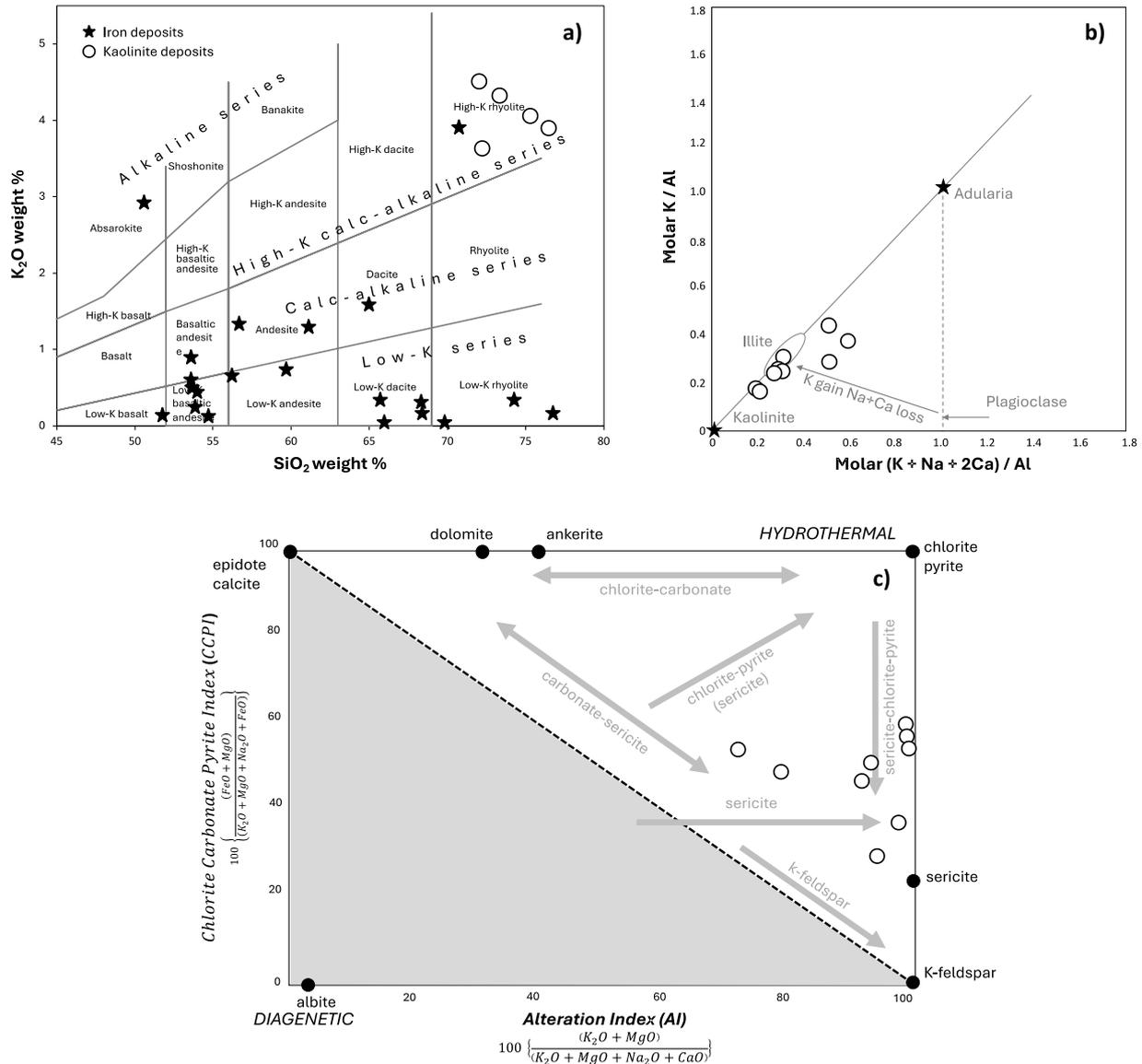


Figure 6. Geochemical classification of volcanic rocks. a) rock name classification by SiO_2 and K_2O ratio (diagram modified from Ewart (1982)). b) plots of K/Al vs. $(K+Na+2Ca)/Al$ by the alteration minerals kaolinite, illite, and adularia plot on a line of slope 1. Unaltered rocks typically have $(K+Na+2Ca)/Al > 1$. Potassium metasomatism leads to decreasing $(K+Na+2Ca)/Al$ and increasing K/Al values (diagram modified from Madeisky (1996) and Booden et al. (2010)). c) Plots of the Chlorite-Carbonate-Pyrite Index versus Alteration Index of studied volcanic rocks on the alteration box plot showing the relative degree of alteration and general alteration mineralogy (diagram modified from Large et al. (2001)).

Meanwhile, the furnace slags collected from inside the ancient kilns in the studied area 3 exhibit TiO_2 levels of up to 0.7839, FeO levels of up to 3.8599 wt%, and MnO levels of up to 0.2915 wt%. Additionally, the analysis of laterites yielded the following ranges: SiO_2 32.0278 - 35.5004 wt%, TiO_2 0.4244 - 0.5524 wt%, Al_2O_3 17.7452 - 29.6636 wt%, FeO 28.6891 - 41.8389 wt%, MnO 0.7055 - 5.6710 wt%, CaO 0.3153 - 0.6526 wt%, K_2O 1.3971 - 1.8717 wt%, P_2O_5 less than 1.1079 wt%, and light elements 39.6858 - 48.8707 wt%. The investigation of chemical ratios, specifically SiO_2 -FeO- Al_2O_3 , utilizing Schellmann's diagram (1981; 1986), indicates that the analyzed laterite has undergone a

weak to moderate laterization process. Further-more, the assessment of Al_2O_3 - $(CaO+Na_2O+K_2O+MgO)$ -FeO or (A-L-F) ratios, based on Babechuk et al.'s diagram (2014), reveals that the laterite undergoes robust laterization, with iron increasing from the dissolution or reduction of silica. Moreover, the analyzed Permian limestone sample, located near the laterite fields, demonstrates the following elemental composition: SiO_2 7.7542 wt%, Al_2O_3 4.0156 wt%, FeO 0.1181 wt%, MnO 0.0185 wt%, CaO 56.4642 wt%, K_2O 0.2351 wt%, P_2O_5 0.1774 wt%, and light elements 54.7049 wt%. Limestones with such CaO content are capable

of producing high-quality white lime, similar to limestones found in conventional white lime production sites across Thailand, which typically contain CaO within the range of 53.26 to 56.52 wt% (Phajuy and Singtuen, 2022).

5. DISCUSSION

According to the report by the Department of Mineral Resources (2008), this region boasts a wealth of mineral resources including salt, iron, mineral veins, manganese, gold, and copper. The expansion of the community at Bang Wang Hat (located in the northwestern part of Sukhothai or Mae Ramphan Upstream) signifies the establishment of short-distance transportation routes specifically aimed at accessing mineral resources. This demographic shift has exerted economic pressures and has catalyzed advancements in cultural production during that period, acting as significant determinants or motivators. It corresponds with the migration of populations from the northeastern region towards the Chao Phraya River basin along the aforementioned inter-regional routes (Glover, 2011; Murphy, 2016).

During the Dvaravati period, the community at Ban Wang Hat likely played a role in the dissemination of Dvaravati culture into inland regions (Wales, 1969). Hence, evidence of the Dvaravati era is also discernible in the Ban Wang Hat community. This era was characterized by movements and transformations among groups across Southeast Asia, particularly in Lower Southeast Asia, driven by technological advancements and economic-cultural factors (Wales, 1969; Glover, 2011; Pryce *et al.*, 2014; White, 2017). These factors included the diffusion of maritime culture from southern China and the coastal communities of northern Vietnam, represented by the Dian culture, Dong Son culture, and long-distance trade between urban centers globally, including India, Greece, Rome, and China.

Such movements reflect an ongoing process of change within these groups, resulting in noticeable transformations dating back approximately 500 years before the Common Era (Glover, 2011; Murphy, 2016). Communities in the ancient territories of Siam have exhibited cross-regional transportation routes since antiquity, marking a continuity in the region's historical dynamics.

The extensive iron smelting site at Ban Wang Hat is located on steep hill slopes deep within the forest, near the Mae Ramphan Upstream, which can be likened to the lifeline nurturing the communities in the Sukhothai region. It is thus conceivable to hypothesize that the abundance of natural resources, particularly minerals, attracted human settlements to establish a base in this area. The industrial development in

the Mae Ramphan Basin appears to be similar to that of communities in the northeastern region and the Lopburi-Pasak River Basin (Pigott and Natapintu, 1988; Mudar, 1993; Bhumadhon, 1999; Gale, 2001; Pollard, 2009; Higham *et al.*, 2011; Higham and Higham, 2009; White, 2008; White and Hamilton, 2009; Singtuen and Phajuy, 2020).

Examining the cartographic representation of the Sukhothai Kingdom during the reign of King Ramkhamhaeng the Great, a period characterized by its utmost prosperity, reveals that the various provincial capitals governed by the Sukhothai Kingdom were endowed with significant geological resources (Figure 7a). For instance, the western region, serving as a route to Mae Sot and Myanmar, was abundant in zinc (Zn) tin (Sn), and gold (Au) ores while the southern region boasted rich deposits of tin (Sn), copper (Cu), and gold (Au) ores. Furthermore, the eastern region exhibited richness in mineral resources such as iron-gold (Fe-Au) ores in Uttaradit, copper (Cu) in Nong Khai, and salt in Udon Thani. Similarly, the northern region served as a hub for kaolinite in Lampang, iron in Uttaradit, as well as gold and copper in Laos (Soysouvanh *et al.*, 2016). The midland capitals were notably abundant in metal ores, including iron (Tak, Sukhothai, Nakhon Sawan, Phichit, Lopburi), gold (Phichit, Phetchabun), and copper (Nakhon Sawan, Phichit, Lopburi) as shown in Figure 7a.

From this urban network governed by the Sukhothai Kingdom, it is evident that the regions were rich in valuable local geological resources, particularly metals suitable for weaponry, tools, ornaments, coinage, and religious artifacts, often derived from prominent ores possibly resulting from impure smelting or provided by the central capitals or border towns.

Additionally, the strategic location and topographical suitability of the city played a pivotal role in facilitating communication with other cities, making it an excellent strategic point. Situated in a fertile plain with abundant rivers, the region was among the most fertile areas. The archaeological sites within the vicinity of ancient Sukhothai reflect the societal, economic, and cultural prosperity during the 19th to 20th centuries. However, the foundation of Sukhothai and its surrounding areas did not commence until the 19th century AD. Nonetheless, traces of human settlements dating back to prehistoric times, continuing through the Sukhothai period, are evident. One significant factor contributing to the long-term habitation in this area is the availability of resources and geographical conditions conducive to urban sustainability, coupled with adaptation to the local environment. These archaeological sites in Sukhothai not only serve as religious symbols but also signify territorial control

or the establishment of sacred spaces in areas with vital resources for urban development, particularly

near water sources and mineral resources, as evidenced by the prolonged settlement near the mountainous watershed.

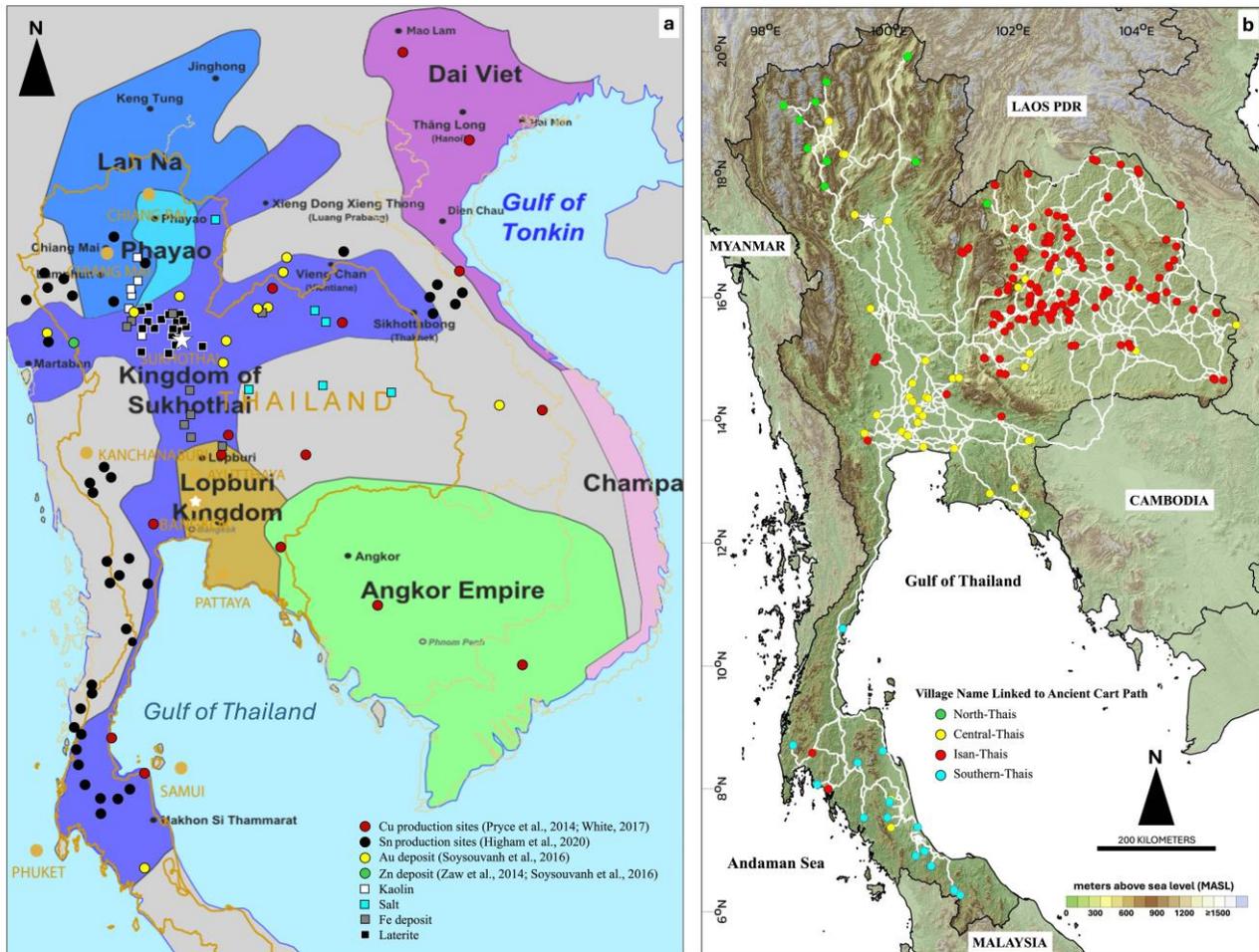


Figure 7. Cartographic representation of Thailand related to studied history. (a) georesources distribution of the Kingdom of Sukhothai and neighbouring towns. The map illustrates zones of influence of Sukhothai and its neighbours in 1300 AD (data from Wyatt (2004)) and the golden line is the recent boundary of the region. (b) ancient cart path investigation of Sukhothai Kingdom in the recent topographic map by toponymy and GIS analysis. The white star is the location of the Sukhothai Historical Park.

The study integrated the Least Cost Path (LCP) analysis with resource distribution to elucidate human mobility patterns in landscapes, based on Zipf's (1949) Principle of Least Effort. This method was used to determine optimal routes linked to the toponymy of villages in Thailand, indicating historical cart paths. LCP analysis combined ancient cart paths to delineate potential movement routes in the past, taking into account variables such as terrain type and slope. The connectivity of the Sukhothai Kingdom with various towns across Thailand is illustrated by the white-line symbols depicted in Figure 7b. In addition to overland transportation, Sukhothai, which received water from the northern regions of Thailand, also facilitated water transportation from the northern Lan Na Kingdom or various cities, as well as from

the southern tributaries of the Chao Phraya River, as illustrated in Figure 2a.

The geochemical study of slag characteristics and mineral deposits reveals that the upstream area of the Mae Ramphan Stream, known as Ban Wang Hat, holds significant potential as a major hub for metal production, whether for internal use, exchange, or trade with other cities. This is attributed to its highly favorable geographical location, which allows for effective control and utilization of valuable resources and facilitates communication with surrounding urban centers in all directions. Consequently, Sukhothai Province serves as an archaeological site with evidence of iron smelting dating back to prehistoric times up to its establishment as a royal capital.

Although the ancient city of Sukhothai has yet to undergo dating of archaeometallurgical slag or artifact typology analysis, the metal smelting developments in the northeastern and central regions of Thailand may provide insights into the technological advancements within the Sukhothai Kingdom. The Thailand Archaeometallurgy Project identified Ban Chiang (northeastern Thailand) and Khao Wong Prachan (central Thailand) as significant industrial sites dating from the 2nd millennium BC to the mid-1st millennium AD, while Phu Lon dates from the 1st millennium BC to the 1st millennium AD, revealing a complex history of copper production and technological evolution (White, 1986; 1988; 2008; Pigott and Napatintu, 1988; Pigott et al., 1992; Pigott et al., 1997; Pryce et al., 2010; Pryce et al., 2011a; 2011b; 2014; Vemon, 1996-1997) as shown in Figure 8. The Bronze Age artifacts examined by the Southeast Asian Lead Isotope Project offer valuable insights into the regional origins of metallurgy in Southeast Asia, with Ban Non Wat in northeastern Thailand emerging as a key site with a well-established chronology (Pryce et al., 2010). Subsequent findings from Ban Non Wat align closely with the Khao Wong Prachan signature, indicating an extensive metal exchange network across central Thai territory and aiding in refining the dating sequence of Ban Non Wat and identifying early copper smelting in Khao Wong Prachan (Pryce, 2010; Pryce et al., 2010). Further investigations at Khao Wong Prachan, particularly at Non Pa Wai, suggest foreign influences on early central Thai metallurgy, highlighting the role of foreign imports and casting technologies in local primary production experimentation (Pryce et al., 2010; Pryce et al., 2011a; 2014). Based on these findings, a revised 'origins' hypothesis proposes simultaneous copper smelting at Khao Wong Prachan and Xepon towards the end of the 2nd millennium BC, aligning with other regional evidence indicating a complex network of technological diffusion influenced by northern contacts (Pryce et al., 2011b; White and Hamilton, 2009). Furthermore, Khamsiri (2022) employs remote sensing and luminescence dating to investigate archaeological sites in Buriram Province, northeastern Thailand, revealing primary transportation routes between the Khorat plateau and present-day Cambodia, consistent with archaeological evidence. Luminescence dating of slag confirms its use in ancient iron smelting, with results indicating terminal activity approximately 140 years ago, aligning with Cambodia's an-

cient iron smelting period. The dating of technical ceramics suggests multiple furnace construction phases spanning during 360-370 years and 1000-1110 years ago (Figure 8), indicating a prolonged operational lifespan and highlighting the significance of ancient transportation routes and industrial zones in the region (Khamsiri, 2022a; 2022b).

Moreover, the primary chemical constituents of laterite include iron or aluminium oxides, often accompanied by impurities such as quartz and kaolinite. While alkaline and silicate elements are present in minimal amounts, regions with abundant iron compounds can serve as sources for iron smelting, and those with high aluminium content can support aluminium metallurgy. Areas, where iron slag is found near laterite deposits (site #3), are likely younger compared to regions with hydrothermal-type mineral deposits, which are located in rugged forests and show no evidence of furnaces (sites #1 and #2). This inference is based on well-preserved furnace structures, indicating a period of iron smelting activity following the use of raw materials from rocks. This aligns with the age of iron slag found in central and northeastern Thailand, suggesting a pattern where early humans initially used raw ores from hydrothermal deposits for smelting (Figure 8), as seen in Khao Wong Prachan, Ban Chiang, and Phu Lon (White, 1986; 2008; Pigott et al., 1992; Pigott et al., 1997), before later turning to lateritic ores, such as in Buriram (Nitta, 1996; 1997; Venunan, 2016; Khamsiri et al., 2022a; 2022b).

In addition to metals crucial for manufacturing tools and weapons, pottery and ceramics hold significance for household utilities, adornments, and decorative items. The oldest evidence of pottery in Thailand is found at Ban Chiang (northeastern Thailand), dating back over 2,000 BC (Alsop, 1975; Wilford, 1976), aligning with the Log Coffin culture's timeline (Carlhoff et al., 2023). Subsequently, Thai pottery was influenced by the Mon people, who used red clay pottery, as evidenced by discoveries in Hariphunchai at the northern Thailand or Lan Na Kingdom (Yip, 1978; Shaw, 1987; Labbé, 2007; Brown, 2009). Concurrently, there was a migration of Chinese settlers, contributing to the fusion of Thai pottery with Chinese cultural elements, leading to the development of ceramics (Yip, 1978; Shaw, 1987; Labbé, 2007; Brown, 2009). This cultural blend is evident in Thai ceramics from Sukhothai and Sawankhalok, characterized by intricate patterns on white clay surfaces or kaolinite (Figure 8).

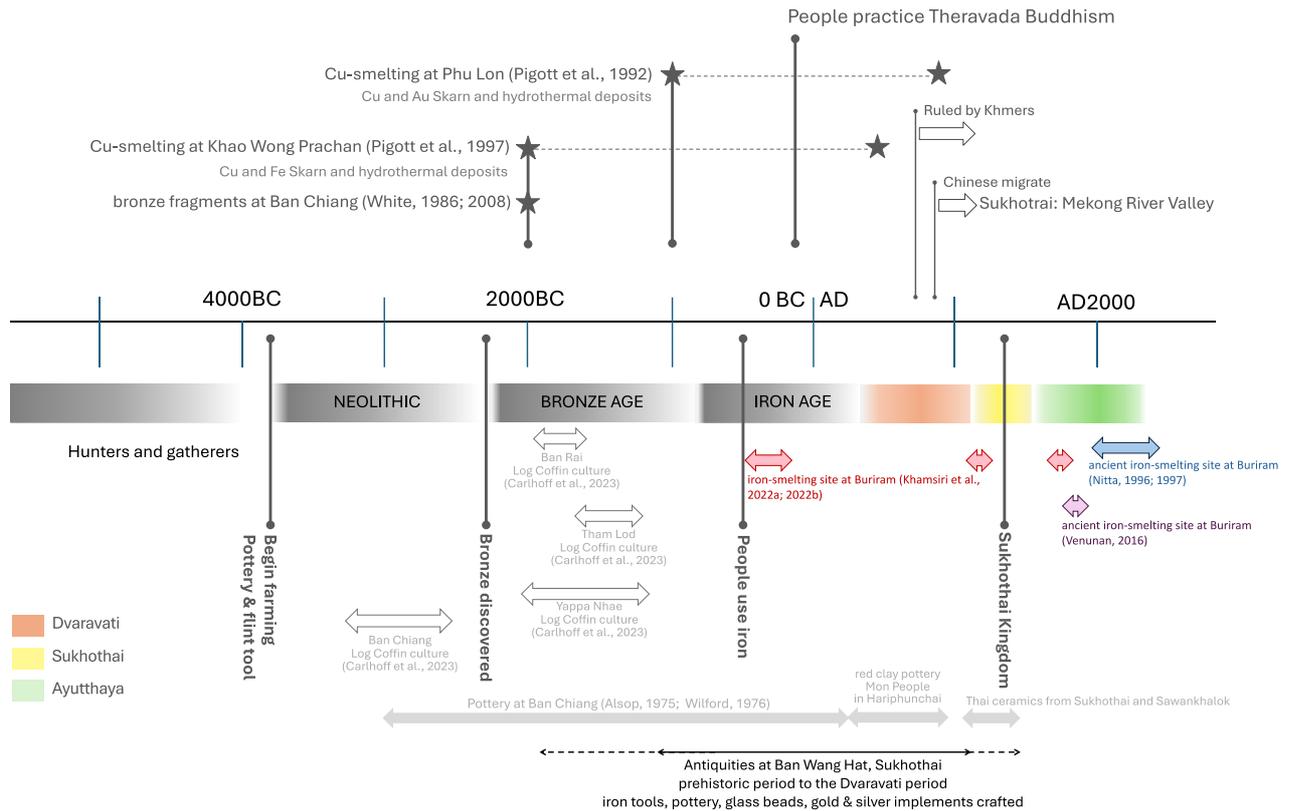


Figure 8. Evolution chart of anthropological development related to georesources in Thailand.

Sukhothai, with its abundant felsic volcanic rocks weathering vast quantities of white clays, resembles a significant hub for large-scale kaolinite resources. The strategic positioning of settlements near the Mae Ramphan Downstream provides an advantage in utilizing the transported white clay, accumulated by waterways, for ceramic production and kiln firing. This is evidenced by widespread ceramics and the arrangement of ancient ceramic kilns along the banks of the Mae Ramphan Stream within the Sukhothai Historical Park.

Despite Sukhothai's geographical challenges for agriculture—owing to its location at the foothills and its relative distance from the Yom River, leading to severe droughts in the summer and flooding during the rainy season—the region's abundant mineral resources, including iron, gold, and kaolinite, have underpinned the prosperity of the Sukhothai Kingdom as a significant production hub. These resources, vital for weapon production and valued as treasures, along with ceramics or porcelains esteemed in the ancient high governance system, have bolstered the kingdom's success. Consequently, establishing a city in this area was more advantageous for controlling these resources than settling in locations more suitable for agriculture or forestry. In contrast, nearby areas such as Phitsanulok, Nakhon Sawan, and Phichit may be

more suitable for agriculture due to their more favorable water resources and soil conditions. Despite the natural challenges of water management due to extreme seasonal variations in water availability, Sukhothai developed renowned water management innovations. These included dams, reservoirs, and the diversion of water into the Phra Ruang canal, which runs parallel to the current Phra Ruang Road (Figures 1 and 2).

The analyzed data and hypotheses from this work highlight the cultural development of Sukhothai, emphasizing its rich georesources (including metal, laterite, kaolinite, and reddish soil) and their connections to culture, history, and archaeology. These sites link Sukhothai Town and nearby cities, facilitating movement based on terrain, slope, hydrology, and ancient roads. This approach is crucial for advancing regional humanities and social sciences, enhancing public understanding of geoarchaeology, and ensuring the sustainability of the Sukhothai Historical Park as a World Heritage Site.

6. CONCLUSION

The Sukhothai Kingdom emerged in the Yom River valley around the 13-14th century AD, serving as a trading post between the Gulf of Martaban and the central Mekong River basin, as well as a hub for both metallic and non-metallic mineral resources. Due to

its historical significance and well-managed infrastructure, Sukhothai has been designated as a UNESCO World Heritage site. Archaeological evidence in the northern part of the park indicates that metal smelting in the Sukhothai area dates back to prehistoric times, continuing through the Dvaravati period and possibly extending into the Sukhothai era. High-value metals, such as iron, were crucial for producing significant weaponry, contributing to the prosperity of Sukhothai. Field surveys have revealed that archaeometallurgical slags in the study area are associated with two types of ore deposits utilized in different periods: 1) hydrothermal vein-type deposits related to volcanic rocks, used earlier, and 2) lateritic deposits presented with ancient kilns in the area, used later. Macroscopic analysis reveals that most archaeometallurgical slags are dark gray to black with a metallic luster, flow patterns, and porous structures indicative of high-temperature smelting. The porosity inversely correlates with specific gravity. Some slag samples exhibit diverse flux residues, appearing as white, orange, and gray fragments ranging from 0.5 to 6 mm in width. Additionally, geochemical analyses using portable X-ray fluorescence show significant variations in FeO content, categorized into three levels: low (10.4641-16.9137 wt%), moderate (48.6875-

61.7968 wt%), and high (72.6560-81.7732 wt%). These slags also contain notable concentrations of metals such as TiO₂, MgO, Bi, Pb, As, Sn, Sb, Zn, and Cu. These findings align with ore sources, including quartz-metal veins in rhyolite, dacite, andesite, basaltic andesite, and absarokite/basaltic-trachyandesite rocks presented with porphyritic texture, all rich in FeO and Zn as well as mentioned metal elements. Lateritic deposits, dense and black, also contain high FeO levels suitable for iron production. Moreover, Sukhothai is rich in rhyolite exhibiting extensive kaolinization and illitization due to hydrothermal processes, making it a potential hub for kaolinite-based ceramics or porcelains. The area also contains red sedimentary rocks weathering into red clay suitable for pottery. Establishing a city in Sukhothai was not only strategic for controlling these valuable resources but also for facilitating trade and communication within the region, as indicated by integrated Least Cost Path (LCP) analysis. Additionally, the findings and hypotheses from this work are essential for regional development, enhancing public understanding of geoarchaeology, and ensuring the sustainability of the Sukhothai Historical Park as a World Heritage Site.

Author Contributions: Conceptualization, V.S. and B.P.; methodology, V.S.; software, V.S. and S.P.; validation, V.S., B.P. and S.P.; field observation, V.S., B.P., and N.P.; formal analysis, V.S., B.P. and S.P.; investigation, V.S., B.P., and N.P.; resources, V.S., B.P. and S.P.; data curation, V.S. and B.P.; writing – original draft preparation, V.S.; writing – review and editing, V.S.; visualization, V.S. and B.P.; supervision, V.S. and B.P.; project administration, V.S. and B.P.; funding acquisition, V.S. and B.P. All authors have read and agreed to the published version of the manuscript.

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