

Article

Study on Stone Blocks Used for Resthouses Along the Northwest Royal Road Connecting Angkor in Cambodia and Phimai in Thailand Based on On-Site Magnetic Susceptibility Measurements and Chemical Composition Analyses

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Abstract: The purpose of this paper was to identify the types of stone used in the “Resthouses” along the Northwest Royal Road connecting Angkor in Cambodia and Phimai in Thailand and to determine their sources through magnetic susceptibility measurements and chemical composition analyses. Laterite was the primary building material for the “Resthouses”, except for Pr. Ku Sila Khan in Thailand. Pr. Ku Sila Khan, located at the northernmost point of the Northwest Royal Road, was primarily built with fine-grained red sandstone. Based on the magnetic susceptibility and the V, Sr, and As contents of the laterite, the following pairs of “Resthouses” were likely sourced from the same quarries: Pr. Sampov and Pr. Saman Teng, Pr. Kok Ac Chring and Pr. Kok Mon, Pr. Ta Muan and Pr. Thamo, and Pr. Ban Bu and Pr. Non Kong. Fine-grained red sandstone, white siliceous sandstone, red siliceous sandstone, and gray sandstone were used for the frame material of the openings. The Rb vs. Ti diagram and magnetic susceptibility measurements suggest that the fine-grained red sandstone and siliceous white sandstone used in the “Resthouses” in Thailand were likely sourced from the Khok Kruat Formation and the Phu Phan Formation, respectively. However, the red siliceous sandstone and white siliceous sandstone used in the “Resthouses” in Cambodia are presumed to have been sourced from the Sao Khua Formation and the Phra Wihan Formation, respectively. Gray sandstone from the Phu Kradung Formation was uniquely used in the frame material of the openings of Pr. Sampov and Pr. Kok Mon in Cambodia. In conclusion, the sandstone used in the door and window frames of the “Resthouses” appears to have been determined by the surrounding geology. Laterite was used as the primary building material for the “Resthouses” along the Northwest Royal Road, whereas valuable sandstone was used for those along the East Royal Road. This suggests that the Northwest Royal Road was of lesser importance compared to the East Royal Road.

Keywords: Northwest Royal Road; Khmer monument; resthouse; laterite; sandstone; Khorat Group; Cambodia; Thailand



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1. Introduction

There are five Royal Roads connecting provincial cities to Angkor in Cambodia: the East Royal Road connecting to the Bakan monument (Preah Khan of Kompong Svay),

the Northeast Royal Road to Prasat (Pr.) Wat Phu (Laos), the Southeast Royal Road to the Sambor Prei Kuk monument (Cambodia), the Northwest Royal Road to Pr. Phimai (Thailand), and the West Royal Road to Pr. Sdok Kok Thom or Pr. Muang Singh (Thailand). The Royal Roads are believed to have been developed by Jayavarman VII (late 12th century to early 13th century). However, based on the magnetic susceptibility of the sandstone blocks, Uchida et al. [1] concluded that the East Royal Road already existed during the early Angkor Wat period (end of the 11th century). Among the five Royal Roads, the most important ones are the East Royal Road and the Northwest Royal Road. Along the East Royal Road, which connects the Angkor area to the Bakan monument (Preah Khan of Kompong Svay), sandstone structures called “Temples d’étape” and “Resthouses, Fire Shrines, or Fire Houses” were constructed approximately every 15 km. Along the Northwest Royal Road, which extends to Pr. Phimai in Thailand, there are sixteen “Resthouses”. These structures do not exist along other Royal Roads. Research on “Temples d’étape” and “Resthouses” along the East Royal Road has previously been conducted, and the results published by Uchida et al. [1] revealed the supply range of sandstone blocks and the construction period.

Lunet de Lajonquière [2] described “Resthouses” as shelters intended for pilgrims. Foucher [3] suggested the term “Dharmaçālā” in Sanskrit for these structures, drawing a parallel with similar buildings in India. Aligning with the interpretation of these “Resthouses” as “Dharmaçālā”, Finot [4] argued that they served as houses of charity (Maisons de Charité), pointing to the Lokeshvara sculpture on their pediments as evidence. Coedès [5], on the other hand, identified them as “Fire Houses” (Maisons du Feu) based on inscriptions found at Preah Khan temple in Angkor (K.908), which document a total of 121 “Resthouses (Fire Houses)”. Various researchers, including Welch [6], Jacques and Lafond [7], and Hendrickson [8], have discussed this type of structure. The “Resthouses” are single buildings measuring approximately 4 to 5 m in width and 14 to 15 m in length [8,9]. Due to their relatively low construction quality, simple carvings, and stylistic elements, they are believed to have been built during the Bayon period (1182–1270 CE) by King Jayavarman VII.

This study focuses on investigating the construction materials of the following sixteen “Resthouses” along the Northwest Royal Road, which extends from the Angkor area in Cambodia to Pr. Phimai in Thailand: Pr. Sampov, Pr. Saman Teng, Pr. Kok Ac Chring, Pr. Kok Mon, Pr. Ta Kill, Pr. Ampil, Pr. Kok Phnov, Pr. Ta Muan, Pr. Thamo, Pr. Ban Bu, Pr. Non Kong, Pr. Nong Phlong, Pr. Non Ta Plaeng, Pr. Samrong, Pr. Huai Kaen, and Pr. Ku Sila Khan. Regarding the Northeast Royal Road, studies have been conducted by Lertlum and Shibayama [10], who used satellite images to identify the Royal Road itself and the locations of the associated “Resthouses”. To date, no research has been conducted on the stone blocks used as construction materials for the “Resthouses” along this route. Therefore, the aim of this study is to investigate the stones used in these “Resthouses” and to deduce the supply range and sources of the stone blocks, which are the primary construction materials. In addition to this, we will discuss the importance of the Northwest Royal Road and the East Royal Road, which have the “Resthouses”, based on the stone materials used.

2. Methods

This investigation was carried out without damaging the building stone. For each “Resthouse”, the following analyses were conducted: (1) a classification of the stones used, (2) measurements of the dimensions of the stone blocks, (3) magnetic susceptibility measurements using a portable magnetic susceptibility meter, and (4) chemical composition analyses using a portable X-ray fluorescence analyzer.

The longitude, latitude, and altitude above sea level of each “Resthouse” were recorded using a GPS device (eTrex Venture, Garmin Ltd., Schaffhausen, Switzerland).

Magnetic susceptibility measurements of the construction materials (laterite and sandstone) were carried out using a portable magnetic susceptibility meter (SM30, ZH Instruments, Brno, Czech Republic). These measurements were conducted non-destructively and on-site. The measurement coil had a 5 cm diameter. The magnetic susceptibility was measured on clean, smooth surfaces of laterite and sandstone, free from algae and lichen, and then in the air (Mode A). Each measurement took approximately 2–3 s, with an accuracy of about 0.001×10^{-3} SI units. From each “Resthouse”, 50 laterite blocks (excluding Pr. Ku Sila Khan) and 6 to 50 sandstone blocks were measured, and the average values for each material at each “Resthouse” were calculated. Taking measurements with a portable magnetic susceptibility meter is both rapid and highly accurate, making it a useful method for measuring the magnetic properties of stone materials. This approach is extremely effective for distinguishing between different types of stone, identifying the construction sequence, and even determining the source of the stone materials. For more information about the methodology of magnetic susceptibility measurements and their effectiveness, see William-Thorp and Thorp [11], William-Thorp et al. [12,13], Alva-Valdivia et al. [14], and Tanikawa et al. [15].

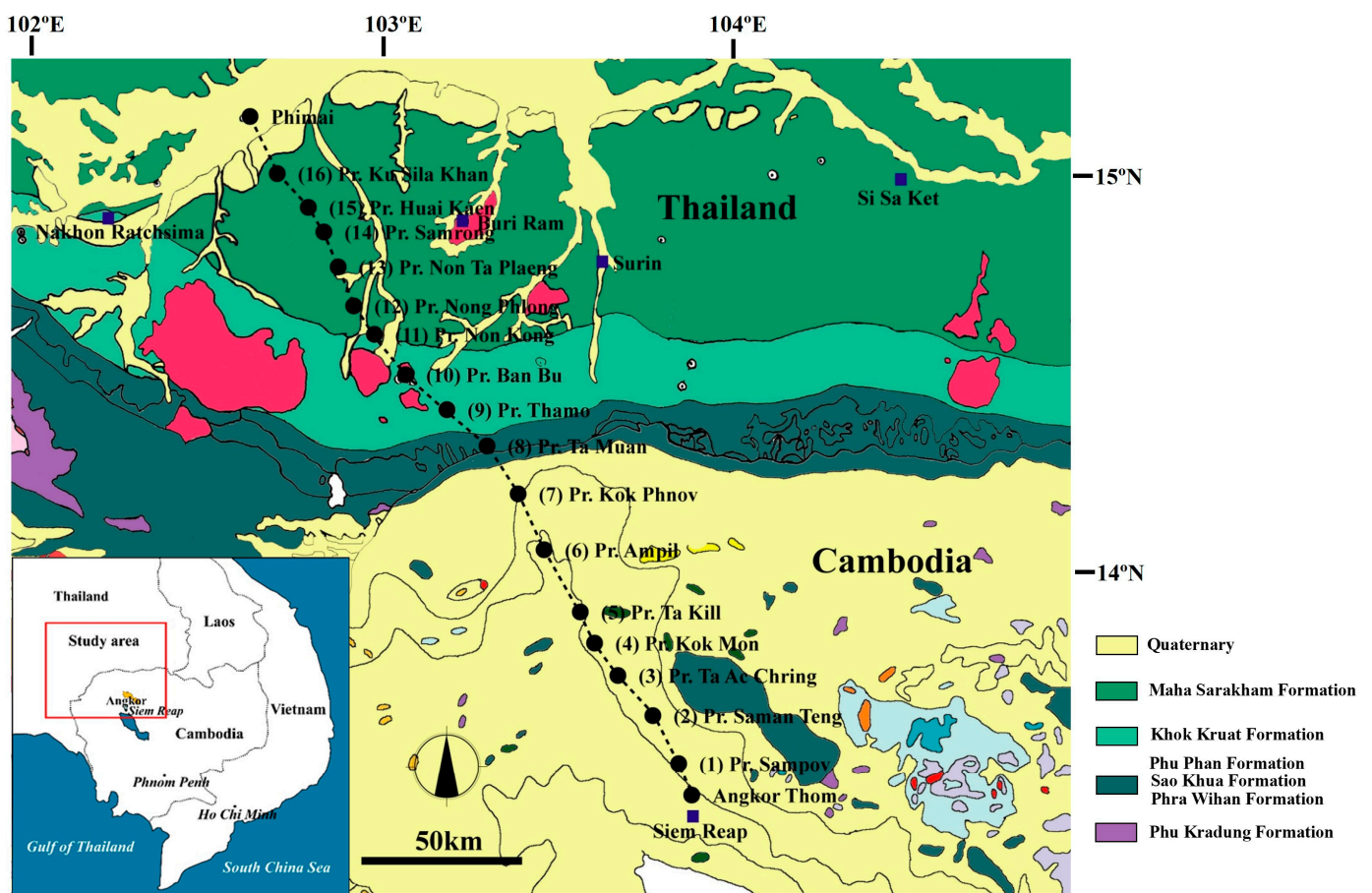
The chemical compositions of the laterite and sandstone materials were analyzed non-destructively and on-site using a portable X-ray fluorescence analyzer (Delta Premium DP-4000-C, Innov-X Systems Inc., Waltham, MA, USA). Rhodium (Rh) was used as an X-ray tube target, with a tube voltage of 15 kV for light elements and 40 kV for heavy elements. The beam diameter of the X-ray was approximately 10 mm. The measurements were performed in “soil mode”, with each measurement lasting approximately one minute. The X-ray fluorescence analyzer was powered by a lithium-ion battery, providing about four hours of operation per charge. According to the instrument manual, the detection limits for the elements used in this study are as follows: Sr, 1 ppm; Rb, 1 ppm; Zr, 1 ppm; As, 1–3 ppm; Ti, 7–15 ppm; V, 5–15 ppm. Prior to measurement, the device was calibrated using ten Japanese igneous rock standard samples (JA-1, JA-2, JB-1b, JB-2, JB-3, JG-1a, JG-2, JGb-1, JR-1, and JR-2) [16]. Each time the device was powered on, it was standardized with stainless steel 316SS. Measurements were taken on smooth, alga- and lichen-free surfaces, which were cleaned with a toothbrush. For each temple, measurements were conducted on five blocks each of laterite and sandstone, and the average values for the laterite and sandstone blocks were calculated for each “Resthouse”. A portable XRF analyzer is useful for performing a non-destructive, on-site chemical composition analysis of rocks, metals, and other materials, and the latest instruments can analyze trace elements, including rare earth elements. In this regard, the application of a portable XRF analyzer in cultural heritage research is extremely beneficial. For more information about the methodology of the portable X-ray fluorescence analyzer, consult Potts and West [17], Mendoza Cuevas et al. [18], and Tykot [19].

3. Results

The longitude, latitude, and altitude above sea level of each studied “Resthouse” are presented in Table 1. The locations of the “Resthouses” are shown in Figure 1, and typical photographs of each “Resthouse” are provided in Figure 2.

Table 1. Longitude, latitude, and altitude above sea level of the investigated “Resthouses” along the Northwest Royal Road.

	Resthouse	Latitude	Longitude	Altitude
Thailand	Ku Sila Khan	N 15°04'48.3"	E 102°36'11.4"	233 m
	Huai Kaen	N 14°58'47.6"	E 102°42'47.2"	175 m
	Samrong	N 14°55'59.2"	E 102°45'14.2"	205 m
	Non Ta Plaeng	N 14°48'44.7"	E 102°47'49.9"	187 m
	Nong Phlong	N 14°43'05.3"	E 102°50'11.2"	186 m
	Non Kong	N 14°38'32.8"	E 102°54'20.0"	174 m
	Ban Bu	N 14°32'01.5"	E 102°58'45.4"	164 m
	Thamo	N 14°27'16.4"	E 103°07'37.3"	177 m
	Ta Muan	N 14°21'20.9"	E 103°15'30.9"	194 m
Cambodia	Kok Phnov	N 14°13'46.5"	E 103°20'32.0"	55 m
	Ampil	N 14°04'44.2"	E 103°24'57.7"	35 m
	Ta Kill	N 13°54'30.6"	E 103°31'49.3"	24 m
	Kok Mon	N 13°49'57.8"	E 103°34'38.4"	36 m
	Kok Ac Chring	N 13°44'39.2"	E 103°38'47.8"	35 m
	Saman Teng	N 13°37'45.6"	E 103°45'26.3"	32 m
	Sampov	N 13°30'20.6"	E 103°49'48.8"	30 m

**Figure 1.** Locations of the “Resthouses” along the Northwest Royal Road on a geological map of Thailand and Cambodia, compiled from maps from the Geological Survey of Vietnam [20] and the Department of Mineral Resources of Thailand [21].

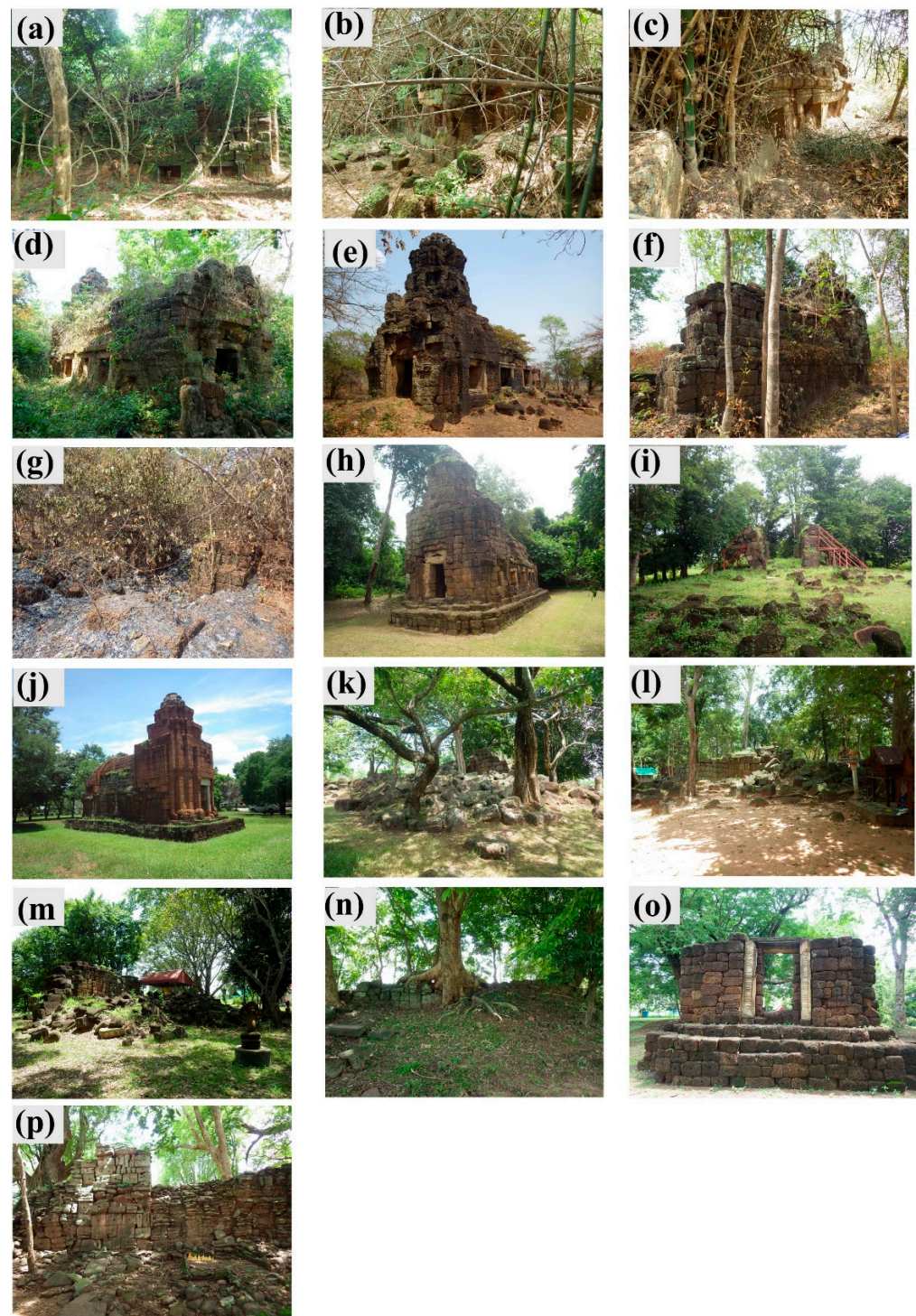


Figure 2. Photographs of the investigated “Resthouses” along the Northwest Royal Road: (a) Pr. Sampov, (b) Pr. Saman Teng, (c) Pr. Kok Ac Chring, (d) Pr. Kok Mon, (e) Pr. Ta Kill, (f) Pr. Ampil, (g) Pr. Kok Phnov, (h) Pr. Ta Muan, (i) Pr. Thamo, (j) Pr. Ban Bu, (k) Pr. Non Kong, (l) Pr. Nong Phlong, (m) Pr. Non Ta Plaeng, (n) Pr. Samrong, (o) Pr. Huai Kaen, and (p) Pr. Ku Sila Khan.

The “Resthouses” in Cambodia are in lowland areas (24–55 m above sea level). In contrast, the “Resthouses” in Thailand are situated on the Khorat Plateau at relatively high elevations, ranging from 164 to 233 m above sea level.

3.1. Description of Each “Resthouse”

The types of stone used in the sixteen investigated “Resthouses” are summarized in Figure 3.

	Cambodia							Thailand								
	Sampov	Saman Teng	Kok Ac Chring	Kok Mon	Ta Kill	Ampil	Kok Phnov	Ta Muan	Thamo	Ban Bu	Nong Kong	Nong Phlong	Non Ta Plaeng	Samrong	Huai Kaen	Ku Sila Khan
Laterite																
Fine-grained red Sandstone (Koh Kruat F.)																
White siliceous sandstone (Phu Phan F.)																
Red siliceous sandstone (Sao Khua F.)																
White siliceous sandstone (Phra Wihan F.)																
Gray sandstone (Phu Kradung F.)																

Figure 3. A summary of the types of stone used in the investigated “Resthouses”. Laterite was the primary building material in the “Resthouses”, except for Pr. Ku Sila Khan. Uniquely, fine-grained red sandstone was the main building material at Pr. Ku Sila Khan. Additionally, small amounts of red or white siliceous sandstone, fine-grained red sandstone, and gray sandstone were used for the frame materials of the openings of the “Resthouses”. The sandstones are listed in order from the upper formation to the lower formation. The thicker the line is, the greater the usage.

3.1.1. Pr. Sampov

The level of collapse of the building is not significant, but the lower part, about 1 m, is buried in the soil. It was built with laterite. Gray sandstone was mainly used for the door and window frame materials, although some parts were built with red siliceous sandstone.

3.1.2. Pr. Saman Teng

The building was built with laterite. The eastern side has almost completely collapsed, and some siliceous sandstone can be observed.

3.1.3. Pr. Kok Ac Chring

This building was primarily built with laterite. About 1 m of the lower part of the building is buried in the soil. Most of the roof has collapsed. Siliceous sandstone was used in the frames of the door and window openings.

3.1.4. Pr. Kok Mon

The state of preservation is relatively good. The building was built with laterite. Siliceous sandstone and gray sandstone were used in the door and window openings.

3.1.5. Pr. Ta Kill

This building was built with laterite. The state of preservation is good. About 1 m of the lower part is buried in the soil. Siliceous sandstone was used for the frame materials of the door and window openings. The surface of the laterite has turned black. The portable X-ray fluorescence analyzer identified manganese as the main component, with more than 20 wt.% Mn. A similar phenomenon of surface blackening on sandstone, laterite, and brick materials caused by manganese oxide has been observed at the Angkor and Koh Ker monuments in Cambodia [22]. Observations using FE-SEM revealed bacterial shapes, suggesting the involvement of manganese-oxidizing bacteria in this blackening process [22]. Siliceous sandstone was used for the frame materials of the door and window openings.

3.1.6. Pr. Ampil

This building was primarily built with laterite. The eastern part of the building has severely collapsed.

3.1.7. Pr. Kok Phnov

This building was built with laterite. The collapse is severe, and the structure has almost lost its original form. Siliceous sandstone, which appears to have been used for the frame materials of the door and window openings, is scattered around.

3.1.8. Pr. Ta Muan

This “Resthouse” was primarily constructed of laterite. Siliceous white sandstone was used for the frames of the door and window openings. The roof on the eastern side has collapsed.

3.1.9. Pr. Thamo

Only the northern and southern walls remain. It was primarily constructed of laterite, with white siliceous sandstone used for the door and window frames.

3.1.10. Pr. Ban Bu

This “Resthouse” was restored by the Fine Arts Department of Thailand about 30 years ago and remains almost completely intact. The main building material was laterite, and white siliceous sandstone was used for the frames of the door and window openings.

3.1.11. Pr. Non Kong

The building has almost completely collapsed. The main building material was laterite, with a few scattered pieces of white siliceous sandstone that were likely used for the frames of door and window openings.

3.1.12. Pr. Nong Phlong

This building has collapsed except for part of the northern wall. The structure was built with laterite, and some white siliceous sandstone pieces are scattered around.

3.1.13. Pr. Non Ta Plaeng

This building has collapsed except for the northern wall. The structure was built with laterite. Some white siliceous sandstone and fine-grained red sandstone, which were likely used for the frames of door and window openings, can be observed.

3.1.14. Pr. Samrong

The building has mostly collapsed. Although it was mainly constructed of laterite, fine-grained red sandstone was used in some parts of the eastern side and for the frames of door and window openings.

3.1.15. Pr. Huai Kaen

The upper structure has collapsed. It was mainly constructed of laterite, but fine-grained red sandstone was extensively used in the eastern part. White siliceous sandstone was used for the frames of door and window openings.

3.1.16. Pr. Ku Sila Khan

The building has almost completely collapsed except for the northern wall. The building material was fine-grained red sandstone, and unlike in the other “Resthouses”, laterite was not used.

3.2. Size of Laterite and Sandstone Blocks

Except for Pr. Ku Sila Khan, where fine-grained red sandstone was the main building material, laterite was the primary stone material in the “Resthouses”. Figure 4 and Table 2 show the average widths and thicknesses of the main stone blocks (laterite and fine-grained red sandstone) (Supplementary Material Table S1). Based on the measurements, the stones had widths of approximately 46–56 cm and thicknesses of about 27–39 cm, with no significant differences observed among the “Resthouses”.

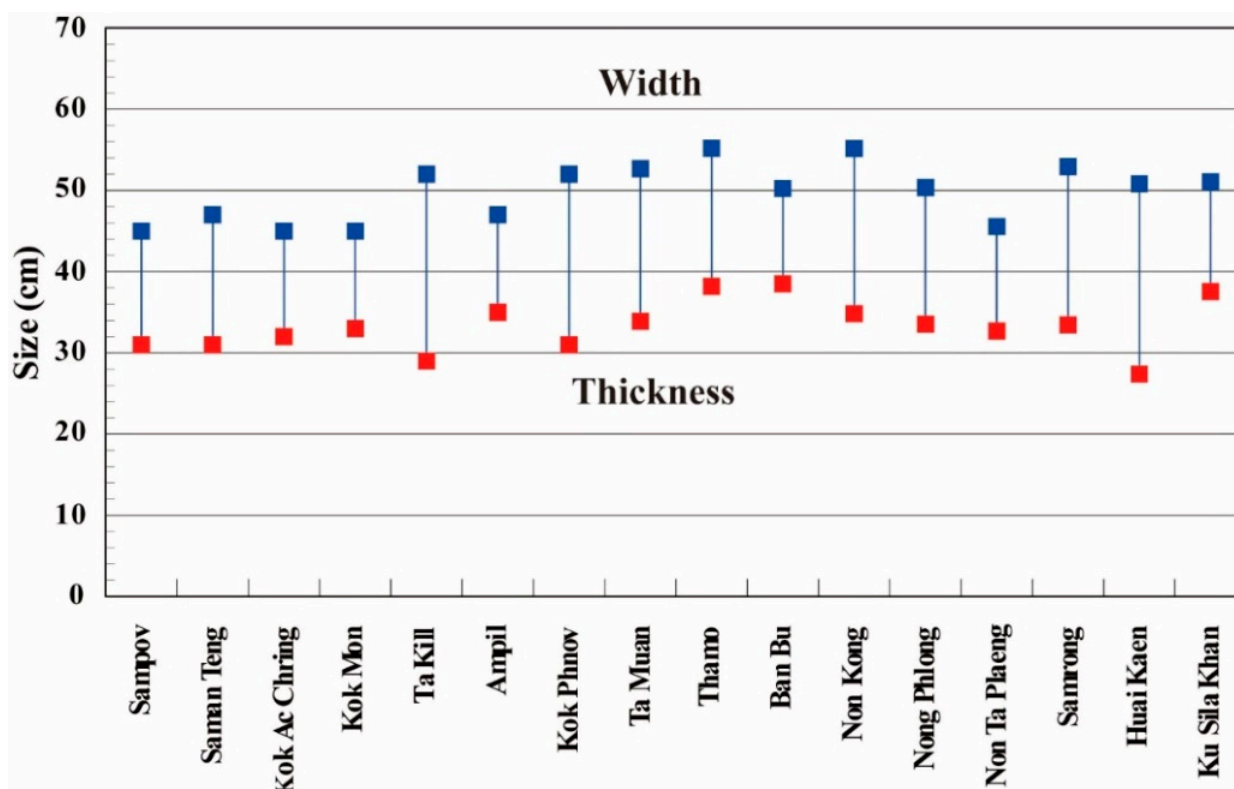


Figure 4. A width vs. thickness diagram for primary stone blocks used in the “Resthouses” along the Northwest Royal Road. The size of the primary stone blocks is not necessarily uniform, but they fall within a range of 46–56 cm in width and 27–39 cm in thickness.

Table 2. The average magnetic susceptibility, chemical composition, and size of laterite and sandstone blocks used in the “Resthouses” along the Northwest Royal Road in Cambodia and Thailand.

Laterite																	
Resthouse	Sampov	Saman Teng	Kok Ac Chring	Kok Mon	Ta Kill	Ampil	Kok Phnov	Ta Muan	Thamo	Ban Bu	Non Kong	Nong Phlong	Non Ta Plaeng	Samrong	Huai Kaen	Ku Sila Khan	
MS * (10 ⁻³ SI)	0.372	0.532	1.045	1.160	0.271	0.455	0.261	0.457	0.518	1.263	0.953	1.072	1.193	0.293	0.804		
Sr (ppm)	96.7	86.1	70.23	55.3	65	129.5	54.5	22.1	22.7	65.8	46.8	19.5	63.6	58.1	49.7		
As (ppm)	105.7	62.9	38.3	28.1	14.8	27.7	144.7	68.5	55.1	24.1	38.8	22.4	25.8	34.7	35.7		
V (ppm)	564	740	1055	503	1259	2288	895	1357	1098	1380	1013	63	961	759	1795		
Width (cm)	44.6	47.4	44.6	45.2	51.5	46.6	52.2	52.7	55.2	50.2	55.2	50.4	45.6	52.9	50.8		
Thickness (cm)	30.7	30.9	31.8	33.2	29.1	34.8	30.8	33.9	38.2	38.5	34.8	33.5	32.7	33.4	27.4		
Red siliceous sandstone								Fine-grained red sandstone									
Formation			Sao Khua Formation						Koh Kruat Formation								
Resthouse	Sampov	Saman Teng	Kok Ac Chring	Kok Mon	Ta Kill	Ampil	Kok Phnov	Ta Muan	Thamo	Ban Bu	Non Kong	Nong Phlong	Non Ta Plaeng	Samrong	Huai Kaen	Ku Sila Khan	
MS * (10 ⁻³ SI)	0.037 **	0.024 **	0.034 **	0.039 **	0.040 **	0.032 **	0.030 **						0.102	0.105	0.083	0.109	
Rb (ppm)	14.1	15.7	15.9	15.9	24.4	18.5							40.2	48.3	41.1	40.6	
Sr (ppm)	32.6	31.6	46.6	52.9	50.2	51.9							71.4	62.8	82.5	59.4	
Ti (ppm)	2534	1876	2128	3400	3191	2045							2100	2358	2056	2570	
Zr (ppm)	136	147	117	215	165	123							240	226	207	300	
Width (cm)																51.1	
Thickness (cm)																37.6	
White siliceous sandstone																	
Formation			Phra Wihan Formation						Phu Phan Formation								
Resthouse	Sampov	Saman Teng	Kok Ac Chring	Kok Mon	Ta Kill	Ampil	Kok Phnov	Ta Muan	Thamo	Ban Bu	Non Kong	Nong Phlong	Non Ta Plaeng	Samrong	Huai Kaen	Ku Sila Khan	
MS * (10 ⁻³ SI)		0.024 **	0.034 **	0.039 **	0.040 **	0.032 **	0.030 **	0.038	0.024	0.024	0.036	0.031	0.026		0.022		
Rb (ppm)			26.3	31.2	36.5	50.1	45.6	14.9	9.1	6.8	6.7	19.5	10.1		9.7		
Sr (ppm)			20.1	36.2	27.8	55.7	31.8	15.1	19.4	34.4	18.6	16.0	24.0		22.5		
Ti (ppm)			1627	1205	1689	1152	1411	1339	1342	1959	1432	1962	1350		1329		
Zr (ppm)			128	112	116	87	101	90	86	61	69	82	58		81		
Gray sandstone																	
Formation			Phu Kradung Formation														
Resthouse	Sampov	Saman Teng	Kok Ac Chring	Kok Mon	Ta Kill	Ampil	Kok Phnov										
MS * (10 ⁻³ SI)	2.960			2.160													
Rb (ppm)	81.8			70.7													
Sr (ppm)	197			236													
Ti (ppm)	3363			3558													
Zr (ppm)	231			212													

* Magnetic susceptibility, ** Average magnetic susceptibility for red sliceous sandstone and white siliceous sandstone.

3.3. Results of Magnetic Susceptibility Measurements and Chemical Composition Analyses

3.3.1. Laterite

The average magnetic susceptibility of laterite ranged from 0.26 to 1.26×10^{-3} SI units (Figure 5, Table 2, and Supplementary Material Table S2). At Pr. Sampov, Pr. Saman Teng, Pr. Ta Kill, Pr. Ampil, Pr. Kok Phnov, Pr. Ta Muan, Pr. Thamo, and Pr. Samrong, the magnetic susceptibility was lower compared with other “Resthouses”, with values between 0.26 and 0.53×10^{-3} SI units. Based on the data of magnetic susceptibility and the contents of V, Sr, and As (Table 2), it is inferred that the laterite blocks used in the following pairs of structures were supplied by the same quarries: (a) Pr. Sampov and Pr. Saman Teng, (b) Pr. Kok Ac Chring and Pr. Kok Mon, (c) Pr. Ta Kill and Pr. Ampil, (e) Pr. Ta Muan and Pr. Thamo, and (f) Pr. Ban Bu and Pr. Non Kong (Figure 5).

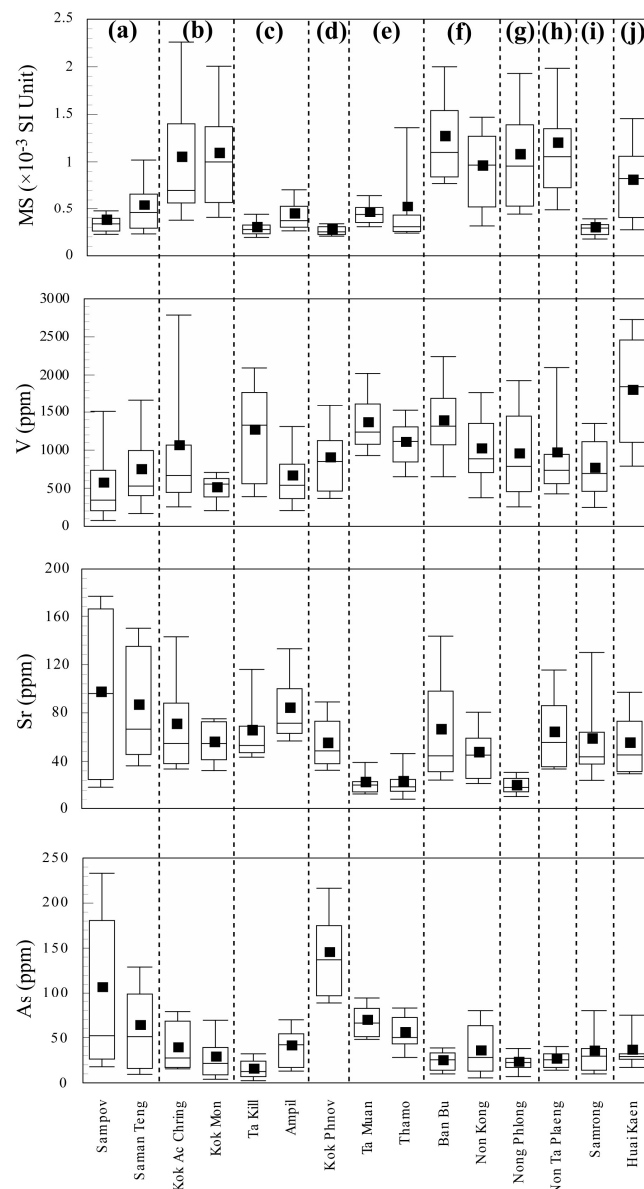


Figure 5. Box diagrams showing the magnetic susceptibility and the contents of V, Sr, and As of laterite used in the investigated “Resthouses”, except for Pr. Ku Sila Khan, where no laterite was used. Based on these data, it is inferred that the laterite blocks used in the following pairs of structures were supplied by the same quarries: (a) Pr. Sampov and Pr. Saman Teng, (b) Pr. Kok Ac Chring and Pr. Kok Mon, (c) Pr. Ta Kill and Pr. Ampil, (e) Pr. Ta Muan and Pr. Thamo, and (f) Pr. Ban Bu and Pr. Non Kong.

3.3.2. Sandstone

The magnetic susceptibility values of the various sandstones used in the “Resthouses” are summarized in Table 2 and Supplementary Material Table S2.

For the white siliceous sandstone and red siliceous sandstone used in the “Resthouses” in Cambodia, the average magnetic susceptibility ranged from 0.02 to 0.04×10^{-3} SI units (Table 2). Gray sandstone was uniquely used in the frame material of door and window openings of Pr. Sampov and Pr. Kok Mon in Cambodia and had relatively high magnetic susceptibility of between 0.27 and 6.64×10^{-3} SI units (Table 2).

For the fine-grained red sandstone used in the “Resthouses” in Thailand, the variation in average magnetic susceptibility among the “Resthouses” was small, with values ranging from 0.08 to 0.11×10^{-3} SI units (Table 2). For the white siliceous sandstone used in the “Resthouses” in Thailand, the average magnetic susceptibility was low across all the “Resthouses”, with values between 0.02 and 0.04×10^{-3} SI units (Table 2).

3.4. Results of Chemical Composition Measurements

3.4.1. Laterite

In the case of the Angkor monuments, the contents of Sr, As, V, and Sb in laterite were found to be useful for estimating its sources [23]. However, since the content of Sb was below the detection limit of the portable XRF analyzer, only the contents of Sr, As, and V were measured in this study (Figure 5, Table 2, and Supplementary Material Table S3). Regarding Sr, the content was lower at Pr. Ta Muan, Pr. Thamo, and Pr. Nong Phlong. The content of As was higher at Pr. Sampov and Pr. Kok Phnov. Additionally, the content of V was higher at Pr. Huai Kaen.

3.4.2. Sandstone

For sandstone, the focus was on the contents of Rb, Sr, Ti, and Zr.

For the white siliceous sandstone in Cambodia, the contents of Rb, Sr, Ti, and Zr were approximately 26–50, 20–56, 1150–1700, and 90–130 ppm, respectively. Regarding the red siliceous sandstone in Cambodia, the contents were about 14–24, 32–53, 1900–3400, and 120–220 ppm, respectively. The gray sandstone was the primary building material of the Angkor monument and exhibited specific ranges of Sr and Rb contents. The average contents of Sr and Rb of the gray sandstone used for the frame materials of Pr. Sampov and Pr. Kok Mon in Cambodia were in the ranges of 197–236 ppm and 71–82 ppm, respectively, which fall within the compositional range of the gray sandstone of the Angkor monument [24].

For the fine-grained red sandstone in Thailand, there were no significant differences in the average contents of Rb, Sr, Ti, and Zr among the “Resthouses”, with values of around 40–48, 59–83, 2100–2570, and 200–300 ppm, respectively (Table 2). Similarly, for the white siliceous sandstone in Thailand, there were no significant differences in the average contents among the “Resthouses”, with values of approximately 7–15, 15–34, 1330–1960, and 58–91 ppm, respectively (Table 2 and Supplementary Materials Table S3). The fine-grained red sandstone tended to have relatively high concentrations of Rb, Sr, Ti, and Zr compared with the white siliceous sandstone.

4. Discussion

The primary stone material used in the “Resthouses” was laterite, except at Pr. Ku Sila Khan, the northernmost structure, and Pr. Huai Kaen, the second-northernmost structure (Figure 3). At Pr. Ku Sila Khan, the entire structure is composed of fine-grained red sandstone. At Pr. Huai Kaen, the primary stone material is laterite; however, fine-grained red sandstone was used in the eastern part as the main building material. Similar sandstone

was also used extensively for the outer enclosure of Pr. Phimai, located at the terminus of the Northwest Royal Road. From this, it is inferred that the fine-grained red sandstone was likely sourced from the area around Pr. Phimai or Pr. Ku Sila Khan.

Except for at Pr. Ku Sila Khan, the primary building material of the “Resthouses” along the Northwest Royal Road is laterite. In contrast, for the “Resthouses” along the East Royal Road, gray sandstone is the main construction material. The gray sandstone used in Angkor monuments was transported from the foothills of Kulen Mountain, approximately 35 km northeast of the Angkor monument, making it a valuable material primarily used for the surfaces of buildings. On the other hand, laterite is widely exposed throughout Southeast Asia and is easier to procure than sandstone. Consequently, laterite tends to be used for less significant parts of structures, such as interiors, foundations, and causeways, in contrast to sandstone. These factors suggest that the Northwest Royal Road may have been of lower importance compared to the East Royal Road. Furthermore, the Northeast, Southeast, and East Royal Roads, which lack “Resthouses”, are inferred to have been even less significant than the East and Northwest Royal Roads.

Based on the magnetic susceptibility and the contents of V, Sr, and As in the laterite (Figure 5), it is inferred that the laterite used at the following pairs of structures was sourced from the same quarries: Pr. Sampov and Pr. Saman Teng, Pr. Kok Ac Chring and Pr. Kok Mon, Pr. Ta Muan and Pr. Thamo, and Pr. Ban Bu and Pr. Non Kong. For the other temples, it is estimated that the laterite was likely sourced from different quarries for each one.

In the “Resthouses” in Cambodia, white siliceous sandstone, red siliceous sandstone, and/or gray sandstone were used in the frame materials of the door and window openings. In the southernmost “Resthouses” in Cambodia, Pr. Sampov and Pr. Saman Teng, no white siliceous sandstone was found. In the northernmost “Resthouse” in Cambodia, Pr. Kok Phnov, no red siliceous sandstone was found. Gray sandstone was used in the frame material of the openings of Pr. Sampov and Pr. Kok Mon (Figure 3, Table 2).

Regarding the door and window frame materials in the “Resthouses” in Thailand, fine-grained red sandstone was used in the “Resthouses” north of Pr. Non Ta Plaeng. In contrast, white siliceous sandstone was used in the “Resthouses” south of Pr. Non Ta Plaeng, as well as at Pr. Huai Kaen (Figure 3)

The fine-grained red sandstone is estimated to have been sourced from the Khok Kruat Formation, based on its relatively high magnetic susceptibility [25] and the Rb vs. Ti diagram (Figure 6). Conversely, the white siliceous sandstone in Thailand is believed to have been sourced from the Phu Phan Formation, based on its low magnetic susceptibility [25] and the Rb vs. Ti diagram (Figure 6).

In contrast, the red siliceous sandstone and white siliceous sandstone used in the “Resthouses” in Cambodia is estimated to have been sourced from the Sao Khua Formation and the Phra Wihan Formation, respectively (Figure 6). Based on the Sr and Rb contents, the gray sandstone used for the frame materials of Pr. Sampov and Pr. Kok Mon is inferred to have been sourced from the Phu Kradung Formation [26].

The Khorat Group consists of the Huai Hin Lat, Phu Kradung, Phra Wihan, Sao Khua, Phu Phan, Khok Kruat, and Maha Sarakham Formations, from bottom to top [26,27]. The Phu Kradung Formation is referred to as the Red Terrain Formation in Cambodia [28]. Additionally, the Phra Wihan, Sao Khua, and Phu Phan Formations are collectively called the Upper Sandstone Formation in Cambodia [28]. The sandstones used for the construction of the “Resthouses” along the Northwest Royal Road were sourced from the Phu Kradung, Phra Wihan, Sao Khua, Phu Phan, and Khok Kruat Formations. The sandstones used in the “Resthouses” in Cambodia were sourced from the Phu Kradung, Phra Wihan, and Sao Khua Formations, while in the “Resthouses” in Thailand, the sandstones were sourced from the Phu Phan and Khok Kruat Formations. The “Resthouses” in Cambodia are in lowland

areas, whereas those in Thailand are situated in highland areas on the Khorat Plateau (Table 1). The Phu Phan and Kok Kruat Formations are observed around the “Resthouses” in Thailand, whereas the Phu Kradung, Phra Wihan, and Sao Khua Formations are present in the relatively low areas of Cambodia. Thus, it was concluded that the sandstones used in the “Resthouses” were determined by the surrounding geology (Figure 1).

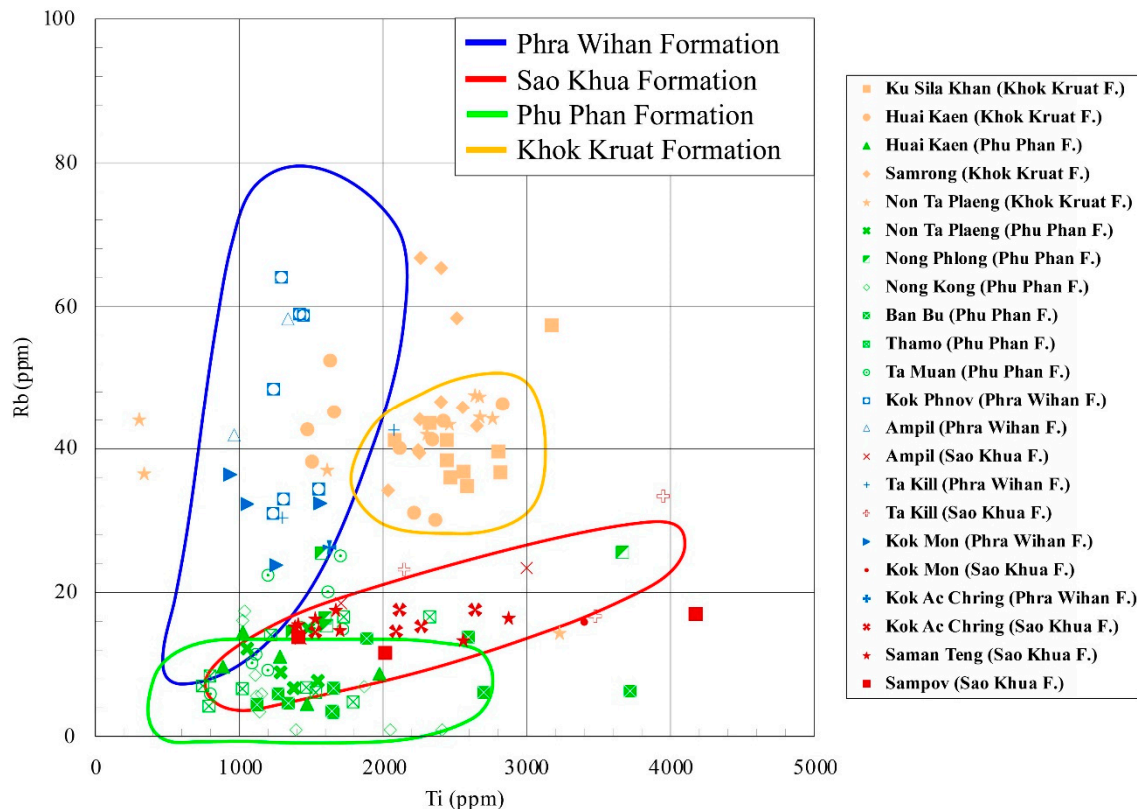


Figure 6. A Rb vs. Ti diagram to identify the formations that supplied the sandstones used in the “Resthouses”. The compositional range of the Phra Wihan Formation was indicated for the sandstones of Pr. Preah Vihear, that of the Sao Khua Formation was indicated for the sandstones of Pr. Banteay Srei, and that of the Khok Kruat Formation was indicated for the sandstones of Pr. Phimai. Additionally, the compositional range of the Phu Phan Formation was determined from the sandstone exposed on the upper part of Kulen Mountain.

5. Conclusions

1. Laterite was the primary building material of the “Resthouses” along the Northwest Royal Road, except for Pr. Ku Sila Khan in Thailand. At Pr. Ku Sila Khan, the northernmost “Resthouse”, fine-grained red sandstone served the main building material.
2. As the primary building material, laterite was used for the “Resthouses” along the Northwest Royal Road, whereas valuable sandstone was used for those along the East Royal Road. This suggests that the Northwest Royal Road was of lesser importance compared to the East Royal Road.
3. The laterite is inferred to have been sourced from at least ten different quarries, based on its magnetic susceptibility and V, Sr, and As contents.
4. The fine-grained red sandstone and white siliceous sandstone used for the door and window frames of the northern “Resthouses” in Thailand may have been sourced from the Khok Kruat Formation and the Phu Phan Formation, respectively.
5. The white siliceous sandstone, red siliceous sandstone, and gray sandstone used for the frame materials of the openings in Cambodia are deduced to have been sourced

from the Phra Wihan Formation, the Sao Khua Formation, and the Phu Kradung Formation, respectively.

6. The sandstone used in the door and window frames of the “Resthouses” appears to have been determined by the surrounding geology.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/heritage8030106/s1>, Table S1: Width and thickness of laterite and fine-grained red sandstone blocks used in the investigated “Resthouses” along the Northwest Royal Road; Table S2: Magnetic susceptibility of laterite and sandstone blocks used in the “Resthouses” along the Northwest Royal Road; Table S3: Chemical compositions of laterite and sandstone blocks obtained using a portable X-ray fluorescence analyzer.

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