REMOTE SENSING AND LUMINESCENCE DATING OF ARCHAEOLOGICAL SITES IN BURIRAM PROVINCE, NORTHEASTERN THAILAND

Miss Sutthikan Khamsiri

A Dissertation Submitted in Partial Fulfillment of the Requirements
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การสำรวจข้อมูลระยะไกลและการหาอายุด้วยวิธีเปล่งแสงของแหล่งโบราณคดีในจังหวัด บุรีรัมย์ ภาคตะวันออกเฉียงเหนือของประเทศไทย

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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Thesis Title	REMOTE SENSING AND LUMINESCENCE DATING OF ARCHAEOLOGICAL SITES IN BURIRAM PROVINCE, NORTHEASTERN THAILAND
By	Miss Sutthikan Khamsiri
Field of Study	Geology
Thesis Advisor	Professor SANTI PAILOPLEE
Thesis Co Advisor	Pira Venunan, Ph.D.

Accepted by the FACULTY OF SCIENCE, Chulalongkorn University in Partial Fulfillment of the Requirement for the Doctor of Philosophy

.... Dean of the FACULTY OF SCIENCE
(Professor POLKIT SANGVANICH)

DISSERTATION COMMITTEE

.... Chairman
(Professor Punya Charusiri)

.... Thesis Advisor
(Professor SANTI PAILOPLEE)

.... Thesis Co-Advisor
(Pira Venunan, Ph.D.)

.... Examiner
(Assistant Professor AKKANEEWUT JIRAPINYAKUL)

.... Examiner
(Professor MONTRI CHOOWONG)

.... External Examiner
(Professor Rasmi Shoocongdej)

สุทธิกานต์ คำศิริ : การสำรวจข้อมูลระยะไกลและการหาอายุด้วยวิธีเปล่งแสงของแหล่งโบราณคดีในจังหวัดบุรีรัมย์ ภาคตะวันออกเฉียงเหนือของประเทศไทย. (REMOTE SENSING AND LUMINESCENCE DATING OF ARCHAEOLOGICAL SITES IN BURIRAM PROVINCE, NORTHEASTERN THAILAND) อ.ที่ปรึกษาหลัก : ศ. ดร.สันติ ภัยหลบลี้, อ.ที่ปรึกษาร่วม : อ. ดร.ภีร์ เวณุนันทน์

งานวิจัยนี้ มุ่งเน้นการประยุกต์เครื่องมือการสำรวจข้อมูลระยะไกล (remote sensing) และการหาอายุด้วยวิธีเปล่งแสง (luminescence dating) เพื่อศึกษาแหล่งโบราณคดี ในพื้นที่จังหวัดบุรีรัมย์ ภาคตะวันออกเฉียงเหนือของประเทศไทย โดยมีจุดประสงค์การศึกษา 3 ข้อ คือเพื่อ 1) จำลองเส้นทางการเดินทางในอดีต จากช่องเขาต่างๆ ตามแนวเทือกเขาพนมดงรัก ไปยังชุมชนโบราณ 297 แห่งที่สำรวจและรายงานไว้บนที่ราบสูงโคราช ภาคตะวันออกเฉียงเหนือของประเทศไทย 2) กำหนดอายุสัมบูรณ์จากตัวอย่างตะกรันเหล็กในแหล่งอุตสาหกรรมถลุงเหล็กโบราณบ้านสายโท 7 และ 3) กำหนดอายุแหล่งอุตสาหกรรมถลุงเหล็กโบราณบ้านสายโท 7 จากชิ้นส่วนของเตาถลุงเหล็ก

ผลการจำลองเส้นทางโดยอาศัยการวิเคราะห์ภูมิสารสนเทศ (Geographic information system) และการพิจารณาข้อมูลภูมิประเทศเป็นหลักบ่งชี้ว่า ช่องเขาตาเหมือน ช่องกร่าง และช่องสายตะกู มีความเหมาะสมในการเดินทางจากที่ราบสูงโคราชไปสู่ที่ราบลุ่มของประเทศกัมพูชา (ปัจจุบัน) ด้วยเหตุผลที่ว่ามีระยะทางโดยรวมสั้นที่สุด สอดคล้องกับหลักฐานทางโบราณคดี เช่น ตำแหน่งโบราณสถานธรรมศาลาหรือบ้านมีไฟ ที่มีความต่อเนื่องจากช่องตาเหมือนสู่เมืองพิมาย เมื่อเปรียบเทียบกับโบราณสถานขนาดเล็กในพื้นที่ พบว่าแนวเส้นทางที่จำลองได้จากงานวิจัยนี้ ผ่านโบราณสถานเหล่านั้นเป็นส่วนใหญ่ นอกจากนี้พบว่าเส้นทางโบราณมีความสัมพันธ์กับตำแหน่งที่ตั้งของกลุ่มอุตสาหกรรมโบราณ อำเภอบ้านกรวด จังหวัดบุรีรัมย์ อย่างไรก็ตาม กลุ่มอุตสาหกรรมถลุงเหล็กโบราณในอำเภอบ้านกรวด มีการกำหนดอายุทางวิทยาศาสตร์พบว่ามีการผลิตในยุคเหล็ก แต่จากความสัมพันธ์ระหว่างแหล่งเครื่องปั้นดินเผาเขมรกับแหล่งถลุงเหล็กโบราณ มีความเป็นไปได้ที่แหล่งถลุงเหล็กโบราณมีการทำต่อเนื่องเป็นเวลานานจนถึงยุคเมืองพระนคร

เนื่องจากปัญหาในการขาดแคลนตัวอย่างที่เหมาะสม สำหรับการหาอายุสัมบูรณ์โดยวิธีทางวิทยาศาสตร์ของแหล่งถลุงเหล็กในประเทศไทย ทำให้ข้อมูลอายุในหลายแหล่งพื้นที่ไม่สมบูรณ์ ในการศึกษาการกำหนดอายุวัสดุทางโบราณคดีด้วยวิธีเปล่งแสง งานวิจัยนี้มุ่งเน้นทดสอบความเป็นไปได้ในการกำหนดอายุสัมบูรณ์จากตัวอย่างตะกรันเหล็ก ซึ่งผลการกำหนดอายุแร่ควอตซ์จากก้อนตะกรันเหล็ก บ่งชี้ว่าการหาอายุตะกรันเหล็กด้วยวิธีเปล่งแสง เป็นวิธีที่มีประสิทธิภาพและน่าเชื่อถือในการหาอายุอุตสาหกรรมเหล็กโบราณ โดยพบว่ามีการถลุงเหล็กเมื่อ 140 ปี ที่ผ่านมา ซึ่งผลอายุการถลุงเหล็ก 140 ปี เป็นอายุน้อยที่สุดที่เคยมีการรายงานไว้ในพื้นที่ที่ราบสูงภาคตะวันออกเฉียงเหนือของประเทศไทย และอายุ 140 ปี ที่ได้จากงานวิจัยนี้ยังสอดคล้องกับ อายุสุดท้ายของกิจกรรมถลุงเหล็กโบราณ ที่มีรายงานไว้ในพื้นที่ประเทศกัมพูชา

ในกรณีการกำหนดอายุตัวอย่างเตาดินเผาที่ใช้ในการถลุงเหล็ก ผลการกำหนดอายุแสดงถึงลำดับการสร้างเตา 2 ช่วงเวลา ได้แก่ 360-370 ปี และ 1,000–1,110 ปี จึงสรุปพฤติกรรมการสร้างเตาถลุงเหล็กว่า มีการสร้างเตาถลุงเหล็กเก่าร่วมกับเตาถลุงเหล็กใหม่ในกองตะกรันเดียวกันเพื่อใช้ในการถลุงเหล็ก ซึ่งผลอายุสัมบูรณ์จากตะกรันเหล็กและชิ้นส่วนเตาถลุงเหล็กมีความสอดคล้องกัน และกลุ่มกองตะกรันในอุตสาหกรรมถลุงเหล็กโบราณบ้านสายโท 7 มีความเป็นไปได้ที่เกิดจากการผลิตเป็นระยะเวลายาวนาน มากกว่าการผลิตขนาดใหญ่ในระยะเวลาอันสั้น และแบบจำลองการเดินทางเดินโบราณจากช่องตาเหมือนในพื้นที่ภาคตะวันออกเฉียงเหนือ มีความสัมพันธ์กับแหล่งอุตสาหกรรมถลุงเหล็กโบราณในอำเภอบ้านกรวด จังหวัดบุรีรัมย์ ที่มีการผลิตตั้งแต่ยุคเหล็ก (5 ปีก่อนคริสต์ศักราช–คริสต์ศตวรรษที่ 6) ยุคเมืองพระนคร (คริสต์ศตวรรษที่ 9–13) และยุคหลังเมืองพระนคร (คริสต์ศตวรรษที่ 15–คริสต์ศักราช 1863)

สาขาวิชา ธรณีวิทยา		ลายมือชื่อนิสิต ....
ปีการศึกษา 2565		ลายมือชื่อ อ.ที่ปรึกษาหลัก ....
		ลายมือชื่อ อ.ที่ปรึกษาร่วม ....

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KEYWORD: Least cost path analysis, ancient path model, OSL dating, Slag, Angkorian Khmer period, Moated site

Sutthikan Khamsiri : REMOTE SENSING AND LUMINESCENCE DATING OF ARCHAEOLOGICAL SITES IN BURIRAM PROVINCE, NORTHEASTERN THAILAND. Advisor: Prof. SANTI PAILOPLEE Co-advisor: Pira Venunan, Ph.D.

This research aims to apply remote sensing and luminescence dating to study archaeological sites in Buriram Province, Northeastern Thailand. There are three main objectives including 1) to model the ancient path from the mountain passes along the Dângrêk mountain to ancient community on Angkor Highland or Northeast Thailand, 2) to directly date slag from the ancient iron smelting site at Ban Sai To 7, and 3) determine the terminal age of Ban Sai To 7 site using technical ceramics.

Firstly, the results of the GIS-based least cost path (LCP) route, using topographic factors, show that Ta Muen, Sai Ta Ku, and Krang are the most suitable for transportation between the Khorat plateau and present Cambodia. These results are consistent with archaeological evidence i.e., Dharmasalas. Most Khmer monuments are located in the vicinity of LCP routes. Moreover, the LCP route of Ta Muen is significant with the location of the ancient industrial zone in Ban Kruat District. However, most ancient smelting sites were in the Iron Age, although they were assumed to be active during the Khmer period when compared with the relative findings.

The major challenge of archaeometallurgy is the limitation of suitable sample for the scientific dating method. Therefore, the second is to investigate the absolute date of slag in the ancient iron-smelting site at Ban Sai Tho 7 by luminescence dating. The result slag shows the luminescence signal. Therefore, luminescence dating is an effective method to directly date slag. Moreover, the results show that the terminal activity of this site is 140 years ago. This result is in good agreement with the terminal period of ancient iron smelting in Cambodia.

Finally, the dates of technical ceramics i.e., furnace and tuyere fragments in the slag heap at Ban Sai Tho 7, show that there were at least two different periods of furnace construction including 360-370 years and 1000-1110 years ago. It is indicated that there are many phrases of smelting in one heap. When comparing the ages between slags and technical ceramics, the results of these two materials are in good agreement. Moreover, this finding shows that the large size of the ancient iron-smelting site at Ban Sai Tho 7 came from a long operational lifespan rather than a large operation in a short period. The route of ancient transportation is significant with the location of ancient industrial zone especially ancient iron-smelting sites that had been since the Iron Age, the Khmer Period and the post-Khmer period.

Field of Study:	Geology	Student's Signature ....
Academic Year:	2022	Advisor's Signature ....
		Co-advisor's Signature ....

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Sutthikan Khamsiri

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ABBREVIATIONS

AD	Annual dose or dose rate
AMS	Accelerator mass spectroscopy
ASTER	Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer
BST7	Ban Sai Tho 7
CAM	Central age model
DEM	Digital elevation model
ED	Equivalent dose
GIS	Geographic information system
LCP	Least cost path
MAM	Minimum age model
NRR	Northwest Royal Road
OSL	Optically stimulated luminescence
SAR	Single aliquot regeneration
TL	Thermoluminescence
XRD	X-ray diffraction

CHAPTER 1
INTRODUCTION

1.1 Introduction

The Khmer Empire, which existed from the 9^{th} to the 15^{th} centuries (Coe & Evans, 2018; Jacques et al., 2007) and was centered in the present Cambodia, is often considered to be one of the most powerful kingdoms in Mainland Southeast Asia (Figure 1.1a). At the peak territory expanse, the Khmer Empire controlled a vast area that included parts of modern-day Cambodia, Thailand, Lao PDR, and Vietnam. This reveals that the Khmer Empire was able to establish a strong centralized government and a powerful military to expand its territory and control a large population. The empire was also an important center of trade (Hendrickson, 2011).

As aforementioned, the Khmer culture has a significant impact on a part of Thailand, particularly in the northeastern region during the late 9^{th} and 11^{th} centuries (Hendrickson, 2010). The most famous Khmer monument in Thailand is the Phimai, which dates back to the 11^{th} century and is the largest Khmer monument in Thailand. The Khmer Empire continued to politically and socio-culturally influence in Northeast Thailand until the 13^{th} century, when the central power of the Angkor began to decline (Talbot, 2003). This is one cause of the abundant archaeological evidence in northeastern Thailand. Besides the Phimai, there are other kinds of remains that found throughout Northeast Thailand such as cutting-stone mine, small monuments, Dharmasalas and ancient industries (pottery and iron productions). Although many remnants in northeastern Thailand present the Angkorian culture. Some evidence presents the earlier period. For example, the moated site as shown in Figure 1.1b associated with the Iron Age occupation (C. F. W. Higham, 2011). The other evidence that has been discussed by the scholars to be Iron Age workshop is iron-smelting site. However, the associated finding in the site was in the Angkorian Period (Lertlum, 2008; Venunan, 2016; Yoopom, 2010). However, in terms of the chronology of the ancient smelting site, there remains a question as to whether the site was active during different periods or if it had a long duration. Previous studies have raised numerous inquiries that require further investigation.

One of the fascinating aspects is the existence of a trade route that connected ancient communities in northeastern Thailand with neighboring regions. As mentioned earlier, moated sites, which signify human presence, were established during the Iron Age. However, there is limited information about the prehistoric route in this area. The distribution of Phimai pottery, as investigated by Welch (1985), indicates a connection between northeastern Thailand and its neighboring areas during the Iron Age. Therefore, the objective of this study is to construct a model that represents the potential ancient route in northeastern Thailand based on this evidence.

Another interesting context is the limitation of chronological data and method for ancient iron-smelting site. Firstly, archaeologists believes that the iron-smelting site in Ban Kruat District, Buriram Province was initially established during the Angkorian Period based on the presence of Khmer ceramics within the iron-smelting site. Furthermore, the survey conducted and the chronology of the ancient iron smelting at the Ban Khao Din Tai site provide additional support for the existence of this workshop during the Angkorian Period (Lertlum, 2008; Yoopom, 2010). In contrast, the Ban Sai Tho 7 site (BST7) as indicated in Figure 1.1c has been identified as belonging to the Iron Age, (Lertlum, 2010; Venunan, 2016). However, the only two sites have been identified with their scientific ages, making it difficult to thoroughly discuss the organization of the sites in Ban Kruat. The scarcity of chronology is a result of the absence of suitable samples for available method.

Therefore, in this study, I focus on two main aspects including the socioeconomic path and the ancient metallurgical site in Ban Kruat. These two investigations will lead us to the concept of human mobility and the understanding of metallurgical sites at BST7. The formal is to model the ancient transportation between northeastern Thailand that is abundance with the moated sites (community features). Moreover, one of the major challenges is to identify the age of ancient metallurgy. Therefore, this study also aims to investigate the age of ancient metallurgy by using the available material in the ancient iron-smelting site.

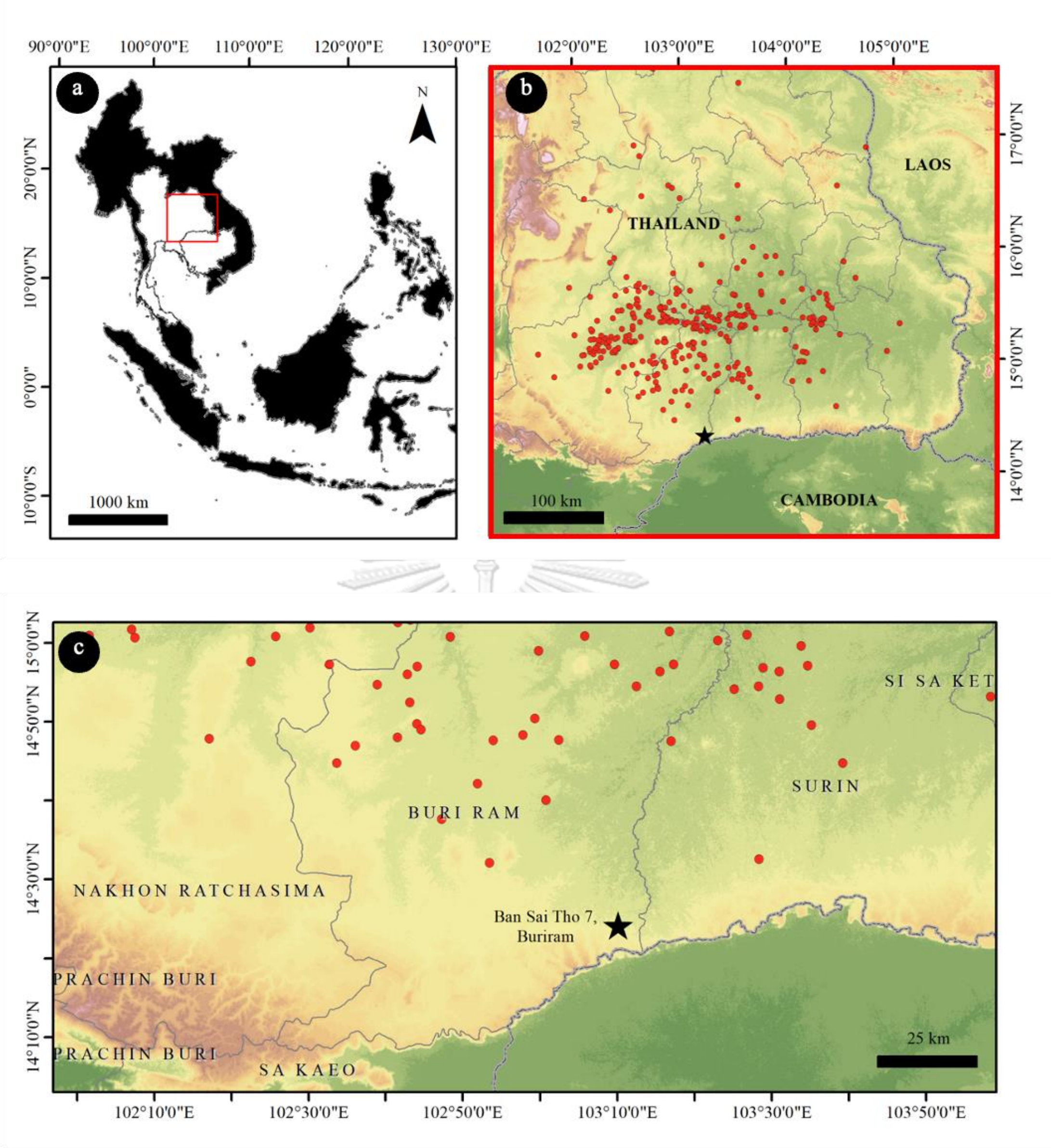

Figure 1.1 Map of the Thailand-Cambodia border showing the locations of moats (circle) in northeastern Thailand and BST7 District, Buriram province (star).

1.2 Objective

This study aims to investigate and extend three main knowledge which include the following:

1. To analyze a possible route passing the eight mountain passes along the Phnom Dângrêk Mountain in order to communicate between people living in ancient

communities in Angkor Highland (present Northeast Thailand) and Angkor Lowland (present Cambodia)

2. To directly date slags from ancient metallurgical site in Ban Kruat District, Buriram Province using luminescence dating technique

3. To determine the date(s) of the smelting activity at BST7, Ban Kruat District, Buriram Province by luminescence dating of surface technical ceramic samples

1.3 Scope of Research

The main aim of this thesis is to investigate an archaeological site in Northeast Thailand. This study is divided into two parts: a regional-scale investigation and a local-scale investigation. The former aims to explore the possible ancient route in northeastern Thailand, while the latter focuses on the chronology of the ancient metallurgical site at BST7, Ban Kruat District, Buriram Province. This research aims to gain insight into the holistic view of archaeology in the area and propose potential methods for metallurgical chronology based on geological knowledge.

1.4 Layout of the Thesis

This thesis is divided into five chapters including an introduction (chapter 1), three manuscripts (chapters 2-4) that have been published in the international journals, and the conclusion (chapter 5). Chapter 2, entitled "reconstructing the ancient route network in the Thailand-Cambodia borders: a case study of the Angkorian Royal Road", presents the reconstruction of an ancient path in Northeast Thailand using least cost path (LCP) analysis. Chapters 3 and 4 are entitled "luminescence dating of archaeometallurgical slag from Buriram province, northeastern Thailand" and "late iron-smelting production of Angkor Highland, metallurgical site at Buriram province, northeastern Thailand: a view from luminescence dating", respectively. These two chapters attempt to identify the terminal period of iron-smelting activity by using luminescence dating of slag and technical ceramics. Finally, Chapter 5 presents the conclusion and recommendations of this study.

1.5 Expected Outcome

The expected contributions of this study to both local and wider archaeology include:

1. the possible ancient route that was used to communicate between Northeast Thailand and Cambodia by considering geographical factors. LCP, which has been rarely applied to explore mobility across archaeological landscapes in Thailand, combining with the considerations of archaeological and geographical contexts as well as other analytical techniques in the study of mobility, will provide a new insight into the human-environment relations in antiquity.

2. absolute dates for iron production loci that will improve our knowledge about the development of ancient industries in Ban Kruat District, in particularly surveyed loci. The applicability of luminescence dating to directly date slag, the most commonly found remain at metal production sites, would constitute a valuable tool for research in Thai archaeometallurgy.

1.6 Theoretical Background and Relevant Research

1.6.1 Least cost path (LCP) analysis

The least cost path (LCP) analysis was first introduced in the Principle of Least Effort (Zipf, 1949), which is based on the concept that humans use all available resources to economize their behavior. This is equivalent to human mobility in a landscape where individuals try to choose an optimal path to save traveling costs (Surface-Evans & White, 2012). This method has helped researchers to understand the complex interactions between humans and the natural environment. There are two main approaches in the least cost path analysis including isotropic and anisotropic. In isotropic analysis, the cost of movement is assumed to be the same in all directions. On the other hand, anisotropic analysis considers that the cost movement depending on the direction of movement. For example, in an isotropic model, the cost of traveling in any direction along a river, whether upstream or downstream, would be considered equal. In contrast, an anisotropic model would consider that moving downstream in the direction of the current is less costly compared to traveling upstream against the current. (Etherington, 2016; Taliaferro et al., 2010).

As aforementioned, the LCP analysis is widely employed across a variety of fields, such as ecology, transportation planning, military strategy, urban planning, and archaeology. In ecology, the method is utilized to investigate animal movement across diverse types of habitats and to recognize potential corridors for species to move between habitats (e.g., Li et al., 2010). In transportation planning and urban planning, it is used to determine the optimal route for a road or rail line, while minimizing the environmental impact (e.g., Sari & Şen, 2017). Similarly, in archaeology, LCP is a commonly employed spatial analysis method used to reconstruct ancient travel routes and to identify potential pathways and barriers that affected human movement in the past (e.g., Güimil-Fariña & Parcero-Oubiña, 2015). The LCP analysis can be used in various archaeological contexts, such as reconstructing prehistoric trade and communication networks and understanding human migration (e.g., Field & Lahr, 2005).

LCP analysis involves the use of geographic information system (GIS) software to calculate the optimal path. By identifying the cost, researchers can identify potential barriers or opportunities for movement based on the concept that different types of terrain have varying levels of resistance, which in turn affect the ease of movement. For example, water body are generally more difficult to move through than dry land, and steep slopes are typically more challenging to traverse than flat terrain.

When performing LCP analysis, the cost surface is typically created by combining different types of data. According to Surface-Evans and White (2012), creating LCP models requires two main types of data: cultural and environmental. Cultural data, such as settlement location, are used to identify the location of start and destination presenting the existence of human activity. Environmental data, such as slope, vegetation cover, and viewsheds, are used as cost components to calculate the cost of each move between raster cells. A cost function is selected to combine the cost components, and a total cost surface is created to express the difficulty of moving between cells. By considering both cultural and environmental data, the resulting path is more likely to be both efficient and realistic as shown in Figure 1.2.

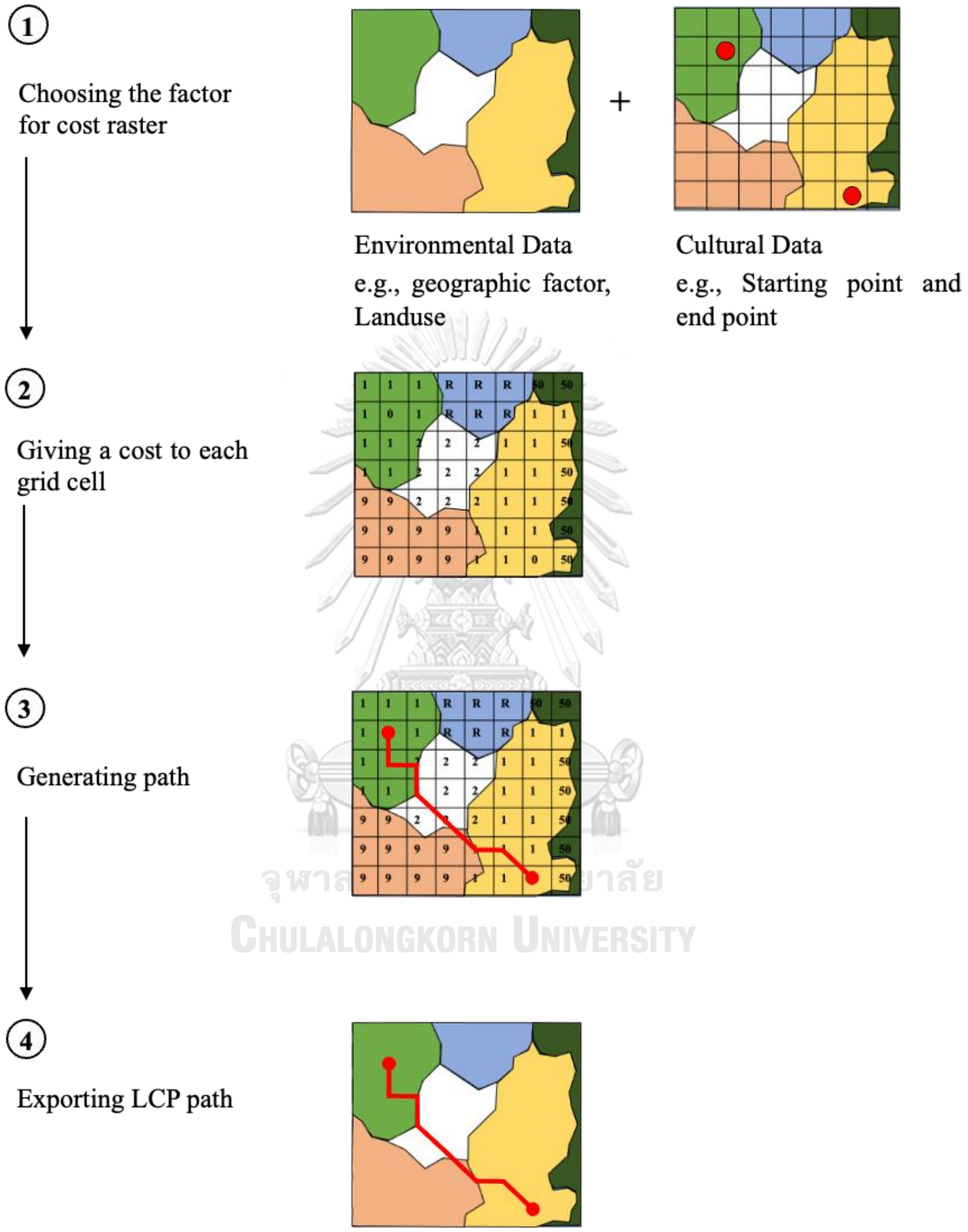

Figure 1.2 An example of the least-cost modelling algorithm

1.6.2 Optically stimulated luminescence (OSL) dating

Luminescence dating is a method of determining the age of archaeological, geological, and environmental materials through the measurement of the amount of light emitted when a sample is stimulated. The method is based on the fact that luminescence minerals, such as quartz and feldspar (Munyikwa, 2016), contain trace amounts of radioactivity that emit ionizing radiation, which can cause the accumulation of trapped electrons or "electron holes" in the crystal lattice of the mineral. When these minerals are exposed to sunlight or heat, the trapped electrons are released and the minerals emit light, known as luminescence. The intensity of the luminescence signal is proportional to the amount of radiation that the mineral has been received to over time, and can be used to estimate the age of the material (Figure 1.3).

One of the advantages of luminescence dating is that it can be used to date materials with wide range of age, depending on the type of material and the environmental conditions in which it was deposited. Another advantage of luminescence dating is that it can provide information about when a material was last exposed to sunlight or heated.

However, there are also limitations to luminescence dating. One limitation is the requirement for samples to be collected and measured in an environment without light, which can interfere the luminescence signal. This means that samples must be processed and analyzed in a darkroom or red-light condition. Moreover, the accurately amount of environmental dose is the most important, but the signal can be lost during the sample collection. Therefore, the work with experienced researchers for sample collection and processing is important to ensure the most accurate results. Despite these limitations, luminescence dating is still an important tool for archaeologists, geologists, and environmental scientists. It has been used to date a wide range of materials, from cave deposits and sedimentary layers to ancient pottery and stone tools.

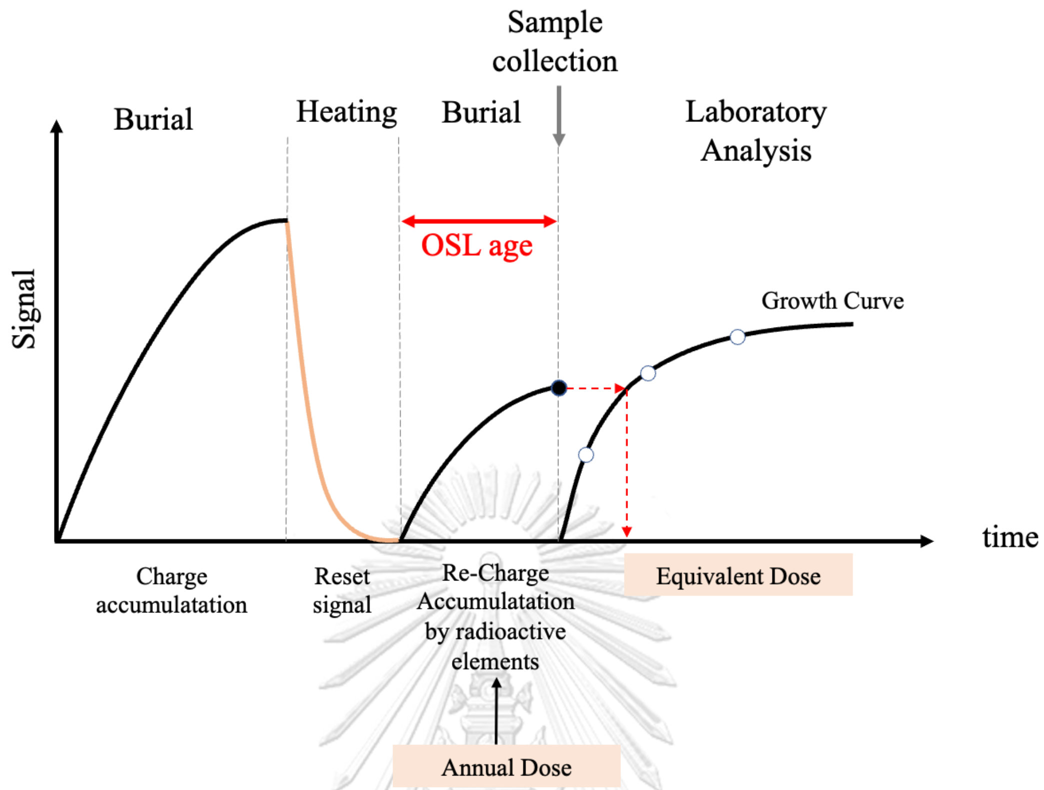

Figure 1.3 The concept of OSL dating

Luminescence dating can be divided into two categories: thermoluminescence (TL) dating and optically stimulated luminescence (OSL) dating. TL dating measures the luminescence signal emitted when the mineral is heated, whereas OSL dating measures when mineral is exposed to light.

After the several years that the luminescence material was introduced, the first successful application of TL dating in archaeology was in 1964 (Aitken et al., 1964). This method allowed archaeologists to directly date prehistoric artifacts and obtain age estimates without relying on other dating methods, such as stratigraphy or relative dating. TL dating was used to date a wide range of archaeological materials, including ceramics, pottery, and burnt material. In the 1990s, the development of OSL dating further expanded the application of luminescence dating that can use the light in stimulation (Munyikwa, 2016). OSL dating can be used to directly date unheated sediments, which was not possible with TL dating, and this creates new opportunities for further research.

Another advantage of OSL dating is that it is less sensitivity change that possibly affects from heating process. Due to the no effect of heating of OSL measurement, single aliquot regeneration (SAR) technique was introduced (Murray & Wintle, 2000). The key innovation of the SAR method is the "regeneration" step, which allowing the same aliquot to be used for multiple measurements. By comparing the luminescence intensities of each aliquot before and after the regeneration step, the SAR method is able to correct for any signal loss or signal bleaching that may have occurred during the first exposure to light or called “sensitivity change”. This correction allows the SAR method to provide more accurate and precise age estimates.

1.6.3 The study area

The study area includes two main scopes of investigation including i) regional scale and ii) site-specific. The regional scale aims to investigate the ancient mobility between Angkor Highland and Angkor Lowland that covered the distribution of the moated sites in Northeast Thailand. Whereas, in the site-specific investigation, I focused on the cluster of slag heaps at BST7 that reveals the unique character.

1. Angkor Highland in Northeast Thailand

There are various types of remnants in northeastern Thailand that provide valuable insights into the history and culture of the Mainland Southeast Asia. For example, Phimai, located in Nakhon Ratchasima province, is a well-preserved Khmer monument. Moated sites were likely used for various purposes especially as indicator of ancient settlement. Moreover, there are several ancient industries, especially, Khmer pottery and ironwork, as well as transportation networks in this region and extended to Angkor Empire.

Firstly, in this study, one of the objectives is to investigate the ancient transportation of human to the moated site in Northeast Thailand. The moated site or ancient communities generally presents a canal, also known as a "moat," that encircled a small hill, or a "mound" (Figure 1.4). The moats served as a physical barrier, providing defense against enemy. Furthermore, the presence of ritual artifacts and other culturally significant items suggests that the central mounds of these sites were likely used for religious or ceremonial purposes. Given the seasonal flooding in the region, the moats could have also been used for irrigation, necessitating a sophisticated water management system for agricultural productivity.

Additionally, some moated sites may have also functioned as administrative or economic centers, where resources and goods were traded and distributed. O'Reilly and Scott (2015) discovered at least 297 moated sites on the Khorat plateau by using a GoogleEarth survey. The majority of these moated sites can be traced back to the Iron Age (Boyd et al., 1999; McGrath & Boyd, 2001; McGrath et al., 2008; O'Reilly & Scott, 2015). The moated sites in Northeast Thailand played a crucial role in the social, cultural, and economic development of the region since the Iron Age.

Figure 1.4 The features of moated sites or ancient communities including a central small hill or mound that surrounded by canal or moat with various shapes. The locations shown in this figure are a) Wat Ban Du, b) Ban Muang Fang, c) Ban Muang Yang, d) Talung Kao, e) Wat Prasat Kaeo, f) Ban Fai.

The abundant moated sites lead to the question of transportation in this region. However, in this area, the evidence of the prehistorical road has never been recorded and reported until the introduction of Angkorian Khmer road. According to the studies by Hendrickson (2007a, 2010, 2011), the six main roads radiated outwards from the central city of Angkor to other major cities, which was the trade center and provided various economic resources. These roads were essential for the transportation of goods, people, and armies throughout the empire, and were also important ways for the spread of Khmer culture and religion.

The "Northwest Royal road" (NRR) was documented that directed from Angkor Wat to Phimai in Northeast Thailand. Phimai was constructed during the late 10th and early 11th centuries (Talbot & Janthed, 2001) and built in the Khmer architectural style, which was characterized by its use of sandstone, intricate carvings, and complex towers with signature pattern. Phimai is an illustration of Khmer's power, wealth, and religion, in Northeast Thailand. The NRR encounters with the difficult transportation in order to cross the present boundary of Thailand-Cambodia. Geography of the boundary is divided by Dângrêk mountain range as shown in Fig 1.5. This zone includes the contrast topography of high mountain range in the present Thailand and low flat area in Cambodia. Although this is the difficult route, the various resources and productions in Northeast Thailand are important especially salt (Hendrickson, 2011) and local productions of ceramics and irons, which were made using local materials and techniques.

Based on the number of moated sites and the only one along NRR, it is possibly that there are other missing economic routes for transportation and exchanges in Northeast Thailand. This is the first objective of this investigation that to find a possible route in the Northeast Thailand. This objective will be discuseed in the Chapter 2 in the publicaion entitled "**reconstructing the ancient route network in the Thailand-Cambodia borders: a case study of the Angkorian Royal road**".

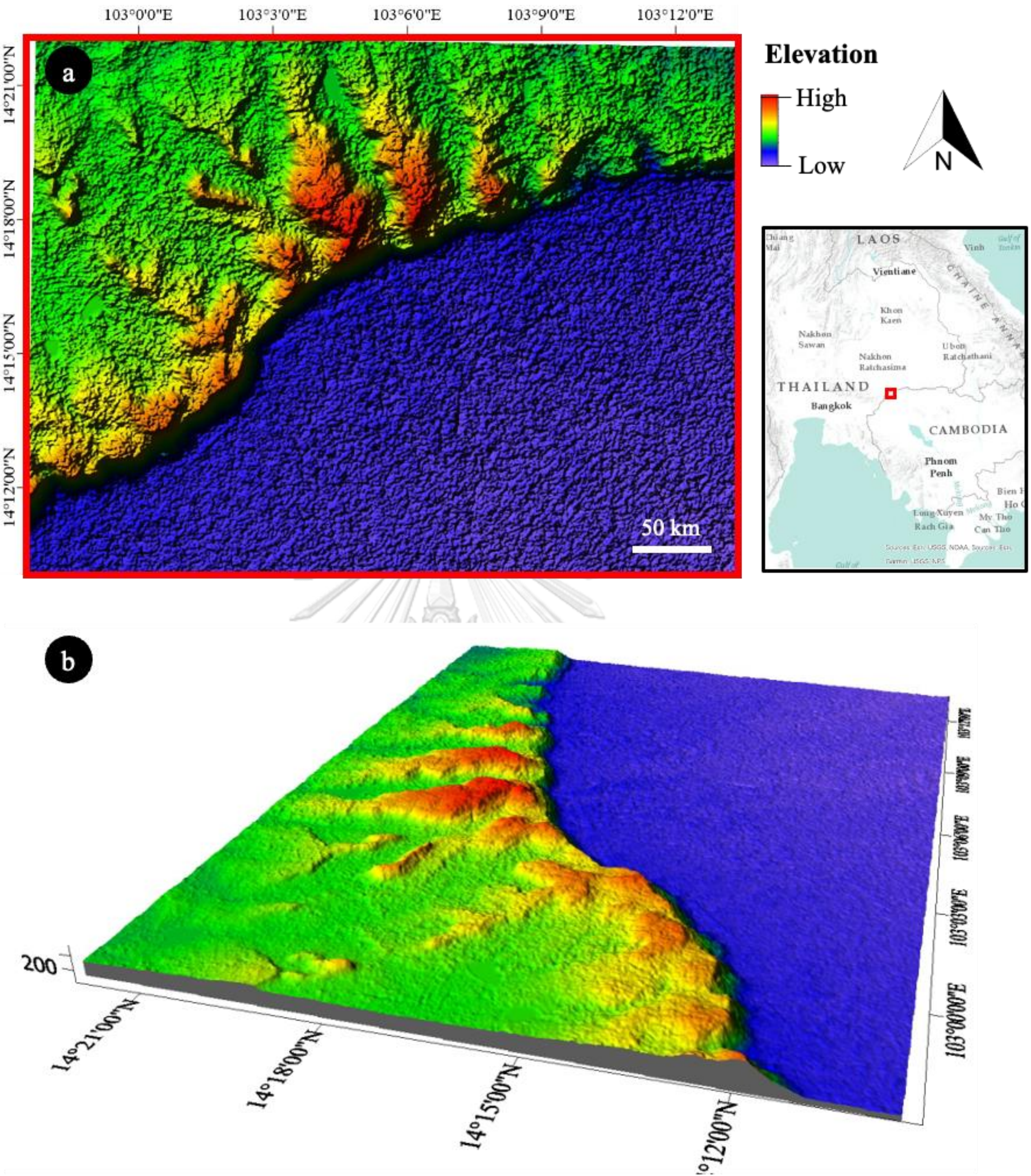

Figure 1.5 The 2D (a) and 3D (b) maps of geographical terrain of Northeast Thailand-Cambodia bounder including the obviously different elevation.

2. Iron-smelting production in Ban Kruat District, Buriram Province

Buriram Province, Northeast Thailand reveals many crucial sites and plays many roles in the archaeological field, particularly for historical investigation in the Khmer period (AD 1000-1300; Welch, 1998). Within only 584 square kilometers of the Ban Kruat District, Buriram Province, there are many ancient remains were discovered e.g., Phanom Rung, Muang Tum, Royal Road, Dharmasalas or resthouse temples, ceramic and iron industry site.

Due to the abundance of ancient remains, a vast amount of literature on the archaeological investigation in Ban Kruat District has been conducted since the century 20s (e.g., Brown, 1988; Chuenpee et al., 2014; Lim, 2014; Miksic, 2009; Prommanot, 1989; Thammapreechakorn, 2010; UCHIDA et al., 2010; Venunan, 2011, 2016; Welch, 1998; Wong, 2014; Yoopom, 2010). In 2005, the team of Living Angkor Road project (Lertlum, 2008) surveyed archaeological remains along the NRR and integrated knowledge. Besides discovering two missing Dharmasalas along the road, there were at least 67 slag heaps and 40 kilns in Ban Kruat District that are the evidence of ancient local industries.

Iron production was an important aspect of ancient societies. The ability to produce high-quality iron products, such as tools and weapons, gave the societies of the region a competitive advantage and allowed them to establish trade relationships with other communities. The extraction of iron from raw ore, also known as the "iron smelting process," is required before the process of iron production. Iron smelting was a highly specialized craft that required a vast amount of knowledge and skills that were most likely passed down through generations and shared among skilled craftsmen (Pryce et al., 2014).

More recent evidence in Ban Kruat site (Chuenpee et al., 2014; Venunan, 2011; Yoopom, 2010) highlights the significance of ancient iron-smelting in terms of chemical composition, culture and smelting technology. Many attempts to identify the date of iron-smelting production have been made, and there are two periods in Ban Kruat area including the early Iron Age and the Angkorian Khmer period (Lertlum, 2008; Venunan, 2016).

In order to clarify our knowledge of ancient iron-smelting of Ban Kruat archaeological site, this study focuses on chronology. In archaeology, radiocarbon dating is widely used to determine the age of archaeological sites, particularly ancient iron-smelting sites. However, a common limitation of radiocarbon dating for smelting sites is either due to the absence of charcoal or the lack of evidence to confirm the in situ. Therefore, this study aims to identify the age of the iron smelting site by using available remain especially slag which is the waste from the smelting process. In the iron-smelting process, when raw ores are melted in a furnace to extract the iron, the non-metallic impurities in the ore (such as silica, limestone, and other minerals) melt together and form a waste material called slag. The composition of slag depends on the quality of the smelting process and the raw material. Due to the variety of slag compositions, it is a challenge to find effective and reliable dating technique. This objective had been discussed in Chapters III in the title of "**luminescence dating of archaeometallurgical slag from Buriram province, northeastern Thailand**".

To compare with the age of slag and to obtain more variety of age of the iron smelting site, the OSL dating of technical ceramics i.e., furnace and tuyère, was measured. This topic aims to investigate the age of the iron-smelting site especially during the terminal phase of production, based on the superposition theorem which states that the younger layer is deposited over the previous layer. The underlying assumption of this objective is that technical ceramics from the upper layer represent the late period of production. This topic is discussed in Chapters IV in the title of "**late iron-smelting production of Angkor highland, metallurgical site at Buriram province, northeastern Thailand: a view from luminescence dating**".

CHAPTER 2
RECONSTRUCTING THE ANCIENT ROUTE NETWORK IN THE THAILAND-CAMBODIA BORDERS: A CASE STUDY OF THE ANGKORIAN ROYAL ROAD

Sutthikan Khamsiri[a], Pira Venunan[b], Chawalit Khaokheiw[b], Praon Silapanth[b], Santi Pailoplee[a,c*]

[a]Department of Geology, Faculty of Science, Chulalongkorn University, Pathum Wan District, Bangkok 10330, Thailand

[b]Faculty of Archaeology, Silpakorn University, Phra Nakorn District, Bangkok 10200, Thailand

[c]Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit (MESA RU), Department of Geology, Faculty of Science, Chulalongkorn University, Pathum Wan District, Bangkok 10330, Thailand

[*]Corresponding author

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ABSTRACT

A large number of ancient remnants from the Angkor kingdom of the 15^{th}–19^{th} centuries are widely observable across present day north-eastern Thailand and Cambodia. Archaeologically, these features represent the ancient communities and were possibly connected according to various socioeconomic reasons. In order to reconstruct the route of human mobility between the remains, the GIS-based Least-Cost-Path (LCP) analysis was employed along the Angkor-Phimai route. By recognizing the geographic parameters, the mobility of 292 moated sites were tracked to eight mountain passes that traverse the barrier of the Dângrêk Mountain Range. The LCP-derived routes revealed that the Ta Muen pass was the most suitable (shortest source-to-site distance) route for almost all moated sites. When compared to a previous interpretation of the Angkorian Royal Road route, our LCP route conforms reasonably well when overlaid with this possible Royal Road. The locations of ancient activities were also in the vicinity of the dense LCP route, and most monuments were located within a 1.5 km buffer line. This underlines that the LCP track obtained in this study is reasonable with a high reliability and is beneficial for guiding further studies to find out more about the ancient remains or archaeological evidence in this area.

Keywords: digital elevation model, least cost path analysis, Khmer Royal Road, Angkor period, northeast Thailand, mountain pass, moated site.

2.1 Introduction

Determining ancient route systems is essential to understanding the spatial interactions of ancient civilisations: how the structure weaved together the elements of human movement, political organisation, exchange and trade, and communication of ideas through the landscape and between communities. Numerous cases exemplify the importance of route systems in building, maintaining, and securing the existence, survivability, and social cohesion of civilisations, as illustrated by the extensive Roman road network (Forbes, 1964; French, 1998; Pažout, 2017), Archaemanid Royal Road (Colburn, 2013), Silk Route/Road (Taylor et al., 2018; Wood, 2002), and the Qhapaq Ñan network of the Incas (Hankey, 1997; Penney & Oschendorf, 2015; Wilkinson, 2019).

In Mainland Southeast Asia, during the 9th–15th centuries, the Angkorian Khmer state was centred at Angkor in Cambodia, and it politically and culturally influenced, and to some extent controlled, a vast part of Mainland Southeast Asia stretching from Cambodia, central and Northeast Thailand, and southern Laos.

They constructed its transportation system, i.e., routes/roads and infrastructures, including bridges and resthouses, in order to facilitate the flow of administrative commands, people, goods, and ideas between Angkor and the regional centres, including Phimai (Figures 2.1 and 2.2b), located in Northeast Thailand, which in turn consolidated and maintained its political influence. This route system has been extensively described archaeologically and in written sources (Hendrickson, 2007b, 2010).

Regional-based archaeological studies have illuminated the spatial interactions of people and can be traced back as early as the Neolithic period (2000–1100/1000 BC) as seen through the migration of people and the introduction of new ideas linked with South China. This became intensified in the Bronze Age (1100–500 BC), as evidenced in the transmission of metal technology from the North and regional exchange of copper and tin (Pryce, 2016; Pryce et al., 2018). In the Iron Age (500 BC–AD 500), Southeast Asia was well connected through extensive exchange networks that were later expanded to involve

China, India, and as far as the Mediterranean (Hung, 2017 and the references therein). Mountain passes, rivers, and seas are likely to have provided natural means for such networks across the region. Despite the region's inter-community networks in the prehistoric and early historical periods, little is known about the routes that people might have travelled on across the landscape. This paper examines this issue using the case drawn from the lower Northeast Thailand.

The human landscape of the ancient lower Northeast Thailand is well defined by the existence of morphologically distinct archaeological sites in the form of moated mounds. Almost 300 moat-and-rampart settlements, mostly circular, have so far been documented and dated to approximately the Iron Age or possibly earlier (Figures 2.1 and 2.2a) (O'Reilly & Scott, 2015; D. O'Reilly & G. Scott, 2015). These mounds were later occupied and modified with new features, in particular by the settlers during the 7th–13th centuries. The region offered various resources, including iron and salt, as well as served as an overland bridge moving people and goods across the region. The production of these commodities existed as iron slag deposits and salt-making mounds that had persisted since the Iron Age (Nitta, 1997; D. O'Reilly & G. Scott, 2015; Venunan, 2016; Welch, 1998). Angkorian Khmers later established ceramic production in at least at two locales: Ban Kruat District, Buriram Province (Chandavij, 1989; Prommanot, 1989) and Ban Ya Kha, Nakhon Ratchasima (Rooney & Smithies, 1997).

Geographically, Thailand and Cambodia are bordered by the Dângrêk mountain range; therefore, ancient pedestrians had to transit through this imposing barrier using a mountain pass (eroded valley) (Figures 2.1 and 2.2e). According to Pimthong (2016), there are at least eight accessible passes across the Dângrêk mountain range, which are delineated from east to west as: (i) Saeng, (ii) Ta Kiew, (iii) Sai Ta Ku, (iv) Ta Muen, (v) Krang, (vi) Chom, (vii) Pra Plai, and (viii) Ta Tao. The exploitation of these passes is clearly evidenced by the presence of prehistoric settlements as well as the settlements of later periods, including Khmer temples that were built near these passes and possibly acted as landmarks for the travellers. The location of moated settlements may have been one of the factors involved in deciding the location of the route. Owing to this, multiple routes could have existed for people to access different areas within the region.

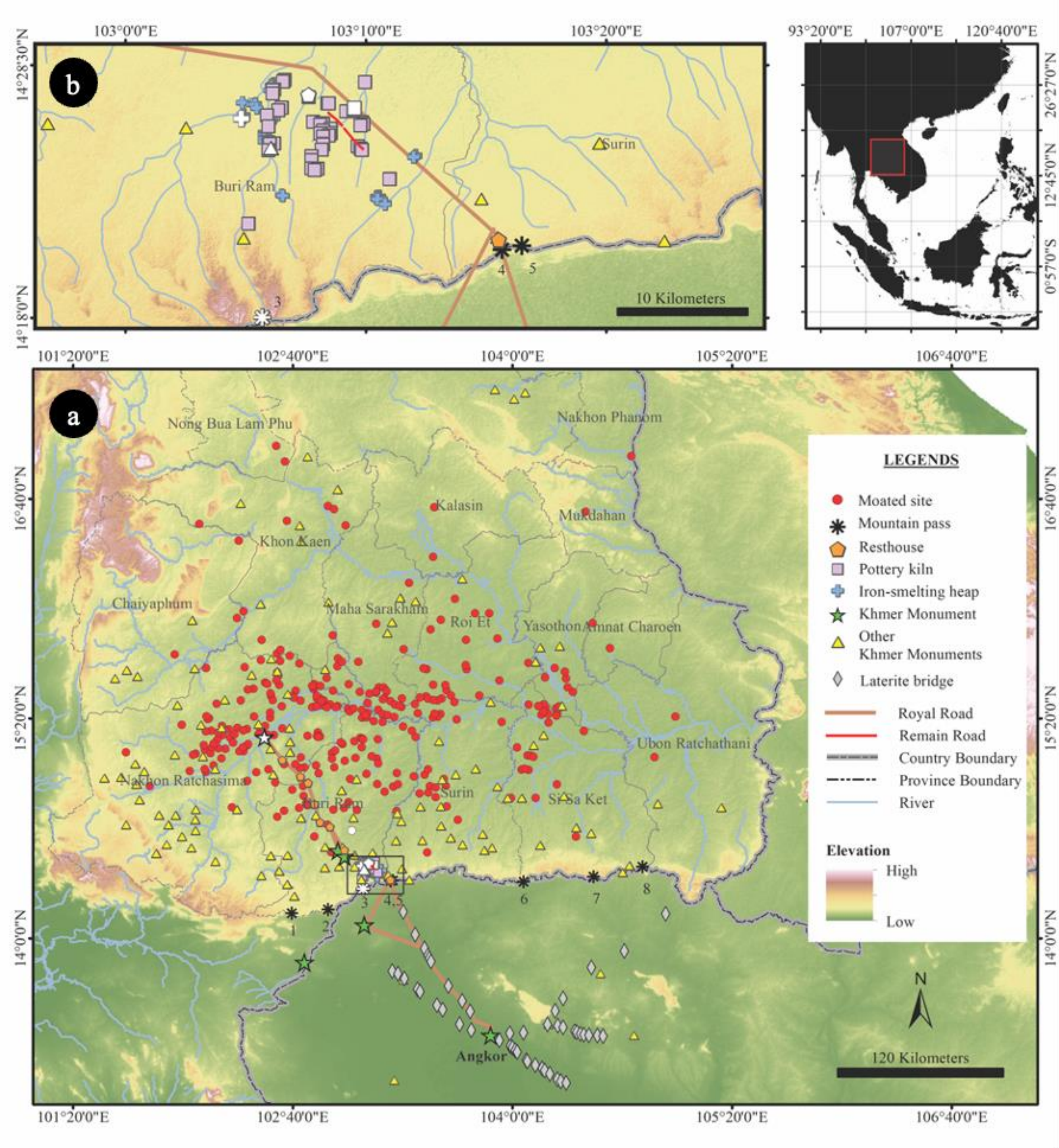

Figure 2.1 (a) Map of the Northeast Thailand- Cambodia border showing the locations of moated sites (circle), authorial monuments (star), Angkorian monuments (triangle), ancient iron-smelting (cross), and pottery sites (square) at Ban Kruat District, Buriram Province (b). Along the Dângrêk mountain range, there are eight mountain passes (asterisk) suitable for mobility: (i) Saeng, (ii) Ta Kiew, (iii) Sai Ta Ku, (iv) Ta Muen, (v) Krang,

(vi) Chom, (vii) Pra Plai, and (viii) Ta Tao. White symbols represent sites shown in Figure 2.2. Orange pentagons represent the site of resthouses delineating the possible path of the NRR (brown line). Thick red line along the NRR refers to the evidence of remaining routes, as shown in Figure 2.2g.

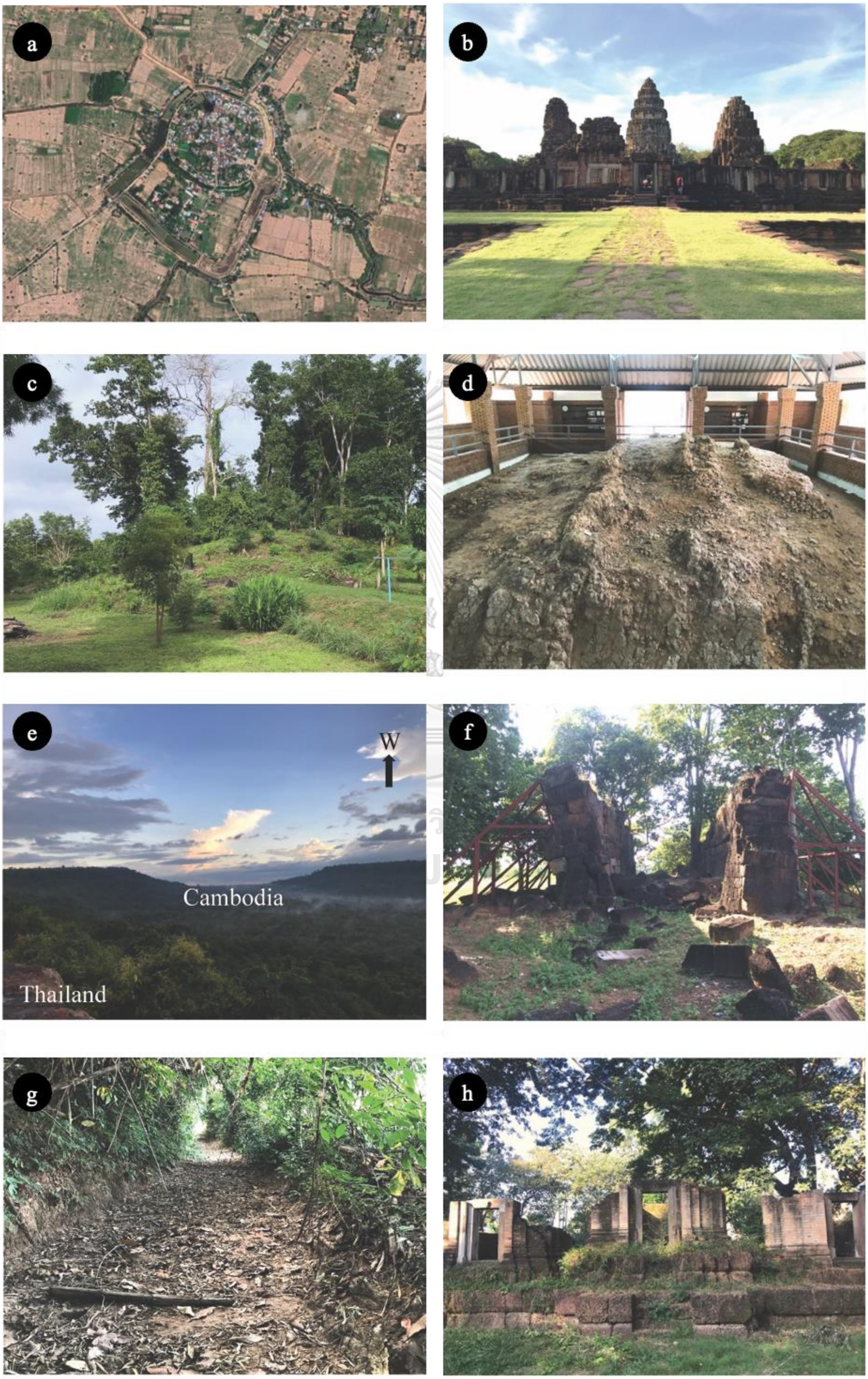
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Figure 2.2 Various examples of the Angkorian remains exposed in Northeast Thailand. The location and distribution of each remain type are described in Figure 2.1. (a) Moated site with a circular and/or rectangular canal surrounding a central mound (white circle in Figure 2.1), (b) Phimai monument, which is one of the most authorial monuments (white star in Figure 2.1), (c) the slag heap (white cross in Figure 2.1) and (d) Sawai Kiln (white square in Figure 2.1) at Ban Kruat District, Buriram Province, (e) Sai Ta Ku mountain passes (white flower in Figure 2.1), (f) Thmor resthouse (white pentagon in Figure 2.1), (g) remains of the NRR (red line in Figure 2.1) and (h) Ban Pra Sat (white triangle in Figure 2.1).

Most previous research characterizing possible routes have used the widely accepted GIS-based Least Cost Path (LCP) analysis. Conceptually, LCP is conducted to analyse any possible ancient route by considering convincing factors in terms of cost surface (Bell & Lock, 2000), such as the (i) topography from a DEM (Becker et al., 2017), including other supplementary factors thereof, such as the slope, (ii) hydrology e.g., streams and rivers (Field & Lahr, 2005), (iii) visibility and viewshed (e.g., (Llobera, 1996, 2001, 2003; Lock & Harris, 1996) and (iv) paleoenvironments (Groenhuijzen & Verhagen, 2015; Kealy et al., 2018).

In order to reconstruct the mobility of the ancient Angkor communities of the lower Northeast Thailand to Cambodia, this study mainly focused on analyzing the possible routes from existing moated sites to the eight proposed Dângrêk mountain range passes recognizing both the geographic (location) and topographic (slope) factors. The LCP analysis was the main approach applied in this study; the same as previous works have done successfully. The obtained results could illustrate more clearly the possible pedestrian habitats of ancient humans, and in particular for the lower Northeast Thailand region.

2.2 Input Archaeological Data

2.2.1 Moated sites

Archaeologically, a moated site refers to a unique terrain feature of a water storage (moat) with a surrounding small hill (mound). At least 297 moated settlements of various sizes have been recorded across the Northeast Thailand landscape (Figures 2.1 and 2.2a) (O'Reilly & Scott, 2015; D. O'Reilly & G. Scott, 2015). Moated sites are evidence of settlement during the Iron Age in response to climate change (O'Reilly & Scott, 2015; D. O'Reilly & G. Scott, 2015). Then, in the late 6th century after the expedition of pre-Angkorian elites, the region was influenced and assimilated into the cultural and political sphere of the Khmers. Therefore, moated sites became a foundation of new settlers in the early history of this area. Moreover, many pre- and Angkorian settlements established upon these existing sites transformed their shape and size as well as introducing new cultural components, i.e., reservoirs and Khmer-influenced buildings.

Due to the abundance of moated sites within the lower Northeast Thailand, it is likely that each moated site was connected to others in order to trade goods and livestock and to gather forest products, and then a number of pedestrians were settled automatically. Besides the domestic transportation in Northeast Thailand, the ancient communities in the upper Khmer (lower Northeast Thailand) also had contact with, and transported goods to, communities in the lower Khmer (Cambodia) due to the expansion of the Angkor Empire and the need for product exchange, such as salt, fish, iron tools, and earthenware (Hendrickson, 2011). These suggest that the lower Northeast Thailand was a significant economic area in the past.

2.2.2 The Dângrêk mountain range passes

Geographically, the elevations of the Angkorian Northeast Thailand and Cambodia are dramatically different. In addition, the Northeast Thailand-Cambodia boundary was bounded by a 130-km long stretch of the Dângrêk mountain range, which is uplifted by the Mesozoic rock formation dipping approximately northwards. According to the weathering process, eight prominent eroded valleys or mountain passes (Figures

2.1 and 2.2e) were formed along the Dângrêk mountain range, which were suitable for transportation between the Northeast Thailand and Cambodia. These eight passes (see also Figure 2.1) were the (i) Saeng, (ii) Ta Kiew, (iii) Sai Ta Ku, (iv) Ta Muen, (v) Krang, (vi) Chom, (vii) Pra Plai, and (viii) Ta Tao, respectively (Pimthong, 2016).

To move between the Higher and Lower Khmer (Northeast Thailand to Cambodia), people had to pass through one of these valleys. Therefore, besides the 297 locations of man-made moated sites, these eight natural-Dângrêk mountain range passes were also recognized as a significant factor in investigating the possible routes of the lower Northeast Thailand- Cambodia connection.

2.3 The LCP analysis

The archaeological GIS was introduced in the past three decades in order to investigate the movement of archaeological landscape (Aldenderfer & Maschner, 1996; Llobera, 1996; Wheatley, 1995). In recent years, the connectivity analysis has been developed in order to model landscape movement and provide more realistic connectivity between two nodes for more complicated areas (Groenhuijzen & Verhagen, 2015; Howey, 2007, 2011; Llobera, 2015; McRae et al., 2008; Pelletier et al., 2014).

This area was selected due to the high density of archaeological evidence; however, the landform shows a low variety of topography. Most area is an alluvial plain surrounded by a range of high mountains. Based on the assumption that where archaeological supplementary data and investigations of ancient migration are limited, a simplistic model is preferred to reconstruct the ancient path (Batten, 2007); therefore, in this study, the geographic factors that are the most stable and widely used variables in LCP analysis (rivers and slopes) were considered for the cost surface calculation.

Rivers can also serve as another general kind of ancient transportation and a common variable for LCP analysis; however, there is no evidence of river-transport in this area (Hendrickson, 2010). Moreover, in terms of geography, the main river in the lower Northeast Thailand is the Mun river, which flows eastwards and meets the Mekong river. Whereas smaller streams flow to the Mun river in a SW–NE direction, as shown in Figures

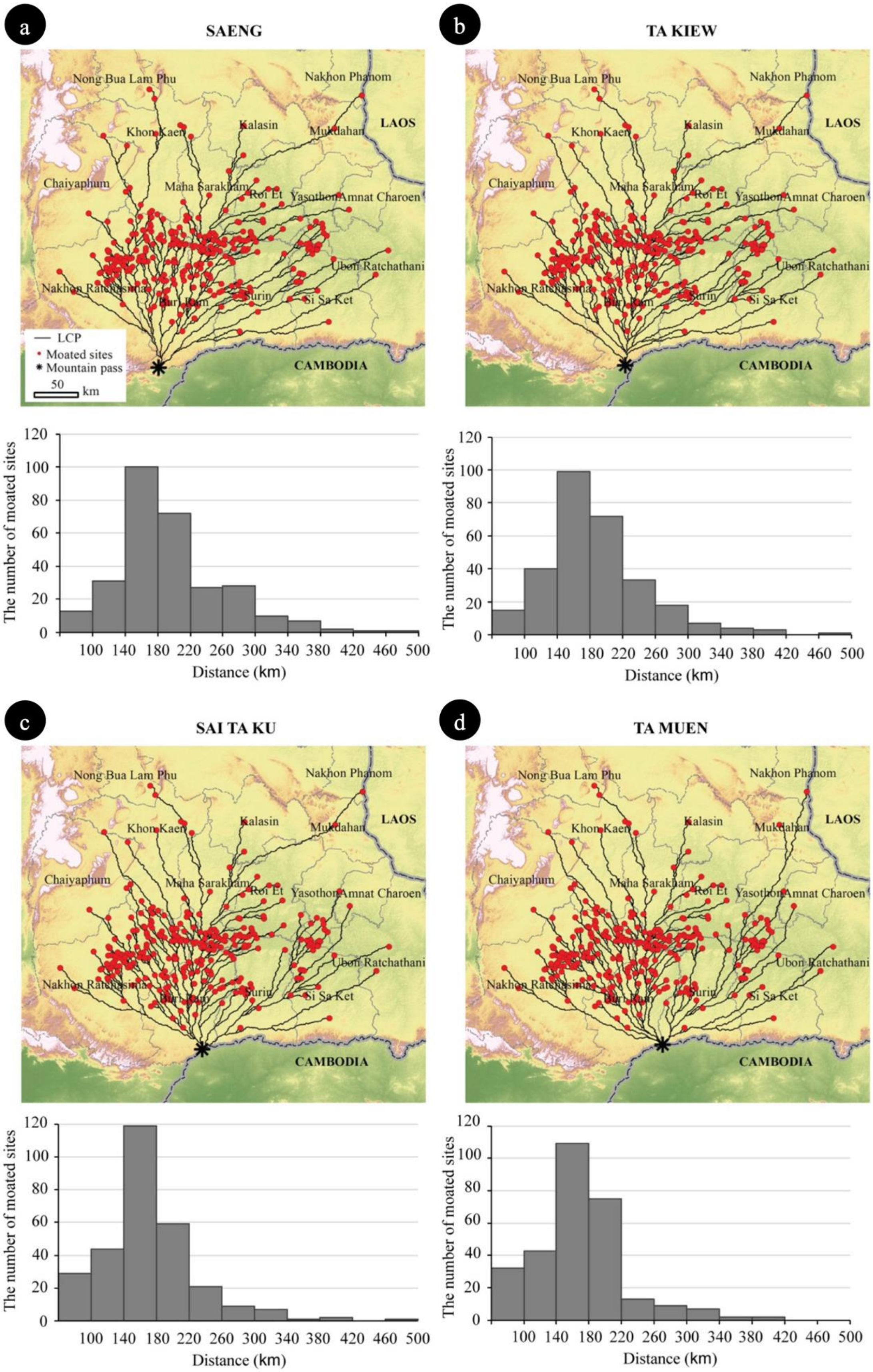
2.1 and 2.5. When correlated with the location of Angkor Wat, the directions of these rivers and displacement to the Angkor Wat are conjugated. Furthermore, many studies using LCP analysis have found that high-order rivers act as an impermeable zone (main channel) (Glennie & Singhvi, 2002). As shown in Figure 2.1, As shown in Figure 2.1, the Mun River is the main river cross the lower area of northeastern Thailand. Thus, if the Mun River was impermeable to passage, people would have to walk along the boundary of the Khorat plateau in order to avoid the Mun River. In this research, the path will be unsuitable for communication to the moated site. With these issues in mind, the river network seems to be inconvenient for transportation. Therefore, slope analysis was conducted to identify the cost surface in this study. Although the slope was only one environmental variant utilized to analyze transportation, significant knowledge of the spatial mobilities was also provided (Field & Lahr, 2005; Ludwig, 2020).

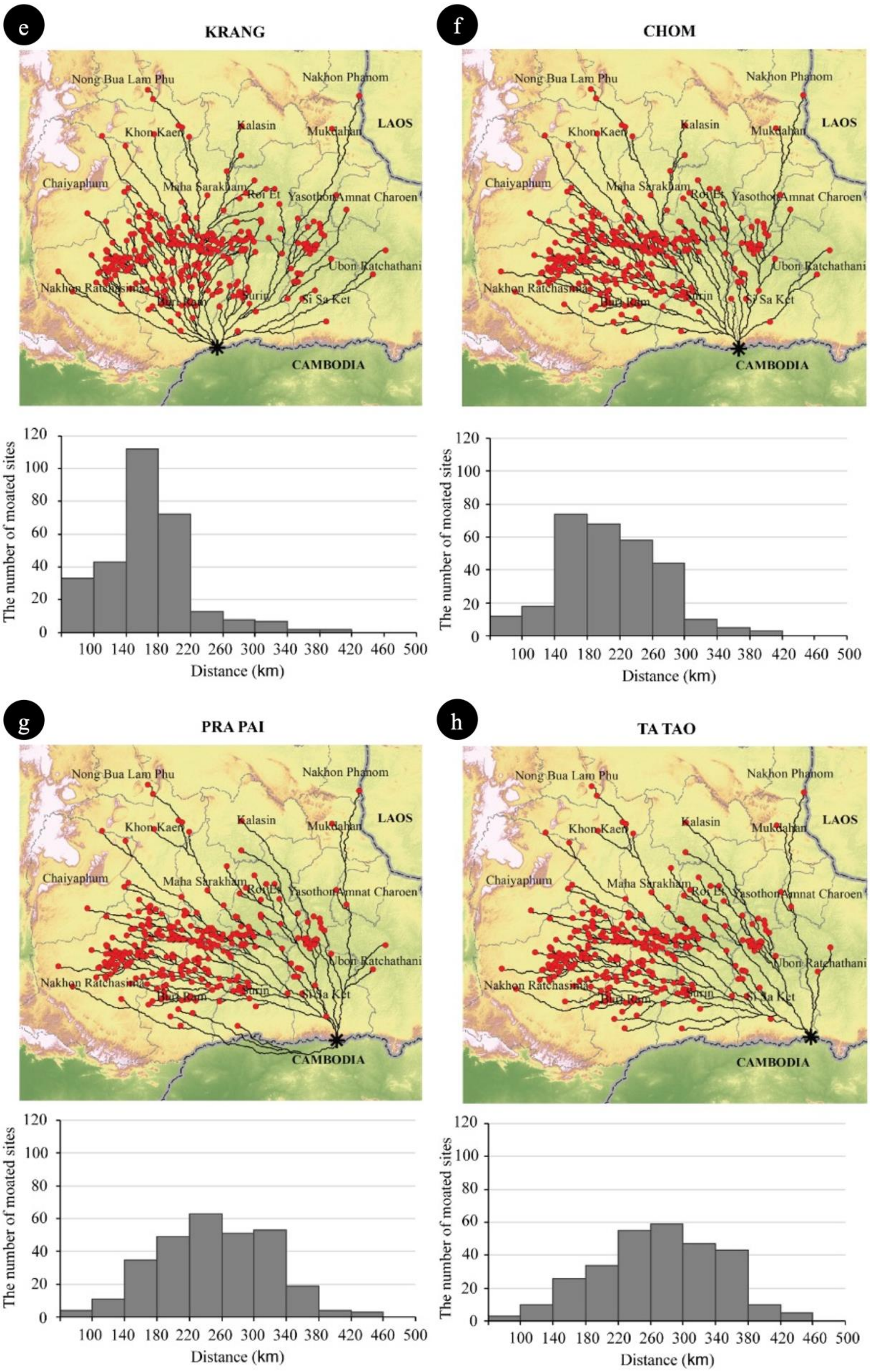
The LCP analysis was conducted within ArcMap 10.8. In order to provide the slope data raster for LCP analysis, the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global (G)DEM Version 3 at a spatial resolution of 1 arc second or a 30-m resolution (available from: www.earthdata.nasa.gov) was employed to cover the study area. Thereafter, the obtained DEM was used to generate the grid of slopes using “slope” in the raster tools. Due to the low variation in the slope in the central area (between 0–25 degrees), the grid value of each slope was used to identify itself, and isotropic analysis was used. These were clipped into the interesting area, and then the “cost distance” on the spatial analysis tool was utilized for evaluating the slope in terms of the cost raster, which is the main recognized factor in this study (Hayakawa et al., 2008). Finally, the optimal path was generated to the endpoints or moated sites by the “cost path” tool and was then calculated as a polyline (Chandio et al., 2012; Lewis, 2017; Orengo & Livarda, 2016).

After receiving all the optimal paths for each of the eight Dângrêk mountain range passes, a histogram was prepared to present the distance from each mountain pass to the moated sites using the length of each path between 100 km and 500 km with a bandwidth of 40 km. This bandwidth presents a clear distribution of the distance between the moated sites and the mountain pass, as shown in Figure 2.3.

2.4 Result

From the LCP analysis, this study generated a path from 292 moated sites located in the Khorat basin to each of the eight Dângrêk mountain range passes. The LCP-generated paths are shown in Figure 2.3, where all the paths are the same or more likely to be the lineament of displacement between an individual moated site to the mountain passes. Some segments during this path show minor variations according to the controlled factors of geography: elevation and slope. Based on Figure 2.3 in detail, the various routes conformed to the valley or the depression zone of the topography. The longest path was 488 km from the Saeng mountain pass, while the shortest was 35 km from the Pra Plai mountain pass. For a preliminarily analysis, the suitable mountain passes, and the probability of pass-to-moated site distances of each mountain pass were analyzed in terms of a histogram (Figure 2.3).


a
SAENG
Nong Bua Lam Phu
Nakhon Phanom
Khon Kaen
Kalasin
Mukdahan
LAOS
Chaiyaphum
Maha Sarakham
Roi Et
Yasothon
Amnat Charoen
Ubon Ratchathani
Nakhon Ratchasima
Buri Ram
Surin
Si Sa Ket
CAMBODIA
LCP
Moated sites
Mountain pass
50 km
b
TA KIEW
c
SAI TA KU
d
TA MUEN
The number of moated sites
Distance (km)
0
20
40
60
80
100
120
100 140 180 220 260 300 340 380 420 460 500


e
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PRA PAI
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TA TAO
Nong Bua Lam Phu
Nakhon Phanom
Khon Kaen
Kalasin
Mukdahan
LAOS
Chaiyaphum
Maha Sarakham
Roi Et
Yasothon
Amnat Charoen
Ubon Ratchathani
Nakhon Ratchasima
Buri Ram
Surin
Si Sa Ket
CAMBODIA
The number of moated sites
0
20
40
60
80
100
120
100 140 180 220 260 300 340 380 420 460 500
Distance (km)

Figure 2.3 (a-h) Maps of the present Northeast Thailand-Cambodia border (past Angkorian territory) showing the spatial distribution of moated sites (red dot) and the reconstructed LCP routes from the moated sites to each candidate mountain pass. Histograms depicting the number distribution of each recognized moat-to-pass distance (km).

Based on the calculated histogram, there are three obvious differences in the distance distribution. For instance, the furthest range distance (420–460 km) are the routes via the Pra Plai and Ta Tao passes that are located in the edge of the eastern area, and the number of moated sites in each distance range shows a likely normal distribution pattern integrated with the peak point at 220–260 and 260–300 km, respectively.

Moreover, the number of moated sites going to the Chom pass shows that almost all of them are more than 140 km apart, whereas there are only around 30 moated sites that can be easily connected with a short path (< 140 km). Finally, the other passes show the furthest familiar normal distribution pattern combined with the short distance range (140–220 km) of an enormous number of moated sites.

Besides the histogram, the average distance of each mountain pass was calculated, revealing three candidate passes: (i) Klang, (ii)Ta Muen, and (iii) Sai Taku passes with an average pass-to-moated site distance of 169, 170, and 173 kilometers, respectively.

2.5 Discussion

2.5.1 Angkorian Royal Road and the LCP routes

The Angkorian road system has been repeatedly linked to the work of King Jayavarman VII, who ruled from AD 1182–1218, through a Sanskrit stela of the Preah Khan temple in Angkor. These described routes run from Angkor to various settlements, including five main destinations: (i) Phimai, its political center in Northeast Thailand, (ii) Sdok Kok Thom in Thailand, (iii) Vat Phu in southern Lao PDR, and (iv) Preah Khan of Kompong Svay and (v) Sambor Prei Kuk, located on the east and southeast of Angkor, respectively, (Hendrickson, 2007b, 2010, 2011; Lustig & Hendrickson, 2012; Maneenetr, 2008). Scholars have viewed this road system as part of the political mechanisms to secure the state's integrity through regular communications between distant communities, the political center, and individuals. Recent studies, however, have postulated that this fabled road system was likely founded upon an earlier establishment of routes that existed since at least the late prehistoric period.

The Angkorian road system has been a subject of interest among scholars for over half a century with a recent exhaustive work being done by Dr Mitch Hendrickson examining the plurality of development and function of the Angkorian transport system using the multidisciplinary approaches of textual analysis, etymology, and archaeology (Hendrickson, 2007b, 2010).

In this paper, the NRR from Angkor to Phimai, which went through the Ta Muen Pass, located on Dângrêk mountain range at the border between present-day Thailand and Cambodia, is our focus. As stated, the stela of the Preah Khan temple provide information about this route having 17 resthouses (dharmasalas) built to facilitate the movement and transportation, which can be traced archaeologically. These resthouses (Figures 2.1 and 2.2f) ascertain the existence of the NRR track in the lower Northeast Thailand (yellow line in Figures 2.1 and 2.2g). In addition, surveys further identified the remnants of bridges (Hendrickson, 2007b, 2010, 2011; Lertlum, 2008; Lustig & Hendrickson, 2012). The movement along the Thai section would pass numerous politically and culturally significant places: large settlements at Phnom Rung and Muang Tham, production locales for ceramics and iron, and the regional political center at Phimai, as well as other Khmer settlements (Living Angkor Road project; (Lertlum, 2008; Tanlasanawong, 2007).

Compared with the three candidate LCP routes obtained in this study, the route system of all the recognized moated sites to the Ta Muen mountain pass were all related fairly well with the possible NRR track. Among 292 generated LPC routes using the Ta Muen, one branch of the route was delineated closely along the NRR (Figure 2.4). As the cost surface was created using only the slope variable, these further support the concept that the simple model is suitable for an area lacking information of ancient movement.

Moreover, based on the density of LCP routes that was constructed using the “density” tool in the ArcMap toolbox (Figure 2.4), three zones of dense routes were revealed in this study: the (i) northeastern, (ii) northern, and (iii) northwestern zones. Although the highest density was in the north zone, the northwestern zone overlaid completely with the NRR track. Therefore, the LCP paths generated in this study seem to be a reasonable result.

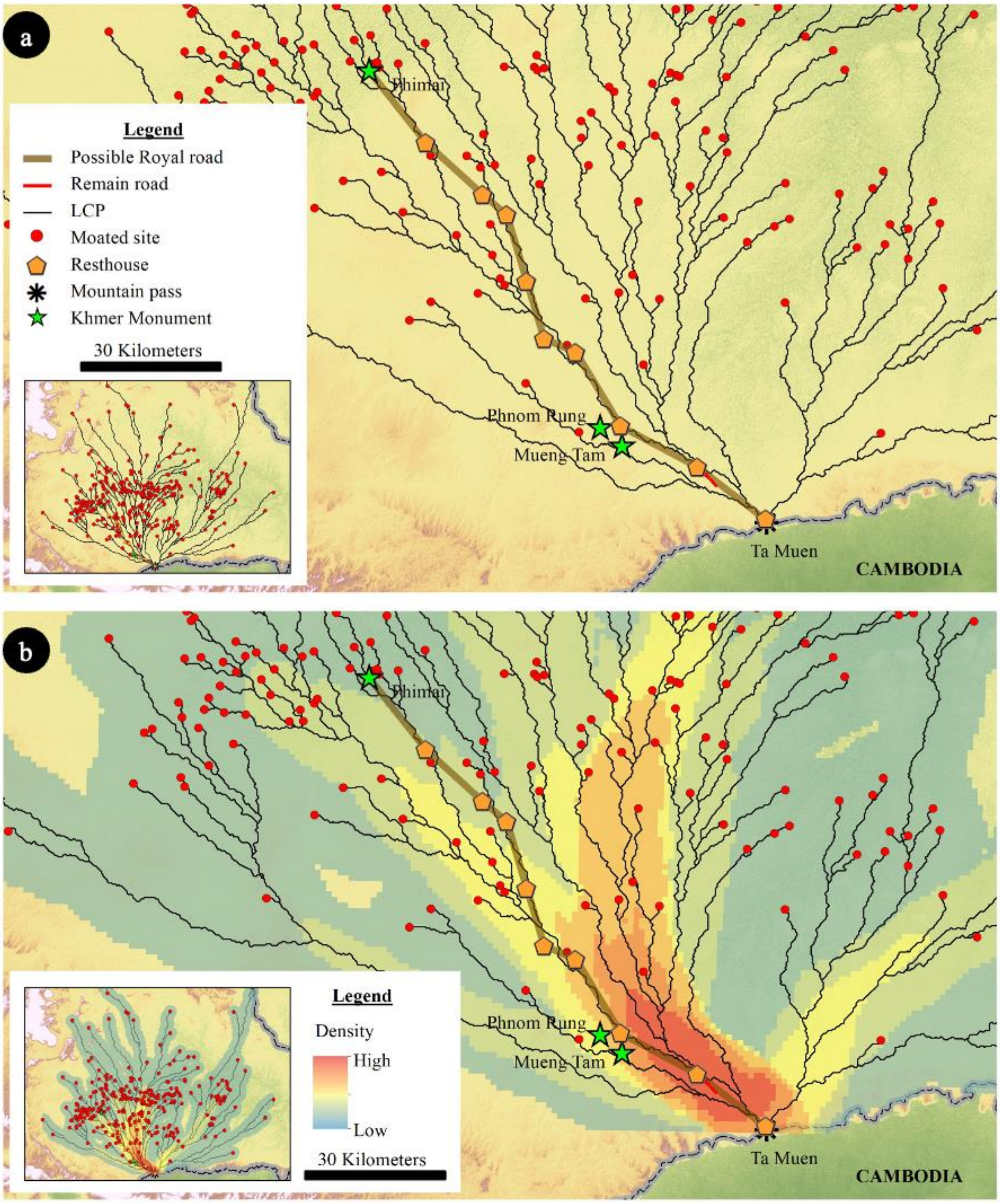

Figure 2.4 (a) Maps of the present Northeast Thailand- Cambodia border showing the calculated LCP route overlaid by the possible NRR (brown line). Orange pentagons represent the location of each resthouse. (b) The density map of LCP route analyzed in this study.

2.5.2 Iron-smelting industry and pottery industry

Regarding the archaeological exploration in 1991 (Nitta, 1991), a large number of slag heaps and ancient kilns were discovered only in the Ban Kruat District, Buriram Province. The heaps imply a former iron-smelting activity while the kilns suggest pottery production. Based on the various sizes and the number (67 sites) of heaps (Figure 2.2c), it indicated this site was a prominent ancient industry in Mainland Southeast Asia (Venunan, 2016). Moreover, the large number of kilns (Figure 2.2d) in the Ban Kruat District suggest that it was a significant site for the production of brown-glazed wares or Khmer ceramics (Thammapreechakorn, 2010). Both the heaps and kilns were defined in the same period that covers the Angkorian period (C. Higham, 2011; Welch & McNeill, 1991), and were assumed to be important sites of economic activity and trading goods in the lower Northeast Thailand and Angkor region (Welch, 1998).

Besides the regional comparison between the NRR and the obtained LCP result, this study attempted to correlate the tract of generated routes with the communities of iron-smelting and pottery production. As shown in Figure 2.5, the spatial distribution of both heap and kiln sites seems to be related systematically or settled fairly closely along the minor stream in the area. This suggests that the locations of these ancient industries provided raw materials for other productions. Moreover, there was an abundance of laterite and forest for iron-smelting (Lertlum & Shibayama, 2009).

Compared with the obtained LCP, it is quite clear that both the iron-smelting and pottery production industries were delineated in the tract of the LCP routes, including the dense zone of the of Ta Muen route density (Figure 2.5). Therefore, the LCP paths generated in this study were constrained locally to be reliable. It can be concluded that the routes were not only for travelling to the end point of Phimai, as indicated by the resthouse, but also the Angkorian people who travelled would communicate or pass through the ancient industry area in Ban Kruat District. Moreover, this study highlighted that this area was suitable as a supply of raw materials (laterite, wood, and clay) and the transportation of products.

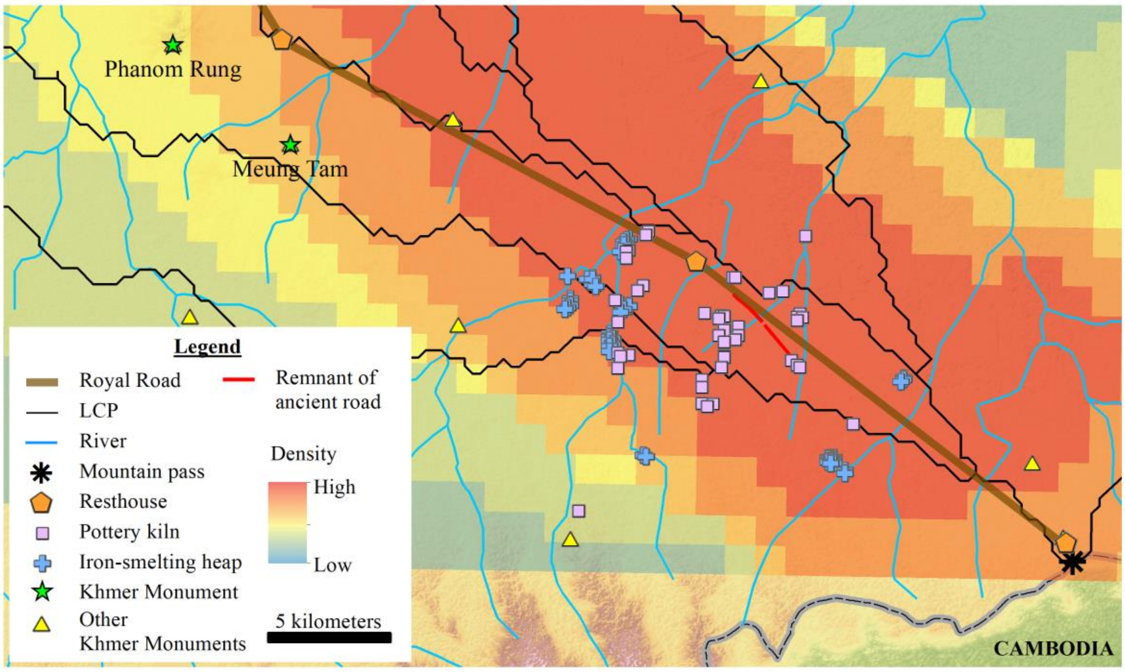

Figure 2.5 Map covering Ban Kruat District, Buriram Province showing the density level of the calculated LCP routes. Brown line shows the possible track of the NRR controlled by the resthouse, and red line refers to the remnant of ancient route. Blue cross and purple square are the spatial distribution of ancient kilns and iron-smelting slag heaps, respectively. The river was extracted from Google imagery.

2.5.3 Monuments and LCP routes

The most significant evidence of Khmer culture in Thailand are stone sanctuaries, which are artistic and religious symbols. Moreover, these were also used for the presentation of power and territory of Khmer. There are three main kinds of sanctuary that can be divided by their roles (Maneenetr, 2008). First, the temple or religious place is commonly presented as a large monument with a beautiful and neatly carved decoration, some of which were called a Prasat or shrine. Second, Arogayasala or hospitals in that period were mainly constructed of laterite and had a central tower and bannalai (or library) with a baray (pond). The third is Dharmasala, which means the house with fire and acted as a hotel for travelers. Its character was similar to Arogayasala in its rough and simple construction. Therefore, the term “monument” stands for all kinds of Khmer buildings.

In the lower Northeast Thailand, Phimai is the largest site and played an important political role in this region. It was built in the 11th century before the construction of Angkor Wat. Besides the large political and ritual monuments. With the best known being Phimai, Phanom Rung, and Muang Tam, and the resthouse temples, there are at least 100 small Khmer buildings (Figures 2.1 and 2.2h) that represented various roles in this region (Wongadsapaiboon, 2012). Moreover, there are larger monuments, such as Phimai that is an administrative center located in the zone of dense population, whereas most small monuments were located along the boundary of the Khorat basin and played a role in the exploitation of natural resources (i.e., salt and iron) (Welch, 1998).

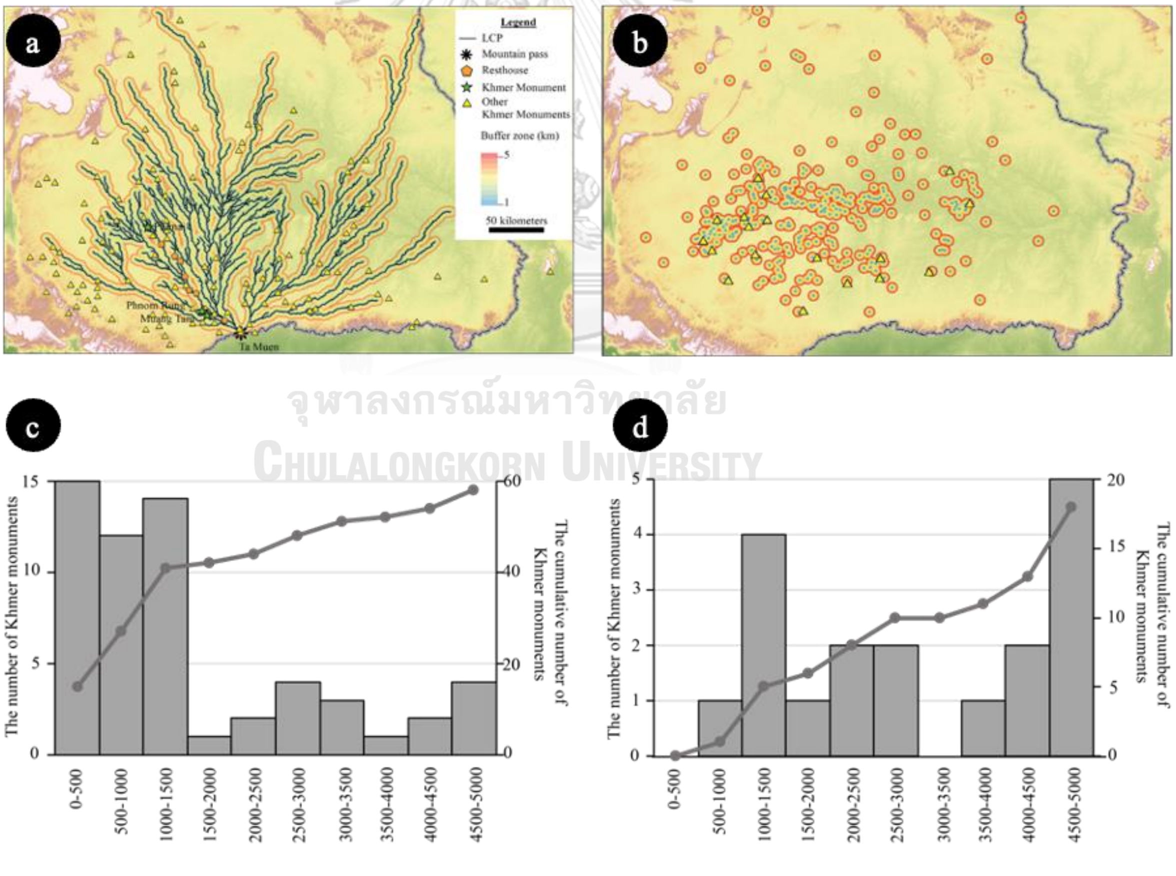

Figure 2.6 Maps of the present Northeast Thailand-Cambodia border showing (a) the track of LCP route (black line), and (b) the moated sites and the 5-km buffered zone. Yellow triangle illustrates the locations of the minor Angkorian monuments. Histograms present

the number and the cumulative number of monuments located in each considered distance away from (c) the LCP routes and (d) the moated sites.

In total, 58 out of 114 monuments were located within 5 km from the LCP line (Figure 2.6) and were recognized and compared with the LCP routes to the Ta Muen pass. In order to clarify this statistically, the buffer zone of the obtained LCP route at a 5 km distance with a spacing of 0.5 km was created using the “buffer” tool in “raster analysis” and then the accumulative number of monuments in each buffer zone was plotted. Thereafter, the number of monuments located within each buffer zone was counted and contributed to the histogram (Figure 2.6). The results revealed that almost all of the monuments (41 out of 58) were located less than 1.5 km away from the defined LCP route (Figure 2.6). Moreover, the buffering was similarly conducted to the moated sites. In the 5 km distance from each moated site, there were only 18 monuments. The number of monuments located in the buffer zone of the LCP path was twice the number in the moated site (Figure 2.6).

The significant number of monuments along the LCP route indicated that the monuments were placed in proximity to the road rather than the moated sites. According to Welch (1998), the distribution of dense communities (moated sites) and Khmer monuments seems to have neither a significant relationship nor a pattern. These are possibly caused by the different periods of construction and roles. Moreover, in comparison to the proposed LCP route of this study, although some monuments are distributed randomly; the location of most monuments is meaningful (non-random) with empirical settlements along or in the vicinity of the ancient route. The obtained results could be useful and beneficial for discovering and surveying further for missing ancient remains along the routes.

2.6 Conclusion

The main aim of this study was to provide new knowledge on the ancient route by examining the situ remains that could have played a significant role in the NRR construction using LCP analysis. In this study, the reconstruction of the NRR was estimated from the location of ancient-moated sites and mountain passes accompanied by the geographical slope conditions. The LCP routes of three passes showed significant travel distances. Moreover, according to the inscription of Preah Khan and the prominent resthouses, the Ta Muen pass, which is one of the significant LCP routes, was the conjunction of the NRR between lower Northeast Thailand and Cambodia. More significantly, the reconstructed LCP routes were barely distinguishable from the possible NRR route delineated by resthouses. Despite the fact that there are some limitations due to insufficient data of ancient movement in this region, this is the first of past landscape connectivity relating to the Angkor territory and could highlight the significance of the LCP route and other important ancient remains at both local and regional scales. The most remarkable correlation is that both ancient industries that are spotted in small areas also conform to the LCP route, indicating that LCP route is reasonable on a local scale. Besides the abundance of raw materials, Ban Kruat District is the best location for these industries because it is located along the route. On a regional scale, the most striking observation to emerge from the location of monuments was that most were within 1.5 km from the proposed ancient NRR route.

In conclusion, these present findings imply that the LCP is an effective method and has important implications for reconstructing ancient routes and is useful for finding missing remains. It is recommended that further research is needed to investigate the ancient landscape connectivity by other models or evidence that may have led to more insight into path role, movement behavior and economic structure in this region. We believe that more investigations will point out that LCP is suitable and effective in this region.

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CHAPTER 3
LUMINESCENCE DATING OF ARCHAEOMETALLURGICAL SLAG FROM BURIRAM PROVINCE, NORTHEASTERN THAILAND

Sutthikan Khamsiri[a], Pira Venunan[b], Chawalit Khaokheiw[b], Praon Silapanth[b], Sirittha Banron[a], Santi Pailoplee[a,c*]

[a]Department of Geology, Faculty of Science, Chulalongkorn University, Pathum Wan District, Bangkok 10330, Thailand

[b]Faculty of Archaeology, Silpakorn University, Phra Nakorn District, Bangkok 10200, Thailand

[c]Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit (MESA RU), Department of Geology, Faculty of Science, Chulalongkorn University, Pathum Wan District, Bangkok 10330, Thailand

[*]Corresponding author

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ABSTRACT

In this study, the possibility of directly dating slags ancient metallurgical site is assessed. The enormous slag heaps distributed in the Ban Kruat District, Buriram Province, Thailand, have been interpreted as one of the most prominent archaeometallurgical sites in Mainland Southeast Asia. Therefore, five slag samples were collected from the topmost level of two heaps. The X-ray diffraction measurement of each slag revealed the existence of quartz minerals, which is conceptually useful to luminescence dating. Based on OSL measurements, two of the five samples showed a weak luminescence signal, which was not suitable for OSL dating, and may reflect the lack of quartz minerals. However, the other three quartz-rich slag samples clearly expressed an OSL signal. Therefore, 40 or 96 aliquots of a single aliquot regenerative measurement were employed to date them.

With the combination of the activated dose rate obtained from environmental radioactive elements (U, Th, and K), two timespans of iron-smelting activity were defined, as approximately 140 years ago and 470–710 years ago. Compared with the radiocarbon dates of the adjacent slag heap in Buriram (560 ± 280 years BP), the 140-y-old slag heap dated in this study is younger and represents the latest (most recently) datable iron-smelting industry in the Angkor highland (Thailand). Meanwhile, the radiocarbon dates (140 ± 20 years BP) of the slag heap in the Angkor lowland (Cambodia) conformed to the date obtained in this study. Therefore, it is concluded that OSL dating is effective for direct dating of the slag-bearing quartz.

KEY WORDS: luminescence dating, archaeometallurgical slag, Ban Kruat Archaeological site, iron-smelting activity

3.1 Introduction

In Mainland Southeast Asia contexts, iron is known as one of the versatile and dynamic materials used in pre-modern times, from its initial appearance in the late 6th or early 5^{th} century BC. Metal and its production activities have long been discussed for their role in the socio-economic development of Southeast Asian societies, in particular in Thailand. Iron artifacts in the form of tools and weapons recovered from late prehistoric and historic sites and numerous slag deposits documented across the present-day Thai landscape have shown their close association with the political and socio-economic sectors. This research draws attention to Ban Kruat District, Buriram Province, located on the northern part of the Dângrêk mountain range, which, over a period of three decades of archaeological research in this area, has identified the vestiges of human occupation since early centuries AD to the 12^{th}/13^{th} century (Figure 3a). The earlier occupation began some time during the last centuries BC, as evidenced by the settlements/cemeteries at Ban Bueng Noi and BST7 South, in which the latter was radiometrically dated to the 4^{th} century AD (cal. AD 253–406) (Venunan, 2016).

The main occupation in the area of our interest, however, occurred during the Angkorian Khmer period (9^{th}–14^{th} century AD). In addition to typical Angkorian Khmer structures, in particular temples, Khmer ceramic kiln sites have attracted interest from archaeologists. These kiln sites in Ban Kruat together with Ban Baranae (also in Buriram Province) form the greatest concentrations of Khmer ceramic production locales in Thailand. In addition to the temples and ceramic production, the location of Ban Kruat District is closely associated with the Angkorian Khmer northwestern route that connected Angkor with Phimai. This is illustrated by the presence of Dharmasalas or resthouses found in the area. These Angkorian Khmer remains give the impression of that the area played an important socio-economic role, especially for local craft production, during this period.

The other evidence that has received attention in only the last few decades is the remains of primary iron production, in the form of slag mounds of various sizes and slag deposits. These slag sites were first identified in the late 1980s and early 1990s by both the Fine Arts Department (Chandavij, 1989; Prommanot, 1989) and a Thai-Japanese archaeology team (Chaikulchit, 1991; Nitta, 1991), but these mounds had never been extensively documented until recently. In 2007, the Thai-Cambodia joint archaeology team explored Ban Kruat area as part of the National Research Council of Thailand funded Living Angkor Road project (2007–2010). As a result of extensive survey, at least 50 slag deposits and mounds have been documented within an area of 140 km^2 (Lertlum, 2008; Venunan, 2016). Given the number of the identified remains and their association with the Royal route connecting Angkor and Phimai, this was initially interpreted as an Angkorian Khmer iron production locale. Two intact slag mounds, Ban Khao Din Tai and BST7 south, were subjected for further excavation and analyses, including chronological determination and archaeometallurgical examination of the production waste (Lertlum, 2008; Yoopom, 2010).

Detailed archaeometallurgical examinations of these finds revealed that both slag mounds were formed by iron smelting activity, based on the direct smelting method using relatively iron-poor but locally ubiquitous lateritic nodules as the ore, but the use of flux was not identified (Chuenpee et al., 2014; Natapintu & Pryce, 2009; Venunan, 2011, 2016). The radiometric dating programs (conventional and accelerator mass spectroscopy; AMS) at both excavated sites of charcoal samples, including four in-slag charcoal samples, in conjunction with the typology of the pottery found, at the sites indicated that the activity was likely to have been carried out during the later phase of the Iron Age (5^{th} century BC–5^{th} century AD) (Lertlum, 2008; Venunan, 2016), and not during the Angkorian Khmer period as previously thought.

Despite this determination, surface surveys of some slag deposits and mounds recorded pottery remains from later periods, suggesting the possibility that iron-smelting may have been continued into historical periods, possibly during the Angkorian Khmer period together with ceramic production. No post-Angkorian material culture has currently been identified in Ban Kruat District suggesting that either occupation was not continued into the post-Angkorian period or evidence for post-Angkorian activities has yet been discovered.

While these remains demonstrate the use of iron over two millennia, an understanding of the role of iron production in ancient societies has been hindered by a lack of systematic dating of the slag remains and so only a few sites have been securely dated. Those dated sites have heavily relied on the relative dating of datable surface finds, in particular ceramic fragments. However, this is not always possible, including at Ban Kruat District where ceramic fragments, etc. have rarely been recovered at smelting sites. Establishing the chronology for the other slag deposits and mounds is, therefore, crucial to allow a better understanding of the origins, formation, and development of the iron production activity and how this production has been integrated into the socio-economic development of the Ban Kruat area.

Dating iron production sites

There are three main methods of dating iron production sites: archaeomagnetism, luminescence, and radiocarbon dating. These are considered indirect procedures since they rely on associated datable specimens with secure archaeological contexts, such as *in situ* furnace structures, charcoal, and in-slag charcoal. Of these techniques, luminescence is arguably the only technique that has a great potential for directly dating slag, a by-product from the smelting and smithing processes, that is always available at production sites.

Both luminescence or trapped-charge dating, i.e. TL and OSL dating, have been explored previously to assess their reliability in calendrical dating. This includes the use of TL to date the ancient slag-bearing quartz collected from Aegean Island, Greece (Elitzsch et al., 1983). Although there is a limitation of the annual dose (AD) approach, the obtained dates, however, conformed well to the other dates obtained from different materials, including the TL dating of porcelain (Pernicka et al., 1981). Haustein et al. (2003) successfully dated slag specimens from the archaeometallurgical sites in both Europe and the Mediterranean using TL dating. Moreover, Gautier (2001) dated quartz extracted from slag samples from Britain and Greece using OSL dating, and both the OSL and radiocarbon dates were in broad agreement with each other the radiocarbon dates of the charcoal. Therefore, both TL and OSL dating with slag-bearing quartz are one of the possible and powerful techniques to directly define the chronological information of iron-smelting sites.

The reliable chronological technique based on thermoluminescence properties was firstly introduced in 1998 (Aitken, 1998). Then, the recently developed technique using light in stimulation, called OSL combining the SAR protocol was carried out in 2000 by Murray and Wintle (2000). Although both TL and OSL are effective and reliable methods for burnt materials, OSL dating more outweighs TL by following three main reasons. Firstly, a key problem of TL is an inter-aliquot error due to the measurement of multiple aliquots for construction of the growth curve to find equivalent dose (a quantity of given dose after heating to reset zero signal; ED). The SAR allows the user to measure all signals from one aliquot and is a reasonable protocol to avoid TL normalization. The second is a required less amount of quartz in OSL dating combination of SAR, and this is extremely suitable for limited quartz-content samples (Barnett, 2000; Gautier, 2001). Finally, SAR in OSL dating provides more accuracy of ED statistic evaluation due to more convenient of a vast number of remeasurements.

In Thai archaeological contexts, metal production sites have heavily been relied on radiometric dating technique of archaeological charcoal specimens, both excavated charcoal and in-slag charcoal specimens. For luminescence dating, it has been less employed to date metal production sites. In case of Ban Khao Din Tai, TL dates were rejected in favor of more conforming radiocarbon, AMS, and relative dating results. Furthermore, it should also be noted that dating slag using luminescence techniques has never been attempted before in Thai archaeology.

In this paper, in order to better establish the calendrical dates for iron smelting activity in Ban Kruat District, OSL measurements of slag samples collected from BST7 were performed with the goal of assessing the possibility and reliability of dating slag-bearing quartz by the OSL technique.

3.2 Materials and Methods

3.2.1 Study area and sample collections

According to a previous archaeological investigation in 2010–2011, BST7 was defined by 10–11 slag mounds of various sizes surrounding a flat central area, creating a crater-like shape (Lertlum, 2010), as shown in Figure 3.1b. The excavation at the central area produced evidence for habitational and burial activities (253–406 cal. AD), from which beads, potsherds, and fauna remains were recovered. These early phases were then replaced by metallurgical activity, represented by a hard floor of smithing slag, which was AMS dated of charcoal to 382–539 cal. AD (Venunan, 2016). Unfortunately, no radiometric dating has been attempted for the slag mounds. In order to define the age of these slag heaps by the OSL dating, five slag samples were collected from the surface of slag heap 1 and 2, i.e., BK 1 and BK 2, respectively (Figure 3.1b-c). The samples were macroscopically different in terms of their color, porosity, density, weight, and other metallurgical features, such as flowing texture (Figure 3.2). For example, BK 1-1, BK 2-1, and BK 2-2 had a high porosity, low density, and different colors of grey, black, and reddish-brown, respectively. In contrast, BK 2-3 and BK 2-4 were reddish-brown dense slags that demonstrated a flowing structure. These differences are likely caused by differences in the raw material, smelting process, or even different smelting episodes.

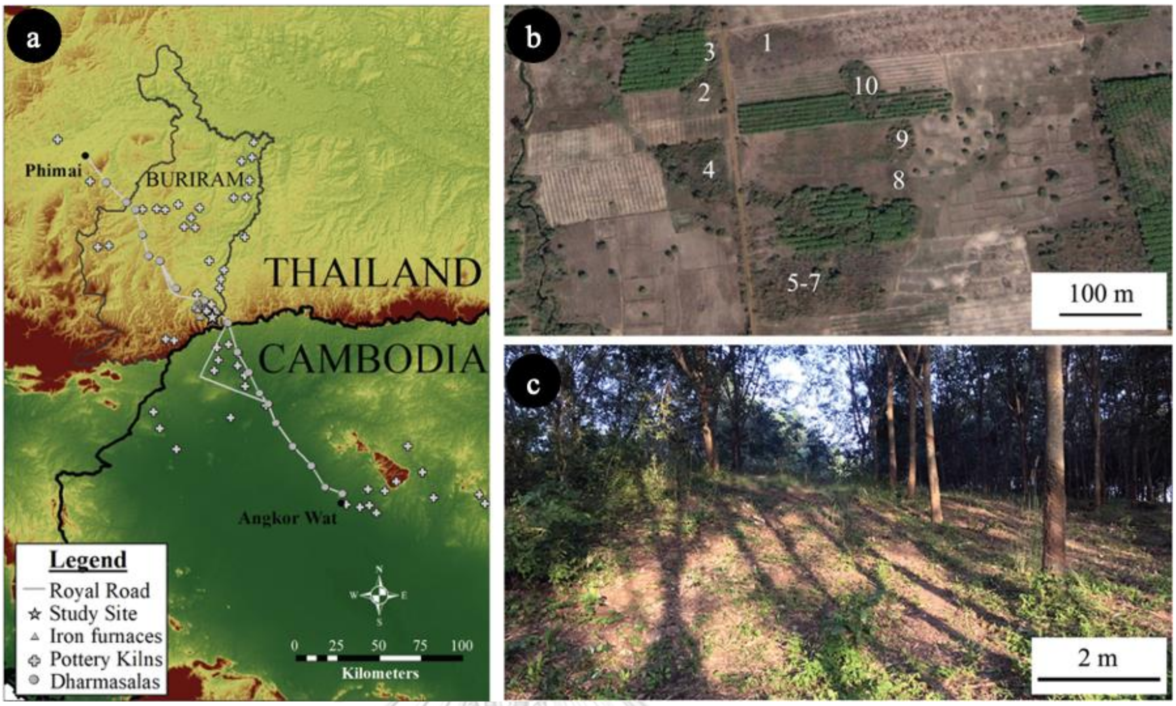

Figure 3.1 a) Map of the Thailand-Cambodia border showing the locations of Dharmasalas (circle), pottery kilns (cross), iron furnaces (triangle), and the location of BST7 (star). (b) Satellite image showing the circular distribution of 10–11 slag heaps in BST7 (Lertlum, 2010). (c) Location of the slag specimens that were collected for the chronological investigation in this study from slag heaps 1 and 2.

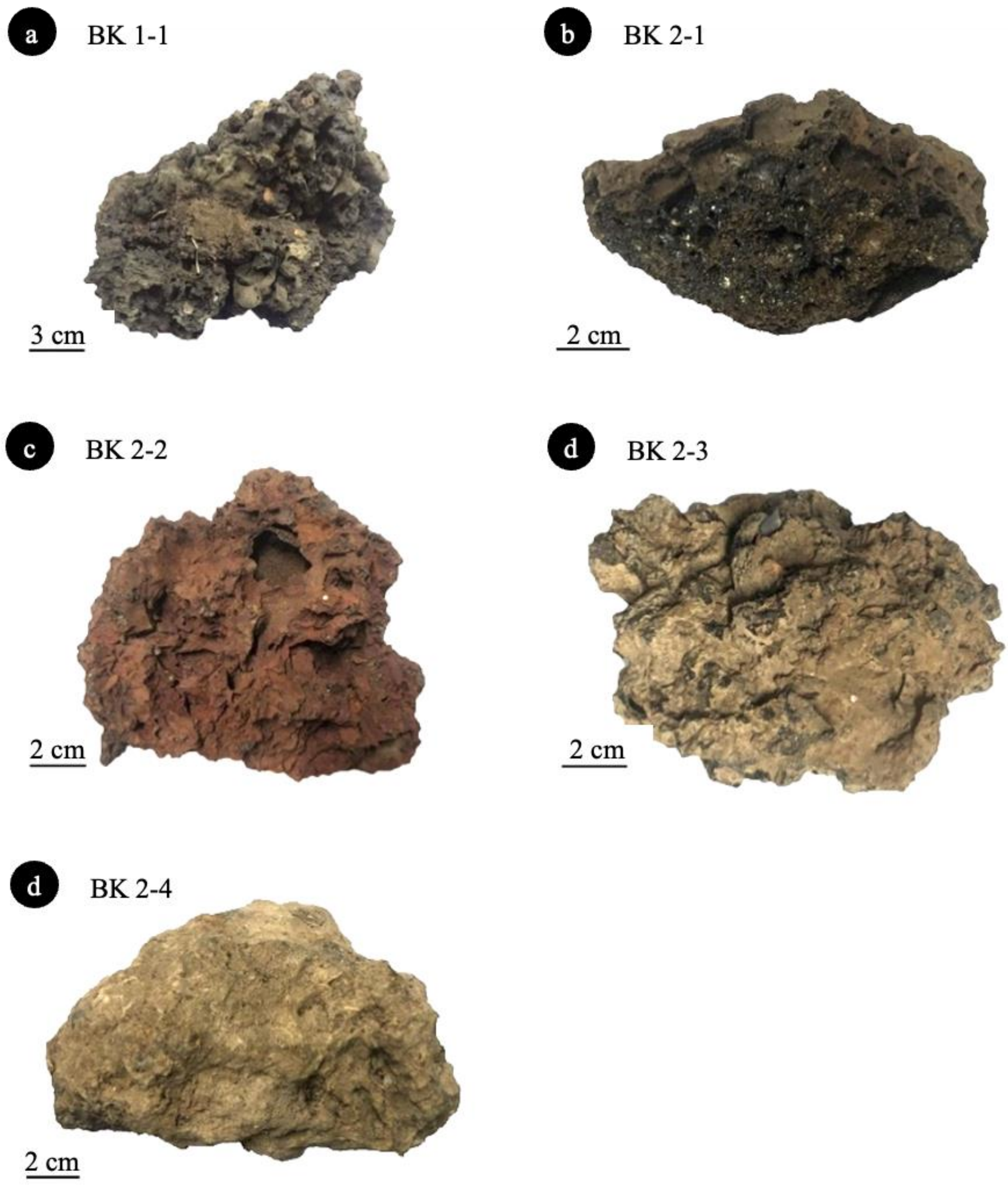

Figure 3.2 Macroscopic features of five slag samples collected at the BST7, Ban Kruat District, Buriram Province. Samples BK 1 (a) and BK 2 (b–d) were collected from slag heaps nos.1 and 2, respectively, as shown in Figure 3.1b.

3.2.2 X-ray diffraction (XRD) measurement

Theoretically, luminescence dating can date various types of minerals, such as calcite, feldspar, quartz, etc. However, in practice, quartz is the most common mineral that is utilized (Guedes et al., 2013; Liritzis et al., 2013; Munyikwa, 2016). In this study, all the slag samples were checked for their mineral composition using XRD analysis before dating.

3.2.3 OSL dating

Based on Gautier (2001) , the elapsed time since the latest iron smelting and the present is determined from the luminescence dating using Eq. (1);

$$\text{Luminescence date} = \frac{\text{Equivalent dose (ED)}}{\text{Annual dose (AD)}}, \quad (1)$$

where the ED in Gy is measured from the luminescence emitted during heating (TL) or optical stimulation (OSL) of the sample. Meanwhile, the AD in Gy/y was evaluated from the concentration of three abundant natural radioisotopes: uranium (U), thorium (Th), and potassium (K), in the environment surrounding the sample. To achieve the OSL dating, the i) radiometric and ii) OSL measurements are required.

1. Radioactive measurement

According to Haustein et al. (2003) and Puttagan et al. (2019), the important part in luminescence dating is the AD analyzed from the concentration of the existing radioactive elements. Theoretically, according to the penetrations of the alpha, beta, and gamma radioactivity, the radioactive elements within a 30-cm surrounding should be recognized. Since the heaps contained only dense slag, the concentrations of the radioactive elements can be analyzed directly from the slag specimen.

To archive, the slag was crushed, weighed, and dried out before reweighing to determine the water content. Next, 300 g of dried slag powder, which had a diameter of < 0.85 mm, was sieved, held in a closed plastic box for 1 month at room temperature, and then the U, Th, and K contents were measured using gamma-ray spectrometry as previously reported (Pailoplee et al., 2016). Finally, with the complement of U, Th and K, and water contents, the AD was calculated according to Bell (1979). The obtained AD results are expressed in Table 3.2.

2. OSL measurement

In this study, the OSL measurement and dating were based on polymineral samples that were purposely selected for dating the slag (Elitzsch et al., 1983). Firstly, all samples were eliminated from around the top 5 mm of the outer layer using a steel file. Thereafter, in each sample, the remaining slag was harvested and crushed by a rubber hammer in order to separate individual grains of slag. Those with a grain size of < 250 μm were sieved and collected for the OSL measurement and ED evaluation. SAR (Stella et al., 2014) was employed using an automated Risø reader (TL/OSL-DA-15). In order to avoid leakage of the luminescence signal, all stages of the preparation were performed under a subdued red-light environment.

3.3 Results and Discussions

3.3.1 XRD analysis

As shown in Figure 3 and Table 3.1, all the slag samples were composed of similar minerals, including i) hercynite, ii) cristobalite, iii) fayalite, and iv) quartz, while v) hematite was found in samples BK 2-1 and BK 2-2. According to the presence of quartz minerals, all five samples collected here were assumed to be suitable for measuring the luminescence signal, and so capable to date using OSL, which is the main aim of this study.

Table 3.1 Mineral composition of the five slag samples, according to the XRD analysis

Sample	Mineral content (wt.%)				
	Fayalite	Quartz	Cristobalite	Hercynite	Hematite
BK 1-1	16.63	27.56	48.76	16.63	-
BK 2-1	49.56	14.32	11.41	18.36	6.35
BK 2-2	6.30	27.38	31.69	8.84	25.79
BK 2-3	15.55	78.91	3.00	2.54	-
BK 2-4	3.99	83.76	-	2.54	-

Remark: fayalite: Fe_2SiO_4, quartz and cristobalite: SiO_2, hercynite $FeAl_2O_4$, hematite: Fe_2O_3.

From the classification of Kramar et al. (2015), the five slag samples can be categorized into two groups according to their mineral composition and content. The first group, comprised of samples BK 1-1, BK 2-3, BK 2-2, and BK 2-4, were defined as silica-rich slags and were comprised of more than 50% silica minerals (quartz and cristobalite). The second, based on the presence of hematite, fayalite, and hercynite, contained sample BK 2-1 and was defined as an iron-alumina slag.

In addition, according to Tsaimou et al. (2015), the presence of fayalite implies the commonly used direct smelting method operated at more than 1,100˚C (Chuenpee et al., 2014). Meanwhile, some archaeometallurgical sites were reported with a composition of kirschsteinite instead of fayalite (Chuenpee et al., 2014) which implies another modified smelting technique that includes lime fluxing with $CaCO_3$ and/or CaO (Chuenpee et al., 2014; Kramar et al., 2015; Paynter, 2006; Tsaimou et al., 2015). Since all five slags collected in this study were composed of fayalite without kirschsteinite, the smelting method utilized at BST7 was direct smelting without any supplementary lime flux. This conforms to the smelting production method proposed at the nearby Ban Khao Din Tai slag heap (Chuenpee et al., 2014; Venunan, 2016).

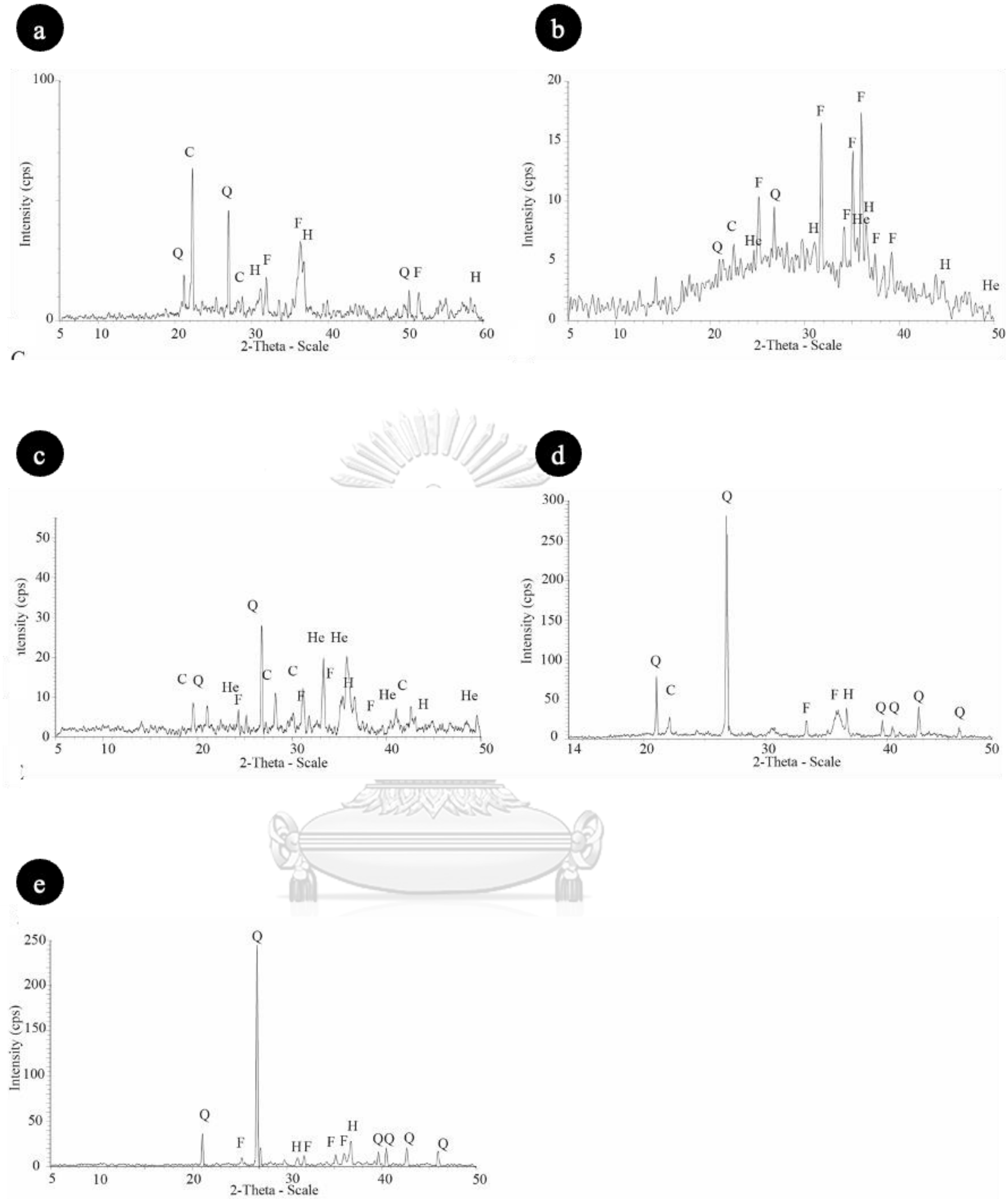

Figure 3.3 Representative XRD results showing the mineral compositions of the (a) BK 1-1, (b) BK 2-1, (c) BK 2-2, (d) BK 2-3, and (e) BK 2-4 slag samples. The x and y axis present the 2-theta and intensity (counts), respectively.

3.3.2 Discussion on the result of dating

Based on the OSL signal as shown in Figure 3.4, although the XRD analysis indicated the presence of quartz mineral, the OSL signals of BK 2-1 and BK 2-2 (Figures 3.4b and 3.4c) were quite low and fluctuated. In addition, even though an artificial additive dose for both samples (1.41 Gy) was demonstrated, the OSL signal was still lacking. There are several cases of low OSL sensitivity from various causes (Preusser et al., 2009). Puttagan et al. (2019) points out that the burnt brick that absented sensitivity may come from an insufficient heating part of a kiln. Contrary, slag is a by-product of the smelting process that melting raw material in a high-temperature condition; therefore, slag had been in a furnace with sufficient temperature. As a result, we summated that both the BK 2-1 and BK 2-2 had no potential for dating using the OSL approach. In contrast, samples BK 1-1, BK 2-3, and BK 2-4 clearly showed OSL decay curves. With respect to the quartz mineral composition, it was notable that BK 2-1 and BK 2-2 were composed of less than 60% quartz. In contrast, the three datable specimens (i.e., BK 1-1, BK 2-3, and BK 2-4) that illustrated an OSL signal were composed of at least 75% quartz. Thus, besides the existence of quartz, the content or quantity of quartz is important to be concerned as well.

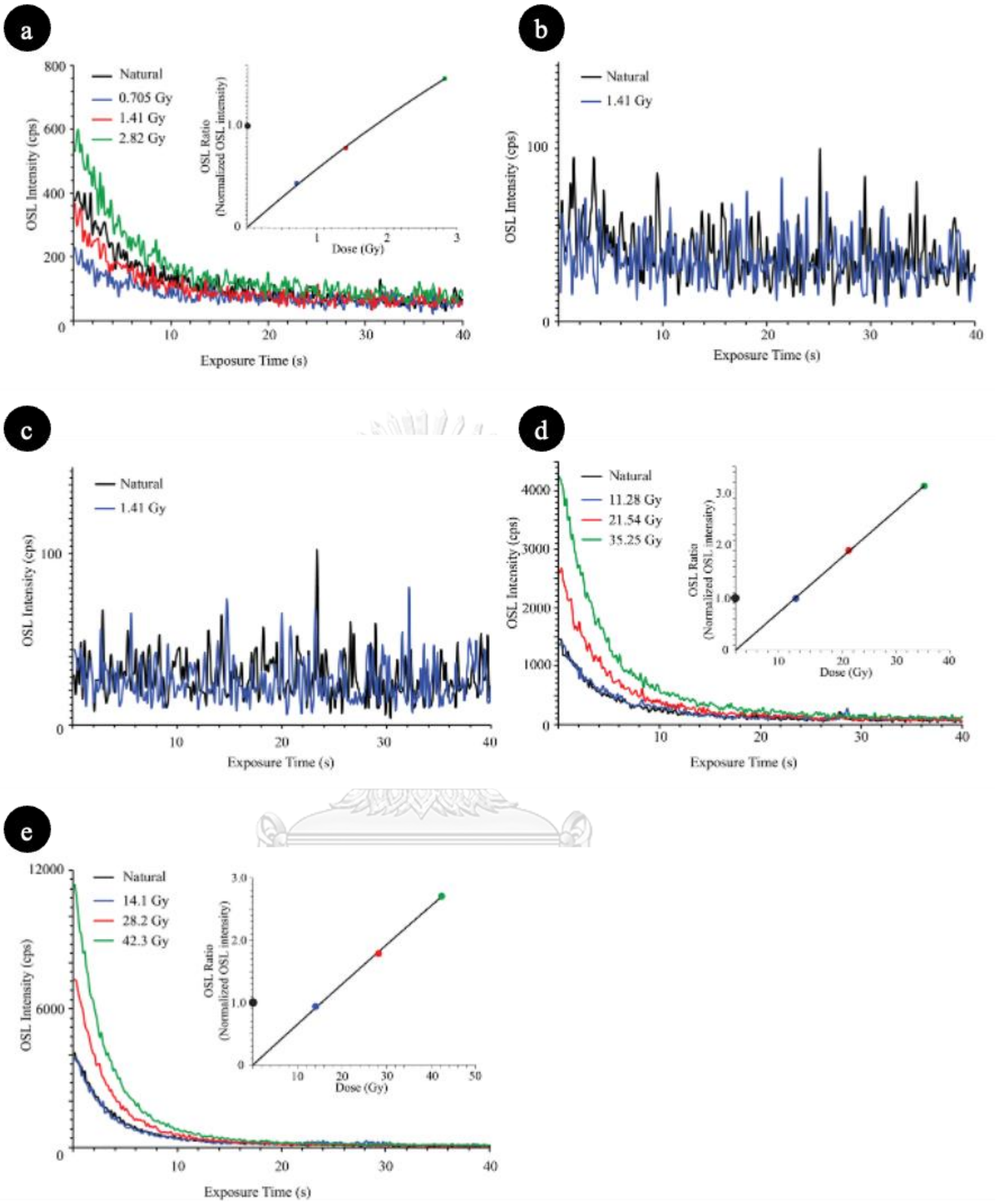

Figure 3.4 The OSL decay curves and growth curves (inset figure) of the five slag samples analyzed in this study. The natural signal is shown in the black line, while the additive beta doses are shown in blue, red, and green lines.

According to the SAR procedure, 40 or 96 aliquots were analyzed systematically. As shown in Figure 3.5, the obtained ED of each sample expressed a different degree of variation. The BK 1-1 illustrated a low variation in the ED when analyzed from 96 aliquots. The net ED of BK 1-1, therefore, was defined at 1.9 ± 0.12 Gy according to the central age model (Galbraith et al., 1999). Meanwhile, the BK 2-3 and BK 2-4 samples had a comparatively high variation in the ED from 40 aliquots with estimated ED values for BK 2-3 and BK 2-4 of 5.4 ± 0.08 Gy and 10.5 ± 0.10 Gy, respectively, based on the minimum age model (Arnold et al., 2009). With the complementary data of the AD, the dates of the three datable slag samples are expressed in Table 3.2.

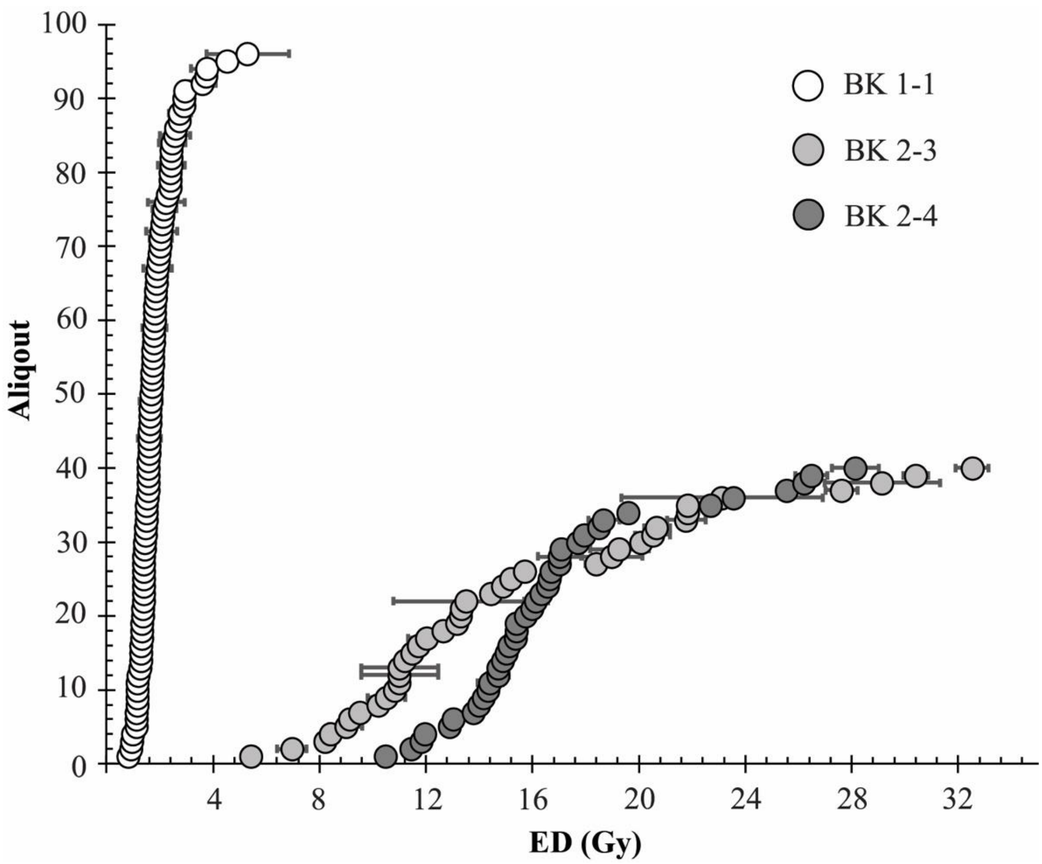

Figure 3.5 Typical ED distributions of the three slag samples analyzed in this study.

Table 3.2 The OSL dating results of three slag samples from the Ban Kruat District, Buriram Province. CAM and MAM represent the central and minimum age models, respectively, while W depicts the content of moisture used in the AD estimation.

Sample	U (ppm)	Th (ppm)	K (%)	W (%)	AD (Gy/ka)	ED (Gy)	Age (y)	Age (model)
BK 1-1	16.32	24.31	0.56	0.414	12.90 ± 0.15	1.9 ± 0.12	140 ± 10	CAM

BK 2-3	14.19	20.23	0.93	0.937	11.46 ± 0.03	5.4 ± 0.08	470 ± 7	MAM
BK 2-4	19.08	23.94	1.09	1.242	14.65 ± 0.03	10.5 ± 0.10	710 ± 9	MAM

As mentioned earlier, all five slags dated in this study were collected from the topmost surface layer of the heaps. The OSL dates, therefore, potentially represent the latest smelting activity at both individual heaps; although, it is also needed to take into account modern disturbance of each site. However, at the studied slag heaps, there was no sign of modern heavy disturbance on the surface. The results of slag dating from two slag heaps suggested three different periods of iron-smelting production: early 14th (BK 2-4), mid 16th (BK 2-3) and late 19th centuries (BK 1-1) as shown in Table 3.2. This chronological difference is also observed in the studies by Hendrickson et al. (2013) and Uchida et al. (2019) using AMS dating of in-slag-charcoal which illustrated slag heaps at Preah Khan of Kompong Svay lasted in later periods of activities. The most recent date of slag from heap no.1 was the youngest date in the lower Northeast Thailand; therefore, comparing the three dates for the two heaps, it can interpret that the iron-smelting activity at heap 2 (Figure 3.1b) was terminated around 470 ± 7 years ago, whereas, at heap 1, it continued to 140 ± 10 years ago.

Comparison between the previously reported ages of the slag heaps (Figure 3.6) and the OSL dates derived in this study revealed that the smelting activity at heap 2 was in the same time span as at the nearby Ban Khao Din Tai (1,100 ± 470 to 560 ± 280 years BP) (Lertlum, 2008). Whereas, for heap 1, the OSL date of 140 ± 10 years ago makes it the youngest iron smelting industry in Ban Kruat District, if not Northeast Thailand. Indeed, this date for heap 1 conformed well with the radiocarbon dates (140 ± 20 years BP) of a slag site in the Angkorian lowland (Cambodia) (Uchida et al., 2019), suggesting that iron smelting in Ban Kruat District might have taken place during the late 19th century; although, it is unsettled if the activity was continued from the Angkorian period.

The dates of heap no.2 from the two slags illustrate that the older slag was in the 14th century during a decline of the Khmer Empire (1431 CE) and the younger one (16th century) was during the early Ayutthaya period (Silapasuwanchai, 1995). According to the hypothesis that the iron smelting sites in Thailand had been continuity conducted by direct smelting technique since the late prehistoric (Nitta, 1996; Venunan, 2016) until Late Ayutthaya (Lertlum, 2008; Silapasuwanchai, 1995) before the transition to indirect smelting technique derived from China in late the 17th century AD (Bronson, 2012), these date results in this study are in good agreement and shed new light of the post Angkorian activities in this site and Ban Kruat District, where it was previously unknown.

More significantly, combining the XRD result presenting contemporary of the direct iron-smelting technique and the youngest age of slag by OSL dating confirms the assumption that iron-smelting in this site had possibly produced in the initial site extend to the post-Angkorian period.

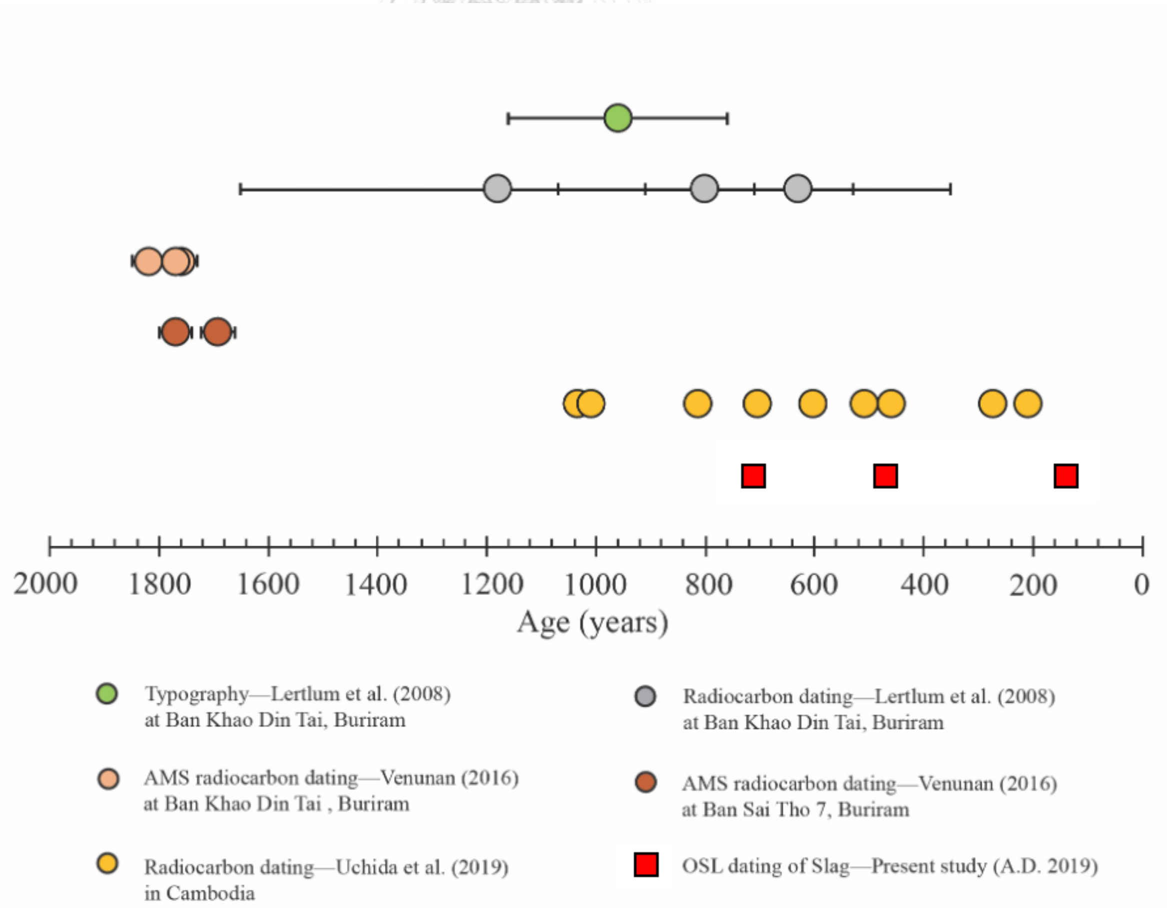

Figure 3.6 Distribution of the preliminary ages for the slag samples and reference ages.

3.4 Conclusion

The main aim of this study is to provide new knowledge of the calendrical dates for iron smelting activity in Ban Kruat District and assessing the possibility and reliability of dating slag-bearing quartz by the OSL technique. This study shows the most recent datable iron-smelting activity in the Angkor highland. Therefore, it can be concluded that the iron-smelting industry at BST7 had a long dynamic history that at least between the late Iron age (the 3rd–the 6th centuries) and the post-Angkorian (the 17th century; this study). Moreover, iron-smelting can be produced in the initial location in several centuries. In addition, OSL dating is seen to be an effective and meaningful method for the direct dating of slag-bearing quartz using polyminerals.

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CHAPTER 4
LATE IRON-SMELTING PRODUCTION OF ANGKOR HIGHLAND, METALLURGICAL SITE AT BURIRAM PROVINCE, NORTHEASTERN THAILAND: A VIEW FROM LUMINESCENCE DATING

Sutthikan Khamsiri[a], Pira Venunan[b], Chawalit Khaokheiw[b], Praon Silapanth[b], Sirittha Banron[a], Santi Pailoplee[a,c*]

[a]Department of Geology, Faculty of Science, Chulalongkorn University, Pathum Wan District, Bangkok 10330, Thailand

[b]Faculty of Archaeology, Silpakorn University, Phra Nakorn District, Bangkok 10200, Thailand

[c]Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit (MESA RU), Department of Geology, Faculty of Science, Chulalongkorn University, Pathum Wan District, Bangkok 10330, Thailand

[*]Corresponding author

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ABSTRACT

In the iron smelting process, slag, which is production waste, usually forms the majority of remains found at ancient metallurgical sites. In Ban Kruat District, Buriram Province, Northeast Thailand, at least 50 slag-bearing sites have so far been documented, which can be divided into nine clusters. One of the clusters, Ban Sai Tho 7 group, demonstrates a quite unique spatial organisation of slag mounds. Here, 10–11 mounds of circular or ellipsoid shape were found surrounding a flat area of 350 x 400 m. Two different stages of iron production were identified between these two areas: iron smelting at the circular mounds and iron smithing on the central plain. Compared with the nearby neighboring heap, this is a comparatively large concentration of slag, and possibly illustrates the long dynamic history of iron-smelting production. Although in 2009 and 2010, this site was estimated to have existed in the Iron age by accelerator mass spectrometric (AMS) dating of in-slag charcoal, the result only reveals the early production of iron-smelting regarding the law of superposition. Therefore, in order to assess the duration of production, optically stimulated luminescence (OSL) dating was employed to date technical ceramics (i.e., furnaces and tuyères) from the topmost layers of the surface slag heap in order to indicate the late or terminal iron-smelting production. The dates of the technical ceramics that came from the different sides of the slag heap show two different periods: the early 10th to the early 11th centuries (around 1000–1100 years ago) and the early 17th century (around 370 years ago). More significantly, the old samples were at the edge of the southern part, while the young samples came from the topmost of the northeastern slag heap. Therefore, these two furnaces were possibly used in different periods and distributed in different areas of the slag heap. The result also illustrates the terminal period (the early 17th century) of metallurgy in the ancient Angkor highlands, particularly at the Ban Sai Tho 7 site. An iron-smelting activity at Ban Sai Tho 7 seems to exist in the same location for several centuries. Moreover, OSL dating is an alternative method to directly date the late period of iron-smelting production.

KEY WORDS: luminescence dating, iron-smelting production, terminal period, furnace, tuyère, Ban Kruat Archaeological Site, Buriram Province, Northeast Thailand

4.1 Introduction

Iron and its production played a crucial role in the economic and political history of lower or southern Northeast Thailand from the Iron Age (fifth century BC to early sixth century AD) onwards, serving agriculture, civil engineering and warfare (Vallibhotama, 2003; Vallibhotama, 2005). The current evidence for ancient primary iron production in Thailand is based on the direct/bloomery smelting process in which iron is produced in the solid or semi-solid state as opposed to the liquid cast iron produced by the indirect/blast furnace smelting process. In the bloomery process, two main reactions occur: the reduction of iron oxides to the metallic form and the separation of the impurities in iron ore from the metal into a liquid slag (the formation of slag). The final product, called bloom, is a conglomeration of metallic iron of varying carbon contents, but generally malleable (soft) iron, and slag. This intermediate product requires further smithing in order to consolidate iron into a billet and expel unwanted slag. Smelting generates a significant amount of slag, residues, and technical ceramics as by-products compared to primary smithing and object forging. This feature is considered an identifier of iron production sites across Thailand and elsewhere.

Close relations between iron production and communities are demonstrated by the extensive distribution of iron slag deposits in the forms of heaps or mounds of the diverse sizes across the landscape of Thailand. Despite the long history of iron in Thailand and the documentation of iron production across the country, our technological understanding of iron smelting has been built upon only a handful of iron production sites that received archaeometallurgical investigation of their production remains, including Ban Di Lung (Suchitta, 1983), Ban Krabueng Nok (Indrawooth, 1990), Ban Dong Phlong (Nitta, 1996, 1997), Ban Khao Din Tai and BST7 (Venunan, 2016). They were all dated to the late prehistoric period. The presence of later production is very plausible and expected to be identified; however, a lack of systematic dating has rendered the reconstruction of iron smelting during the historical period very difficult. Furthermore, questions concerning the transformation of technologies and production organisation over time are very difficult to address based on current evidence.

Looking outside Thailand, few studies have clearly illustrated smelting evidence belonging to historical periods: the 8^{th}–9^{th} century AD iron smelting in Saphim, Northwest Lao PDR (Évrard et al., 2016; Pryce et al., 2011) and production during the Angkorian Khmer (Hendrickson et al., 2019; Leroy et al., 2018; Leroy et al., 2015) to post Angkorian Khmer period in Cambodia (Hendrickson et al., 2013; Hendrickson et al., 2017; Hendrickson et al., 2018; Pryce et al., 2014; Uchida et al., 2019). The latter identified the distribution of 18–22 slag deposits/sites with Preah Khan of Kompong Svay, east of Angkor, demonstrating the continuation of iron smelting activities from mid-13^{th} to the early 17^{th} centuries with the possibility of pre-13^{th} century production. This highlights the possibility that slag deposits within a single locale or area can be dated to different periods.

It should further be noted that radiocarbon dating techniques, both conventional and AMS, have often been employed on production-associated charcoal samples to chronologically define production remains. Nevertheless, not all slag deposits are able to offer dateable material, such as charcoal fragments from secure contexts, i.e., those associated with iron production or charcoal trapped in slag or diagnostic pottery/ceramic fragments. The availability of technical ceramics, e.g., tuyère and furnace fragments, in slag deposits therefore opens new possibilities for chronometric analysis through the employment of luminescence techniques.

Iron production remains at Ban Sai Tho7 (BST7), Ban Kruat District

A special attention was paid here to the clusters of slag deposits in Ban Kruat District, Buriram Province, lower Northeast Thailand. Human activities in Ban Kruat District have largely been defined by two main features; i) the late Iron Age as attested by burial contexts at Ban Bueng Noi and BST7 archaeological sites and ii) the Angkorian Khmer period, which is considered the main and extensive occupation, by various Khmer-influenced cultural elements, including Khmer buildings and ceramic production vestiges. The other characteristic remains in Ban Kruat District are from iron production which is the focus of this paper. Previous surveys documented more than 50 slag heaps distributed across the landscape grouped into nine clusters (Lertlum, 2008; Venunan, 2016). Owing to the extensive Angkorian Khmer evidence in the area, previous investigators associated the remains with the Angkorian period, establishing Ban Kruat as one of craft-producing locales for the Angkorian Khmer state. This proposition was later reassigned to the late Iron Age by AMS dating of in-slag charcoal extracted from excavated slag samples from two production sites, Ban Khao Din Tai and BST7, supported by a relative dating of associated pottery sherds (Venunan, 2016). The definition of Ban Kruat iron production remains has been limited due to only radiocarbon dating attempts at two excavated sites or surface collections where Khmer ceramics were documented at some slag mounds. Accordingly, iron production has currently been dated broadly spanning the Iron Age to the Angkorian Khmer period, covering almost two millennia from 500 BC to AD 1453. Based on archaeological evidence and local history in Ban Kruat District, there seems to be a historical gap between the retreat of Angkorian Khmer political influences from Northeast Thailand in the late 14th–15th centuries and the coming of new settlers in the 19th century. However, the area might have seen some travellers and military moving between the Khorat Plateau in the present-day Thailand and the Mekong Lowlands and Central Plains of Cambodia. It is historically known that iron remained important socioeconomically and politically throughout the 15th–19th centuries; although only limited evidence has been available to demonstrate this. Compared to what was observed at Preah Khan of Kompong Svay where iron production continued during the terminal Angkorian Khmer periods, to what extent were similar socioeconomic phenomenon archaeologically observable in Ban Kruat?

To address this, we focus on a particular cluster of slag deposits at BST7 where 10–11 heaps were identified within the area of 350 x 400 m. Each heap was circular and measured approximately 50 x 60 m and 3–5 m in height. Compared to other clusters, the spatial organisation of metallurgical remains was arguably characteristic as it exhibited a ring of 11 heaps surrounding a flat central area. Previous archaeological investigation suggested the initial phase of occupation was associated with habitation and burial activity. The metallurgical activities were later introduced in the second phase. Archaeometallurgical analysis identified both smelting, associated with circular slag mounds, and primary smithing activities, within the central area. This patterning suggests the spatial organisation of a workshop (Lertlum, 2008). Initial activities were dated by radiocarbon dating to AD 200–500 (Venunan, 2016); however, the smelting mounds have not been scientifically dated but were assigned to the late Iron Age based on the relative dating of metallurgical waste and pottery sherds.

To better chronometrically characterise slag mounds and to assess if they may be of similar age ranges, the technique of OSL was employed. Dating also allows us to address whether post-Iron Age smelting activities might have continued in later historical periods.

4.2 Field Survey and Sample Collection

Surface survey identified various degrees of disturbance by present-day agricultural activities (heaps no. 1–3, 10) and levelling (heaps nos. 4–9) (Figures 4.1b–c). Therefore, the ancient metallurgical materials at the top of the heap were interpreted as a mixed zone. However, due to these disturbances, technical ceramics were also exposed on the mixed surface of slag heap no. 2 (Figure 4.1c).

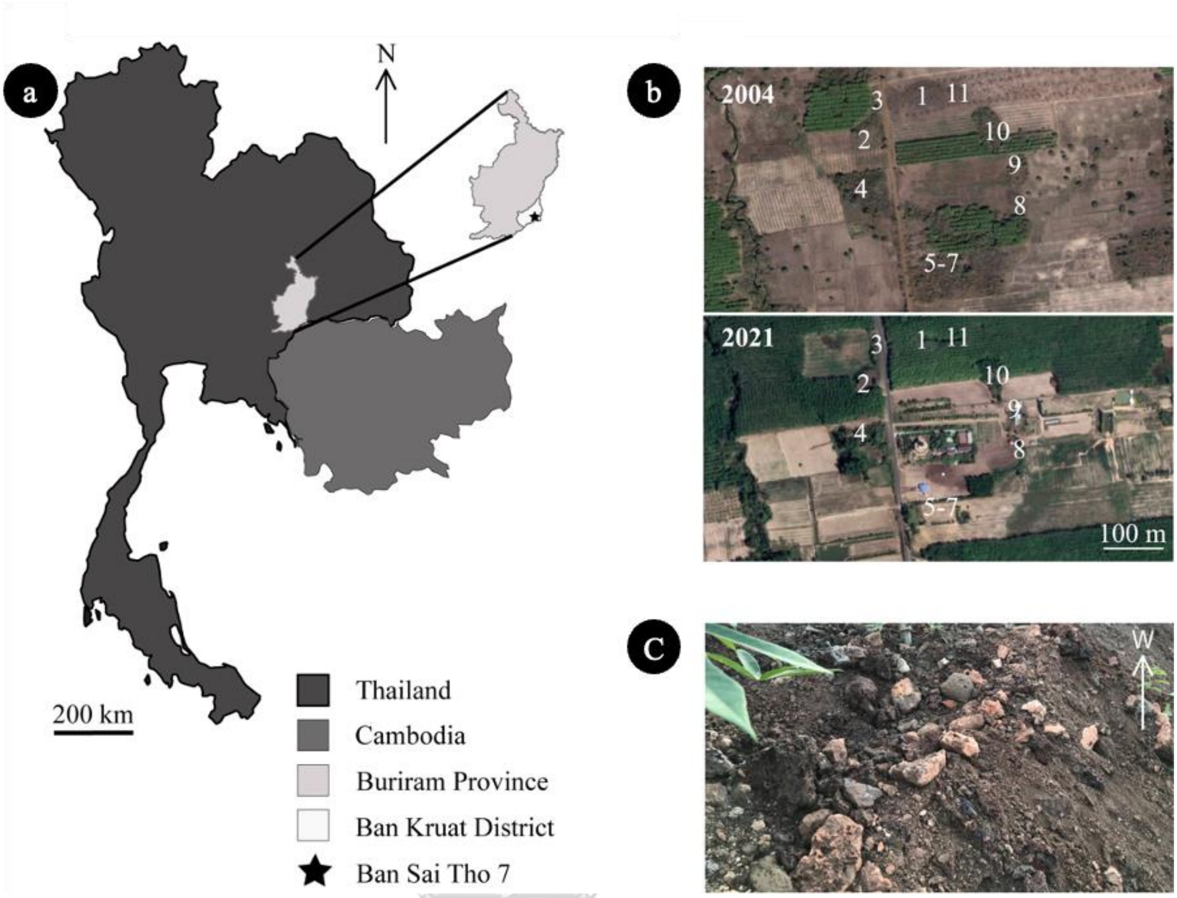

Figure 4.1 a) Location and (b) satellite image in 2004 (top) and 2021 (bottom) of the metallurgical site at BST7, Ban Kruat District, Buriram Province, Thailand. (c) The distribution of technical ceramics exposed on the surface of heap no. 2.

At slag heap no. 2, two clusters of technical ceramics were classified at the northeast and southwest edge. We preliminarily interpreted that these two groups of technical ceramics as two different furnaces that possibly represent different periods of smelting activity. Moreover, according to the morphology of the exposed technical ceramics in each group, the two different macroscopic features can be defined as i) a wall furnace fragment which is dense and homogenous (FNE and FSW) and ii) a tuyère consisting of an internal curve or bore character (TNE and TSW) (Figure 4.2) (Leroy et al., 2020; Pryce et al., 2014; Venunan, 2016). In order to constrain the date of each portion of the technical ceramics, samples from both wall and tuyere were collected from both the northeast and southwest fragment groups. Four samples were collected: samples FNE and TNE (Figure 4.2a and 4.2c) from the northeast edge and samples FSW and TSW (Figure 4.2b and 4.2d) from the southwest.

OSL dating is one of the powerful scientific dating methods useful for dating the most recent heat of the burnt materials (Aitken, 1998).The principle is that the new OSL signal will be accumulated from an environmental radiation after the resetting or erasing an older signal in sample from the latest heating process. Two main measurements are required including i) equivalent dose (ED) showing the latest accumulated OSL signal and ii) annual dose or dose rate (AD) presenting the annual natural radiation (Aitken, 1998). According to the potential dating problems of mixed slags, both furnace and tuyere fragments were collected for dating in this study. All dates here represent the latest heat and are hoped to imply the latest known smelting activity at this slag heap.

Figure 4.2 Photographs of the samples: (a, b) furnace fragments (a) FNE and (b) FSW and (c, d) the tuyère samples (c) TNE and (d) TSW.

4.3 Preparation and Measurements

OSL dates were calculated from the ratio of the ED and AD as previously reported (Aitken, 1998), where ED (Gy) is the intensity of luminescence from the quartz mineral and AD (Gy/y) is a number of the natural radioactive elements of uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K) surrounding the sample. In order to date the furnace wall and tuyère samples, portions were prepared for ED and AD estimation.

4.3.1 Determination of the AD

Theoretically, there are conditions that should be considered in interpreting an ancient metallurgical site. First, the site included heterogeneous types of remnant industrial wastes, i.e., the technical ceramics were buried in the slag deposit. The AD of each sample was, therefore, determined from both the internal dose of the technical ceramics and the external dose of the surrounding slag. Both the technical ceramics and the surrounding slag were crushed separately into a powder (diameter < 0.85 mm) as reported (Bailiff & Holland, 2000). The powders were subsequently dried and packed in a sealed plastic box for one month. The radioactive contents, in terms of ^{238}U, ^{232}Th, and ^{40}K, were then measured using a gamma spectrometer. Water content was measured from slags surrounding each sample in order to calculate external dose by using the web-based DRAC (dose rate and age calculator) that freely accessible at www.aber.ac.uk/alrl/drac (Durcan et al., 2015), where both the AD values of the internal and external portions were obtained.

Comparison of the internal and external doses in each sample revealed that the internal dose was significantly (around 70 times) lower than the external dose, as shown in Table 4.1. The high external dose is undoubtedly because it came from the mixing of raw material during the smelting process. Moreover, the calculated AD had a similar value to the external dose. It should be noted that iron ores and/or iron-bearing materials generally have higher concentrations of radioactive element(s) than clay material, and so the consideration of the external dose is necessary.

4.3.2 Determination of the ED

In order to avoid the loss of the OSL signal, the sample preparation for ED measurement was performed under subdued red-light conditions. First, at least 2-mm of the furnace sample's surface was removed. Then, each sample was crushed and sieved to a 74–250 μm size (Puttagan et al., 2019). The samples were treated with (suspended in) 10% (v/v) hydrochloric acid (HCl) for 24 h to remove carbonates, and then washed with deionized water before treating with 30% (v/v) hydrogen peroxide (H_2O_2) to eliminating organic materials. The samples were then treated with 37% (v/v) hydrofluoric acid (HF) for 40 min to eliminate feldspar, retreated in 37% (v/v) HCl for 40 min to remove the fluoride, washed with purified water (Puttagan et al., 2019), and then dried at 50 °C for 24 h. Finally, the ferro-minerals were screened and separated by a magnetic separator.

X-ray diffraction analysis (XRD) was applied to check the mineral contents of all the treated samples. The result revealed 95% quartz (SiO_2) content in all the treated samples, indicating that they were acceptable and suitable for the measurement of the OSL signal including the ED determination (Takashima & Honda, 1989).

With respect to the OSL measurement, SAR (Murray & Wintle, 2000) was employed. Each aliquot was stimulated by blue LEDs (470 ± 30 nm) at 125 °C temperature. The luminescence signal was measured under a combination of BG-39 and U-340 filters. A preheat treatment of 210 °C/10 s for natural and regeneration doses, and a cut heat of 160 °C for test doses were used. The OSL decay curve of each measurement revealed the decay of the OSL signal (Figure 4.3).

To construct the OSL growth curve, each aliquot was irradiated by the 90Sr/90Y beta source. The ED value was then calculated by interpolating the OSL signal of the natural sample on the linearly fitted OSL growth curves (Figure 4.3). Based on the procedure of SAR mentioned above, 60 aliquots of ED were estimated in each sample, and all ED measurements with a higher than 10% error were excluded.

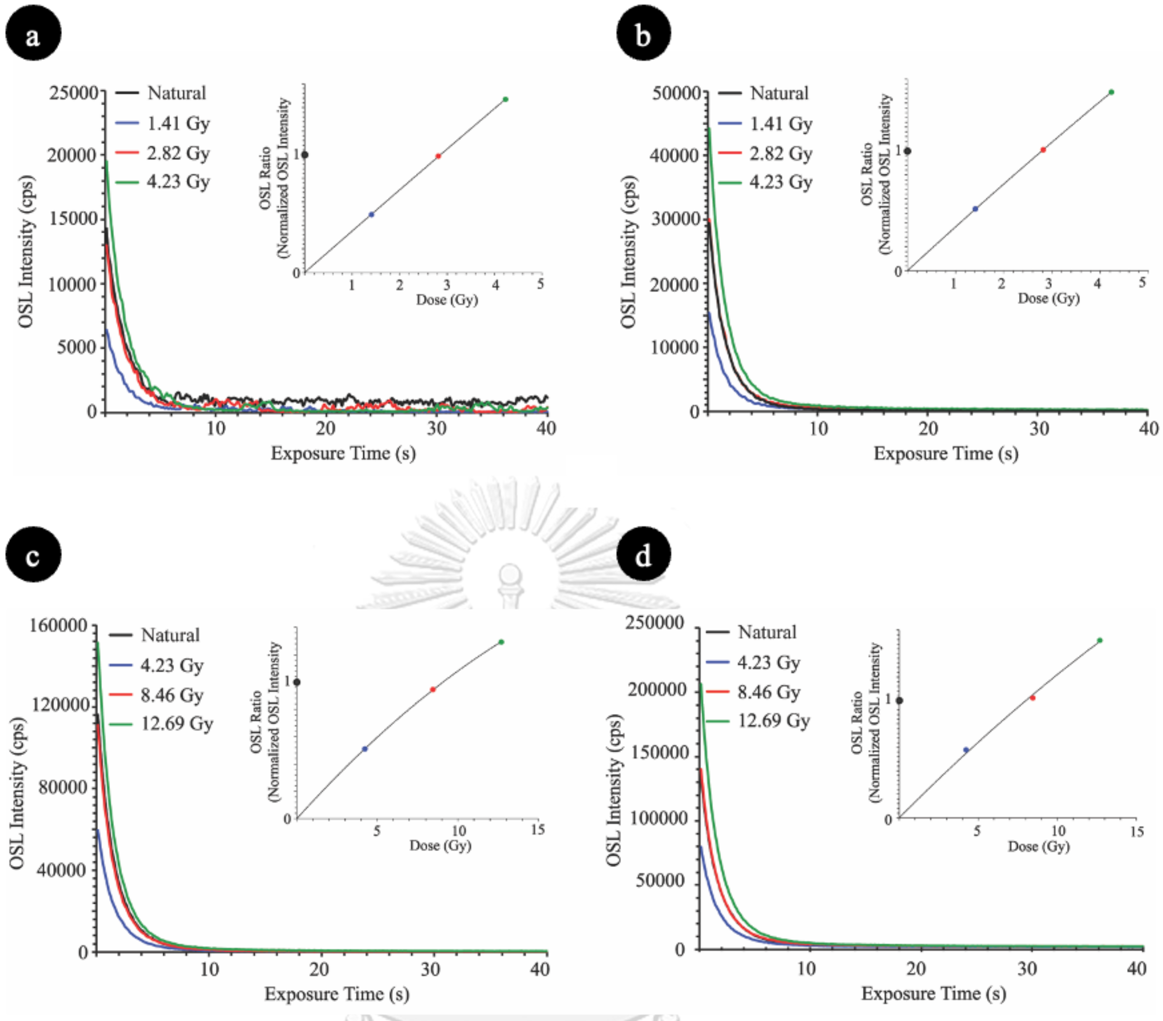

Figure 4.3 Decay curves obtained from the OSL measurements of sample the (a) FNE, (b) TNE, (c) FSW, and (d) TSW samples and (Insets) the growth curve created by the additive beta doses. The different coloured solid lines illustrate the signals from different sources, where black line is the natural dose, and the blue, red, and green lines are the signal from three different additive beta doses.

4.3.3 Age determination

According to Galbraith et al. (1999), the representative ED in each sample was estimated by the statistical age model. Generally, the low distribution of ED values that represent the sample with completely erased the residual signal is suitably calculated by mean age model or central age (CAM). Meanwhile, the minimum age model (MAM) was suggested for more variable ED values because the quartz grains were assumed to have been partially bleached or burned/heated (Liang, 2019).

To determine the representative ED of each furnace sample, all ED values of 60 aliquots were statistically investigated using a radial plot (Galbraith, 1988) while kernel density estimates were used for the continuous values (Galbraith & Roberts, 2012). This study attempted to evaluate the ED date according to both CAM and MAM (Table 1). As a result, both CAM and MAM dates of this study were comparable; however, according to the value of overdispersion i.e., standard deviations (Liang, 2019), the MAM was more constrained and statistically appropriate than the CAM (Figure 4.4). In addition, the MAM was more meaningful than the CAM according to the concept of complete bleaching of the signal (Liang, 2019). Therefore, in each sample, the ED and dates were analysed and determined by the MAM. According to the MAM, there were at least two periods of iron-smelting activities. The first activity was around 1000–1110 years ago and the subsequent activities 360–370 years ago (see details in Table 4.1 and Figure 4.5).

Table 4.1 The ages of furnace and tuyère samples calculated from annual dose (AD) and equivalent doses (ED). W is water content. Internal and external AD refer to annual dose from individual samples and environment materials, respectively. Mean ED illustrates an equivalent dose that calculated from the Central age model (CAM), while Min ED is obtained equivalent dose by the minimum age model (MAM). All ages mean the year of sampling (AD 2020)

Sample	W (%)	Internal AD (Gy/ka)	External AD (Gy/ka)	AD (Gy/ka)	OSL (Mean ED)		OSL (Min ED)	
					ED (Gy)	Age (Y)	ED (Gy)	Age (Y)
FNE	1.69	0.09 ± 0.006	7.39 ± 0.044	7.48 ± 0.045	3.07 ± 0.05	410 ± 7	2.77 ± 0.13	370 ± 18
TNE	1.61	0.10 ± 0.007	7.40 ± 0.044	7.5 0 ± 0.045	2.84 ± 0.04	379 ± 6	2.73 ± 0.06	364 ± 8
FSW	3.02	0.11 ± 0.006	7.28 ± 0.044	7.39 ± 0.045	9.47 ± 0.15	1282 ± 22	8.2 ± 0.1	1110 ± 10
TSW	2.73`	0.13 ± 0.009	7.30 ± 0.044	7.43 ± 0.045	7.86 ± 0.08	1058 ± 12	7.44 ± 0.06	1001 ± 15

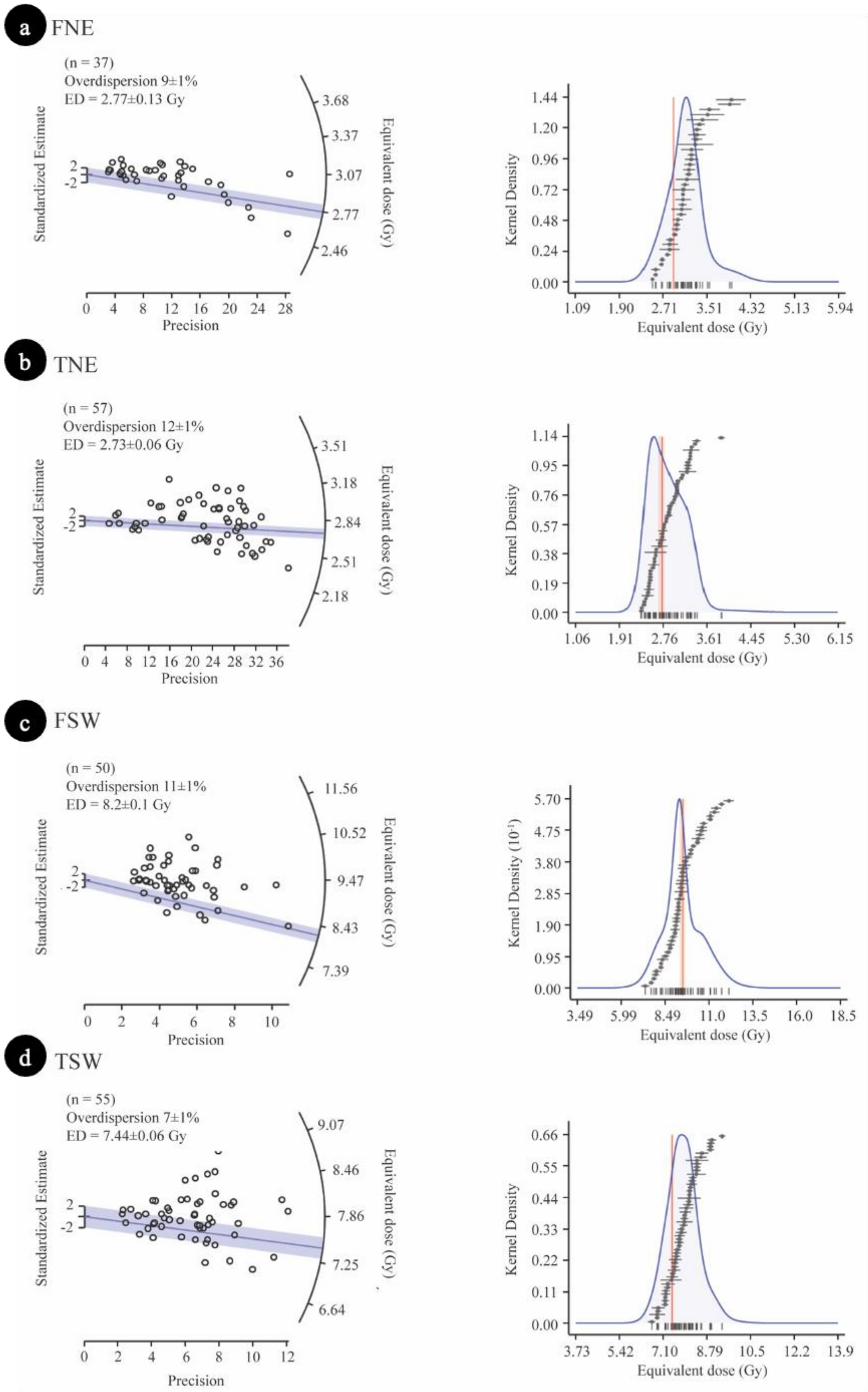
a FNE
(n = 37)
Overdispersion 9±1%
ED = 2.77±0.13 Gy
Standardized Estimate
Precision
Equivalent dose (Gy)
3.68
3.37
3.07
2.77
2.46
Kernel Density
1.09 1.90 2.71 3.51 4.32 5.13 5.94
b TNE
(n = 57)
Overdispersion 12±1%
ED = 2.73±0.06 Gy
3.51
3.18
2.84
2.51
2.18
1.06 1.91 2.76 3.61 4.45 5.30 6.15
c FSW
(n = 50)
Overdispersion 11±1%
ED = 8.2±0.1 Gy
11.56
10.52
9.47
8.43
7.39
Kernel Density (10⁻¹)
3.49 5.99 8.49 11.0 13.5 16.0 18.5
d TSW
(n = 55)
Overdispersion 7±1%
ED = 7.44±0.06 Gy
9.07
8.46
7.86
7.25
6.64
3.73 5.42 7.10 8.79 10.5 12.2 13.9

Figure 4.4 The radial plots (left) and Kernel density estimation plots (right) of samples (a) FNE, (b) TNE, (c) FSW and (d) TSW show the obtained equivalent dose (ED) from minimum age model (MAM) distributions and unmixed samples, respectively.

4.4 Discussion and Conclusion

Dating the iron production sites in Ban Kruat District, based on surface surveys may only provide a broad timespan of human activities. Such sites may not be composed of diagnostic artifact types. In-slag charcoal samples are considered an arguably reliable source of information for temporal frameworks owing to the direct association with smelting actions but are not likely to be available at all sites. Dating based on technological characteristics or signatures of iron production was also not of any help since no visible sub-groups could be observed from the analysis of slag samples collected from nine clusters (Venunan, 2016).

These limitations render chronological determination notoriously difficult, hindering the reconstruction of the development of Ban Kruat iron production and the meaningful interpretations of its roles in the society. Therefore, an alternative dating method is required to overcome this issue. In production activity areas besides datable charcoal, technical ceramics are the other type of datable artifacts via the application of luminescence dating techniques. This specific type of ceramics is the other major component in the production process and can represent an action of production activity at a specific point of time, thus offering archaeologists a broad view of when production activity was taken place. In the context of Ban Kruat District, technical ceramics were commonly found during surface survey compared to much rarer diagnostic artifacts such as pottery sherds; OSL, therefore, provides an opportunity to establish temporal frameworks for Ban Kruat iron production. Nevertheless, surface finds can be modified through a range of taphonomic processes, including modern agricultural activities and land-levelling. This alters the landscape context of such assemblages and their interpretation, potentially creating a mixture of production remains from various periods, if present. The excavations at Ban Khao Din Tai clearly illustrated the transformation of smelting workshops during the Iron Age: furnaces at the end of the smelting process were partially destroyed in order to extract bloom or final products, and subsequently repaired or built over with a new furnace structure (Lertlum, 2008; Yoopom, 2010).

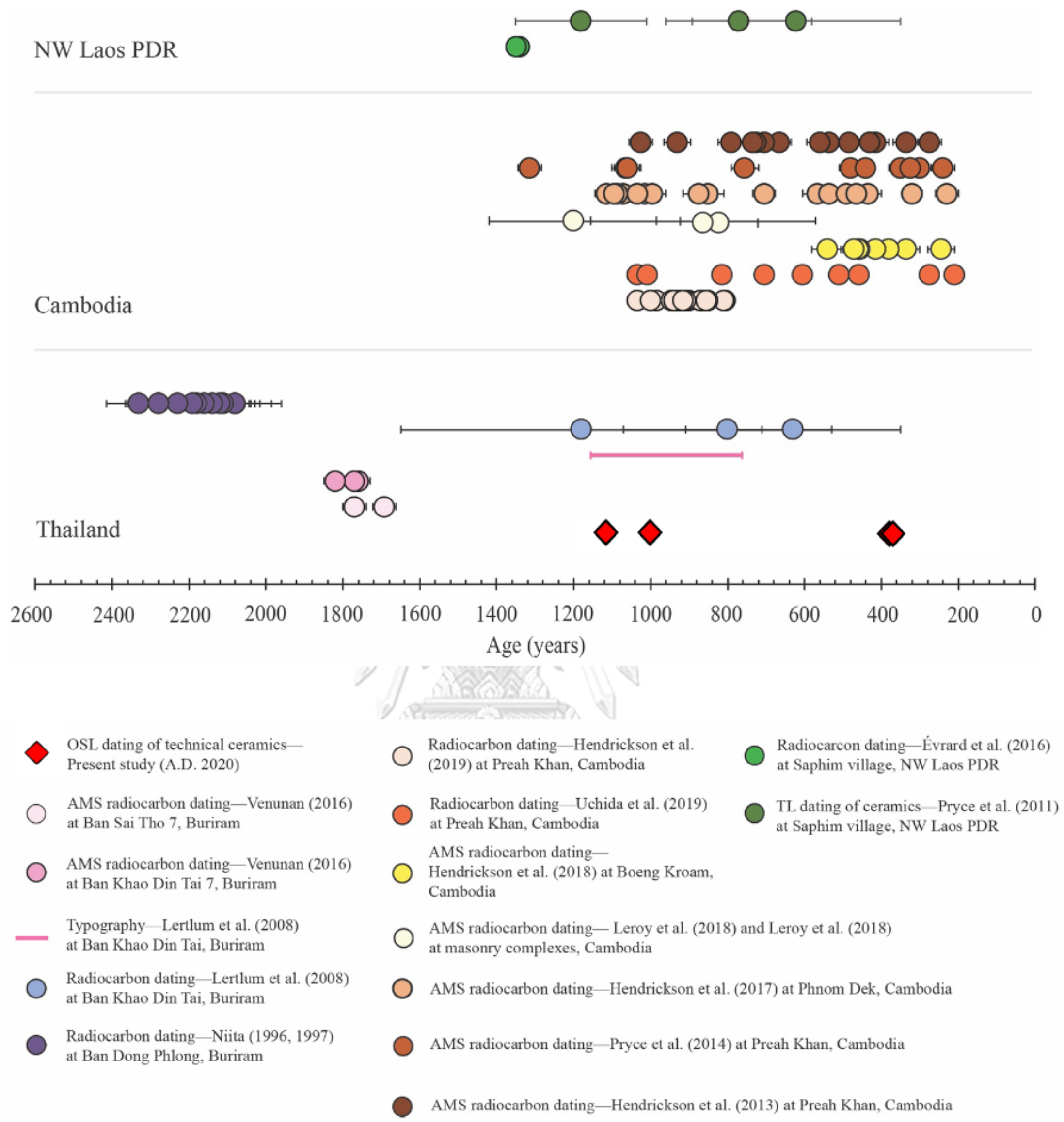

Figure 4.5 The illustration shows the ages of iron-smelting timespan in Buriram, Lao PDR and Cambodia from OSL dating of furnace and tuyère samples, the AMS and conventional radiocarbon dating of charcoals and pottery typology.

Therefore, this paper employed OSL dating of technical ceramic fragments collected from the surface of the studied site as a preliminary temporal indicator in order to give a broad framework for further investigation.

The OSL results revealed different dates between the NE (around 360–370 years ago) and SW (around 1000–1110 years ago) samples implying at least two separate smelting phases at this particular workshop (mound). The SW sample is likely to have been associated with the early Angkorian Khmer period (9^{th}–10^{th} centuries), while the NE sample with the 17^{th} century, contemporary with the Ayutthaya period as shown in Figure 4.5.

The former date was supported by local Angkorian Khmer evidence and previous studies, i.e. typology of ancient material fragments and nearby ancient remains, in Ban Kruat District (Lertlum, 2008), but this is the first time the presence of iron production has arguably been identified. Considering similar morphological and chemical characteristics of Ban Kruat iron slag regardless of clusters, this Angkorian Khmer period production was possibly a continuity of such craft activity from the late Iron Age and, interestingly, at the same site where earlier iron production had taken place. Iron was considered an important commodity for Angkor, being exploited extensively for agriculture, civil engineering, construction, and warfare. We suggest that the assimilation of Ban Kruat into a political and cultural sphere of Angkor might have meant the control over iron resources in addition to its location being on the route connecting Angkor to Phimai, a regional administrative center in lower Northeast Thailand. Together with the establishment of Angkorian Khmer ceramic production, this transformed Ban Kruat into a production locale on the NRR serving possibly local communities, regional centers, and, more importantly Angkor.

The latter date that is consistent with previous findings in Cambodia (Hendrickson et al., 2013; Hendrickson et al., 2019; Hendrickson et al., 2017; Hendrickson et al., 2018; Pryce et al., 2014; Uchida et al., 2019) (Figure 4.5) was indeed intriguing for human activities during the 17^{th} century has not yet been documented in Ban Kruat District, and if reliable, the production is demonstrated to have been present in later phases. During this period, the political center in the Buriram area moved to Phutthaisong from the previous seat of power at Phnom Rung and Muang Tam. The centers of Phnom Rung and Muang Tam, including Ban Kruat, largely decreased in both sizes and power, almost completely forgotten based on historical documents. The area was still on the route connecting Ayutthaya to the Central Plains of Cambodia but was of less importance as political focus had shifted to western and southern areas of Thailand. The existence of iron production, which is likely to have been continued to this period based on similar smelting techniques from preceding periods, might have been done on much smaller and insignificant scale in order to serve the local needs of smaller communities. By the 19th–20th centuries, the influx of mass-produced or industrial iron from the West posed a serious threat to traditional ironmaking activities/industries in Thailand (Bronson, 1985), Lao PDR (Pryce et al., 2011), and Cambodia (Pryce et al., 2014). As traditional smelting required usually more investment of time and labour to acquire ore and fuel compared to modern ironmaking industries, industrial iron put competitive pressure on pre-industrial ironmaking. This seems likely to have forced many smelters to abandon their activities and turn to blacksmithing using industrial iron instead. The dating of this site suggests a similar trajectory for iron working in Ban Kruat District. Moreover, traditional smelting sites in upland areas of the Angkorian realm possibly existed longer. Ban Kruat District, located far from the center of Angkor, may have had less access to the exchange of mass-produced iron (Pryce, 2013).

Combining previous chronometric analysis with the current dates provided here, Ban Kruat interestingly saw a long continuity of iron production starting from the late Iron Age (Venunan, 2016), through the Angkorian Khmer period, and into the 17th century.

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CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Research compilation

The main aims of this research are: 1) to analyze a possible route passing the eight mountain passes along the Phnom Dângrêk Mountain in order to communicate between people living in ancient communities in Angkor Highland (present-day Northeast Thailand) and Angkor Lowland (present-day Cambodia), 2) to directly date slags from ancient metallurgical site in Ban Kruat District, Buriram Province using luminescence dating technique and 3) to determine the date(s) of the smelting activity at the slag clusters of BST7, Ban Kruat District, Buriram Province by luminescence dating of surface technical ceramic samples.

Extensive archaeological documentation of past activities in lower Northeast Thailand has illustrated very active mobility of people crossing the Dângrêk Mountains since the later Prehistory, probably using existing numerous mountain passes situated along the mountain range. These passes provided choices for locals to access to various parts of lower Northeast Thailand and further hinterlands. According to Welch and McNeill (1991), in addition to the movement of Indo-Pacific glass beads in both sides, the investigation revealed that the presence of Phimai black pottery in both the Phimai region and the Khmer region, demonstrating an cultural interaction between people across the mountain range. The interaction between people living on both sides of the Mountains became increasingly intensive after the rise of Khmer political powers centred at Tonlé Sap in the 7th century, for the Khmers had put an interest in the lower Northeast Thailand and later incorporated the region into their political realm around the 11th century during the height of the Angkorian state. In the reign of Jayavarman VII (1125-1218), the construction of the route connecting Angkor, the core of the Khmer political power, and Phimai, the regional administrative centre overseeing the Mun and Chi River Valleys was able to allow the transportation and communication between two areas more efficiently and effectively (Hendrickson, 2010). This Northwest route is well documented not only by the inscription at Preah Khan temple but also the existence of Dharmasala or resthouses and laterite bridges along the route. Güimil-Fariña and Parcero-Oubiña (2015) note that the Roman road networks appear to have been established on the existing routes. Similarly, in a study conducted by Welch (1998), it was suggested that the routes in the Khorat plateau possibly existed since earlier periods, i.e. later Prehistory.

Despite the notion of ancient routes for regional mobility, there was previously no full assessment of optimal paths or potential mobility to better explore the mobility of people crossing the mountain range and the geographical condition was rarely taken in account in terms of how effective each pass could have been used for the transportation.

Welch (1985) noted the limitations of relevant evidence obstructing a sound identification of the specific means of land transportation in these areas. Employing the LCP model and the application of GIS as potential tools to explore the mobility issue, this study aims to generate the models of land transportation of northeastern Thailand which will permit better assessment of land routes connecting both sides of the mountain range, focusing on three viable mountain passes from the Dângrêk mountain to moated sites, namely Ta Muen, Sai Taku, and Krang.

Cross-comparing the three potential LCP routes identified with the Angkorian Northwest route, the route crossing the Ta Muen pass into lower Northeast Thailand (Surin and Buriram Provinces) generated by LCP are closely associated with moated sites and has a good alignment with the Angkorian Northwest route, suggesting the establishment of the Northwest route on the foundation of earlier route. A study by Lertlum and Shibayama (2009) suggested that Ta Muen features a lowest slope, making it highly conducive for transportation between Phimai region and Angkor Region. This current study further emphasizes that Ta Muen is the most suitable pass for accessing the moated sites or ancient communities within the region.

In addition, in the Ban Kruat District, situated close to the Sai Taku pass, numerous evidence of material production were found: iron smelting (slag heaps) and glazed ceramic productions (brown-graze were and Khmer ceramics; Thammapreechakorn, 2010). Archaeological investigations demonstrate that iron smelting began in late Prehistory (AD 200-400) before later joined by the ceramic production in the 11th century (Brown, 1988; Prommanoj & Pichaichumphon, 1989). This industrial locale is situated along the Angkorian Northwest route as evidenced by local resthouse (Prasat Thmor). At the beginning of this PhD research, although iron smelting was thought to have been continued into the Angkorian period, no solid evidence was identified until the excavation at Ban Nong Chik Krachai by Fine Arts Department in 2021 brought the Angkorian iron smelting in Ban Kruat into light (Yukongdi et al., 2022).

The locations of these two productions show that they were located along the local stream system (tributaries of the Lam Chi River flowing northeastwardly to join the Mun River). When comparing with the LCP model of the Ta Muen pass, the LCP route clearly traverse the zones of iron-smelting and pottery production sites, meaning that during the Angkorian period, any person who journeyed on this Northwest route would pass through this industrial locale. Moreover, a number of monuments along the LCP route implies that these monuments were situated near the road rather than in close proximity to the moated sites. This finding is consistent with the previous study by Welch (1998), which suggests that there is no relationship between moated sites and Khmer monuments.

To the issue of the chronological determination of iron smelting activity in Ban Kruat, archaeological works documented at least 40 slag deposits across the area, but only three deposits have so far been dated radiometrically. It should be noted that datable artefacts, i.e., characteristic ceramic sherds, were rare, obstructing obtaining relative dating of each slag deposits. Without the sound chronological determination for each slag deposits, this poses a challenge to the construction of the development of such metal production and how this production played a role in each period (Venunan, 2016). Being able to determine a date(s) for slag deposits will surely improve this situation. This leads to the second and third aims of this thesis involving the dating determination of slag deposits through iron smelting waste: slag and technical ceramics using OSL. Considering the smelting process, slag is an appropriate sample for OSL dating because it has undergone heating or exposure to light. This method can determine the time when the sample was last heated or exposed to light. The results of OSL measurements indicate that three out of five samples exhibit excellent OSL signals. On the other hand, the absence of an OSL signal in the remaining two samples could be attributed to the low presence of quartz, which is the luminescent mineral.

Furthermore, the most significant finding of this study is the relatively youngest age (the late 19^{th} century) of the ancient iron-smelting site, which had not been previously identified during the excavations. Based on the law of superposition, the slag samples were collected from the surface of the heap; therefore, the obtained age is to certain extent assumed to represent the final activity of ancient iron-smelting production in Ban Kruat.

The next objective is to determine the age of the BST7 site. In this case, technical ceramics that were exposed on the surface of the slag heap were collected, following the principle of superposition. The OSL dating of these technical ceramics yielded an approximate age of the 17^{th} century. This result aligns well with the age of the slag sample found in the same heap (Khamsiri et al., 2022). Therefore, by combining the dating results of both the slag samples and the technical ceramics, it can be concluded that this site represents a long-lasting ancient production site that existed from the Iron Age through the Angkorian Period and into the post-Angkorian Period.

5.2 Conclusion

This investigation has outlined the important knowledge of the ancient movement network and sheds new light of the investigation of transportation in Angkor territory and neighboring area. Based on the archaeological evidence, the NRR seems to linearly direct from Angkor to Phimai by using Ta Muen pass. This study emphasizes that, in addition to the Ta Muen pass, the Krang and Sai Taku passes have been identified through LCP analysis as the most suitable routes between the eastern part of lower Northeast Thailand and northwest Cambodia. Moreover, this investigation also highlights the significant correlation between the locations of Khmer monuments in northeastern Thailand and the potential ancient routes. It is also indicated that the presence of Khmer monuments in the region aligns with the ancient LCP routes, further supporting the importance of these routes in the transportation during that time. Therefore, this investigation not only provide the first LCP model of ancient movement in northeastern Thailand, but also could be implemented as a predicting model for the identification of possible monumental remains along the LCP-indicated routes.

In term of the chronological dating determination of the slag mound within the BST7 cluster, the results are able to provide chronometric dates or date range for the production site via the application of OSL dating of slag and technical ceramic. The analysis suggests that the iron smelting activity at BST7 might have been continued into the post-Angkorian periods, providing a new approach to directly date metallurgical remains from the metallurgical site in addition to the radiocarbon dating of carbon-based materials, especially charcoal. Moreover, these findings contribute substantially to the understanding of ancient metallurgical site at BST7 that the large size of this production relates to the long duration of the activity (the late Iron Age to Post Angkorian period) (Figure 5.1).

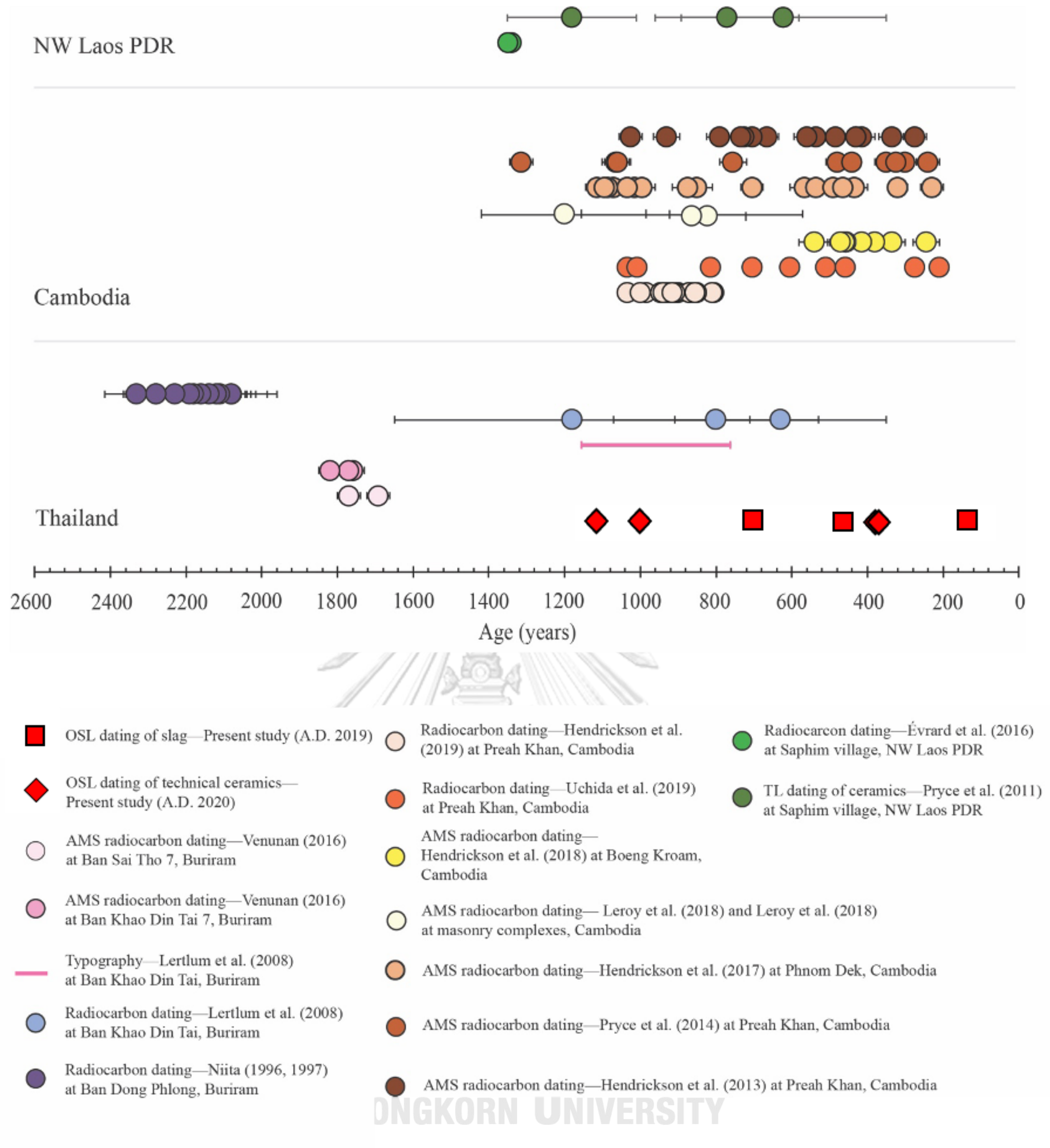

Figure 5.1 The illustration shows the ages of iron-smelting timespan in Buriram, Lao PDR and Cambodia from OSL dating of slag and furnace and tuyère samples, the AMS and conventional radiocarbon dating of charcoals and pottery typology.

5.3 Recommendation

1. As aforementioned, in terms of LCP analysis, the controlling factor of movement is crucial for greater accuracy. In some sites, such as Northeast Thailand, where evidence and information are scarce, it may be more appropriate to rely on basic and general factors to prevent researcher bias. However, when the beneficial data is discovered, it is

crucial to shift the focus of further study towards the paleoenvironment, specifically landuse and the remnants of ancient transportation.

2. Due to the limitation of this study, all moated sites were used to generate the ancient route. However, if more data regarding the age of each moated site becomes available, it would be advisable to conduct the LCP route after classifying the age of the moated sites. This additional step would provide further insights into the study.

3. In terms of OSL dating, there are some limitations to directly dating slag. Firstly, some samples seem to lose the OSL signal even though the sample includes quartz grains. The cause of this phenomenon is the quantity of quartz. Therefore, it is necessary to check the amount of quartz before dating.

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VITA

NAME	Sutthikan Khamsiri
DATE OF BIRTH	6 January 1996
PLACE OF BIRTH	Prachinburi
INSTITUTIONS ATTENDED	Chulalongkorn University
HOME ADDRESS	16/4, Moo 16, Ban Phra Subdistrict, Mueang Prachinburi District, Prachinburi province, 25000
PUBLICATION	1. Sriwichai, M., Rachanark, B., Assavapanuvat, P., Wattanachareekul, P., Makakum, C., Watcharamai, T., Ardkham, P., Chaikam, A., Phujareanchaiwon, C., Srisunthon, P., Leknettip, S., Kaewpaluk, S., Khamsiri, S., and Chawchai, S. (2018). Preliminary Study on Petrography and Geochemistry of Basaltic Rock in Central Phetchabun, Thailand. Bulletin of Earth Science of Thailand, (9)1. 44-54 2. Khamsiri, Sutthikan, Pira Venunan, Chawalit Khaokheiw, Praon Silapanth, Sirittha Banron, and Santi Pailoplee. "Late iron-smelting production of Angkor Highland, metallurgical site at Buriram Province, northeastern Thailand: A view from luminescence dating." Archaeological Research in Asia 31 (2022): 100395. 10.1016/j.ara.2022.100395 3. Khamsiri, Sutthikan, Pira Venunan, Chawalit Khaokheiw, Praon Silapanth, Sirittha Banron, and Santi Pailoplee. "Luminescence dating of archaeometallurgical slag from Buriram Province, northeastern Thailand." SCIENCEASIA 48, no. 6 (2022): 788-796. 10.2306/scienceasia1513-1874.2022.114 4. Khamsiri, Sutthikan, Pira Venunan, Chawalit Khaokheiw, Praon Silapanth, and Santi Pailoplee. "Reconstructing the ancient route network in the Thailand-Cambodia borders: a case study of the Angkorian Royal Road". Archaeological Prospection (2023). https://doi.org/10.1002/arp.1897
AWARD RECEIVED	B.Sc. in Geology in the second honor class from the Faculty of Sciences at Chulalongkorn University in 2018