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Supply ranges of stone blocks used in masonry bridges and their construction period along the East Royal Road in the Khmer Empire, Cambodia

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Abstract

During the Angkor period, there were five Royal Roads linking the capital city of Angkor with provincial principal cities. Seven Temples d'étape, six Fire Shrines, and 25 masonry bridges were constructed along the East Royal Road to Preah Khan of Kompong Svay. We conducted measurements of magnetic susceptibility and chemical composition of laterite blocks and magnetic susceptibility of sandstone blocks used for the construction of the bridges to determine the supply ranges of the stone blocks and the construction ages based on the results obtained in this study and previous studies of Temples d'étape and Fire Shrines. The results suggest that most of the sandstone blocks for the bridge balustrades were supplied from quarries in the southeastern foothills of Kulen Mountain, but that the bridges close to Preah Khan of Kompong Svay have sandstone balustrades supplied from nearby quarries. In contrast, cluster and principal component analyses and t-tests using data for chemical composition and magnetic susceptibility of laterite blocks revealed that there were five sources of supply. These results elucidated that the supply ranges of laterite blocks were narrower than those of the sandstone blocks. Judging from magnetic susceptibilities, supply ranges, shapes, orientations of bedding planes, and stacking methods of the stone blocks, it was concluded that the construction age of the bridges is highly likely to have been in the early Angkor Wat period.

Keywords: Khmer monuments, East Royal Road, Bridge, Laterite, Sandstone, Chemical composition, Magnetic susceptibility, Cluster analysis, Principal component analysis

Introduction

The Khmer monuments consist of Hindu or Buddhist temples widely distributed across Cambodia, Thailand, Laos, and Vietnam, constructed mainly from the 9th to the 13th centuries. Among them, the temples distributed in and around Siem Reap, Cambodia, are now called the Angkor monuments. The Angkor area was the center of the Khmer Empire and covers approximately 400 km². Conservation and restoration of the Angkor monuments

have been conducted since 1907, especially by the École Française d'Extrême-Orient (EFEO).

The buildings of the Angkor monuments were constructed mainly with sandstone and laterite blocks. Bricks were also used in the relatively old monuments constructed in the 9th and 10th centuries. The sandstones used in the Angkor monuments have been studied by Saurin [1], Delvert [2], Fusey [3], Uchida et al. [4, 5], and Carò and Im [6], and the laterites by Uchida et al. [7].

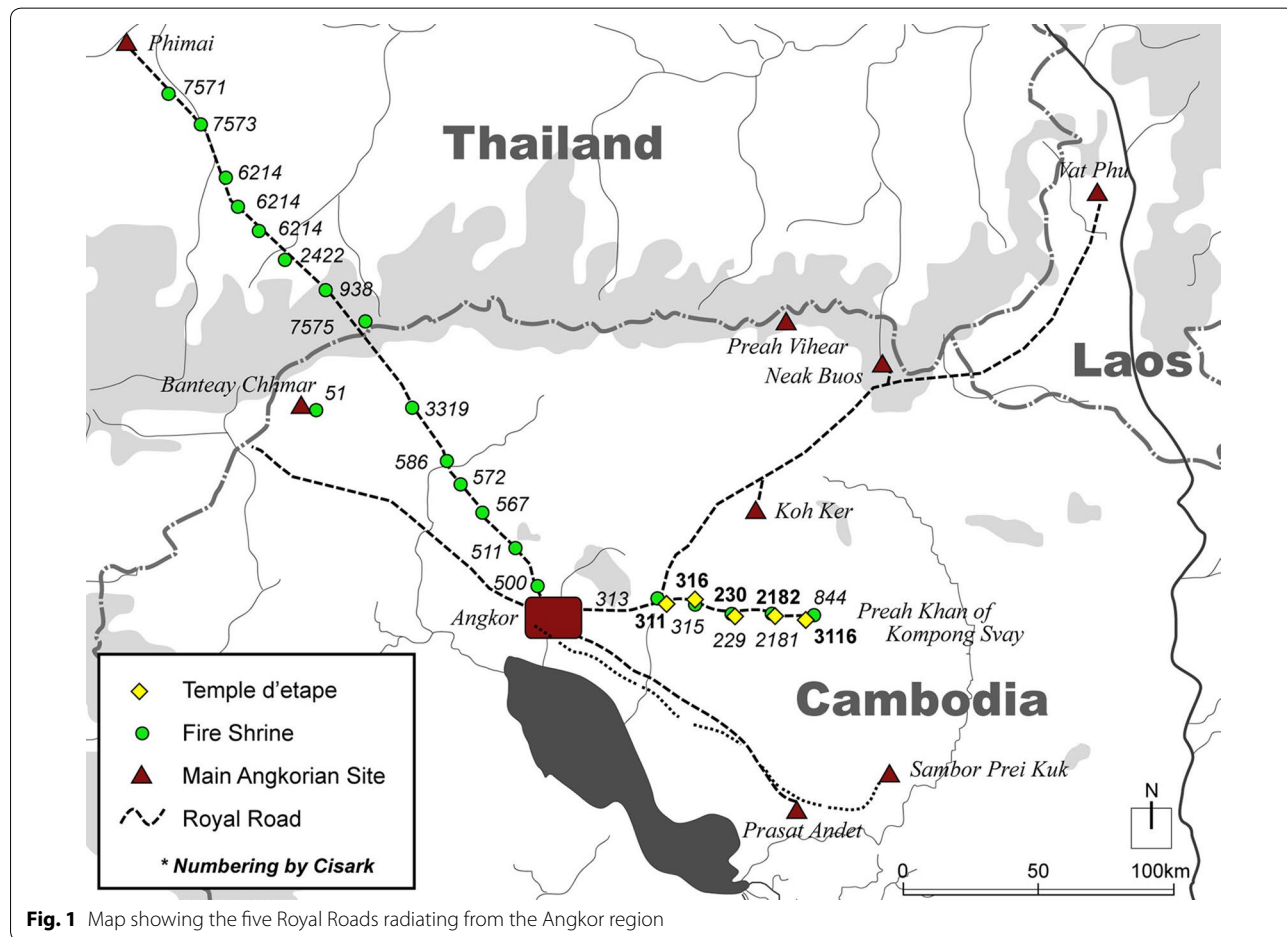
There were five Royal Roads connecting the capital city of Angkor to provincial cities: Preah Khan of Kompong Svay (East Royal Road) and Sambor Prei Kuk (South-east Royal Road) in Cambodia, Phimai (Northwest Royal Road) and Sdok Kok Thom (West Royal Road) in

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Thailand, and Wat Phu in Laos (Northeast Royal Road) (Fig. 1) [8]. Six Temples d'étape (from west to east, Prasat Banteay Ampil, Prasat Chrei, Prasat Trapeang Khnar, Prasat Pram, Prasat Supheap Tbong, and Prasat Trapeang Chambok), seven Fire Shrines (from west to east, Fire Shrine of Preah Khan, Fire Shrine of Ta Prohm, Prasat Kansaeng, Prasat Toap Chey, Prasat Ta En, Prasat Supheap Cheung, and Prasat Kuk), and 25 masonry bridges were constructed along the East Royal Road that connects with Preah Khan of Kompong Svay (Prasat Bakan), which is located approximately 95 km east of the Angkor area (Fig. 2). There were approximately 17 Fire Shrines built with laterite blocks but no Temples d'étape along the Northwest Royal Road [9, 10]. No Temples d'étape nor Fire Shrines exist along the other Royal Roads. These facts suggest the importance of the East Royal Road [11] compared with the other Royal Roads. Because many of the constructions along the East Royal Road were built with sandstone and/or laterite blocks, this Royal Road is useful for understanding the supply ranges of the sandstone and laterite blocks. Uchida et al. [12] conducted magnetic susceptibility measurements

using a portable magnetic susceptibility meter on sandstone blocks used for Temples d'étape and Fire Shrines along the East Royal Road, and reported on the supply ranges of sandstone blocks in the Angkor Wat period (the late 11th to middle 12th centuries) and the Bayon period (the late 12th to middle 13th centuries) when these buildings along the East Royal Road were constructed, respectively. Temples d'étape and Fire Shrines are located about every 14 to 15 km along the East Royal Road. Temples d'étape are of an Angkor Wat style consisting of a Central Sanctuary, two Libraries, two or three Gopuras, and an Enclosure wall of similar dimensions (32 to 33 m wide and 37 to 38 m long), and are only found along the East Royal Road. A Fire Shrine is also called Dharmaçalā, Teap Chei, Maison du charité, Gîte d'étape, Guest House or Resthouse [9, 13–21]. Fire Shrines built with sandstone blocks consist of a single building 4 to 5 m wide and 14 to 15 m long. In this study, non-destructive magnetic susceptibility measurements and chemical composition analyses were carried out for laterite and sandstone blocks used in the construction of the bridges along the East Royal Road, to clarify their supply ranges.



In addition, combining the results obtained in this study with those obtained previously by Uchida et al. [12] for the sandstone blocks in Temples d'étape and Fire Shrines, we investigate the construction age of the bridges along the East Royal Road.

There are 25 bridges built mainly of laterite blocks along the East Royal Road. Sandstone blocks were used for balustrades. The bridges have a corbel arch structure, in which laterite blocks are offset to meet at the apex of the archway. The sizes of the bridges vary, but many bridges are 10 to 30 m in length and 6 to 10 m in width. The largest bridge along the East Royal Road is Spean Ta Ong (no. 319, according to the Carte Interactive des Sites Archéologiques Khmers (CISARK; <http://cisark.mcfa.gov.kh/>), which was constructed over the Chikreng River at 65 m in length and 13 m in width (Fig. 3a). Several small bridges have no names, and several have the same name, “Spean Khmeng” (Fig. 2). According to Uchida et al. [7], two types of laterite can be distinguished in the Angkor monuments: porous laterite and pisolitic laterite. Both types of laterite consist mainly of the same minerals: goethite, hematite, kaolinite, and quartz. However, differences in the content of minor elements such as arsenic (As), antimony (Sb), vanadium (V), and strontium (Sr) were found between them. Porous laterite is relatively rich in Sr, As, and Sb, but is depleted in V. The laterite blocks used in the bridges in general show an intermediate texture between porous and pisolitic.

Sandstone blocks were used for the balustrades of the bridges, although many have been lost. Both ends of some balustrades were decorated with multi-headed Naga figures. The sandstone is gray to yellowish brown (feldspathic arenite) [4]. This sandstone occurs in the Red Terrain Formation (called the Phu Kradung Formation in

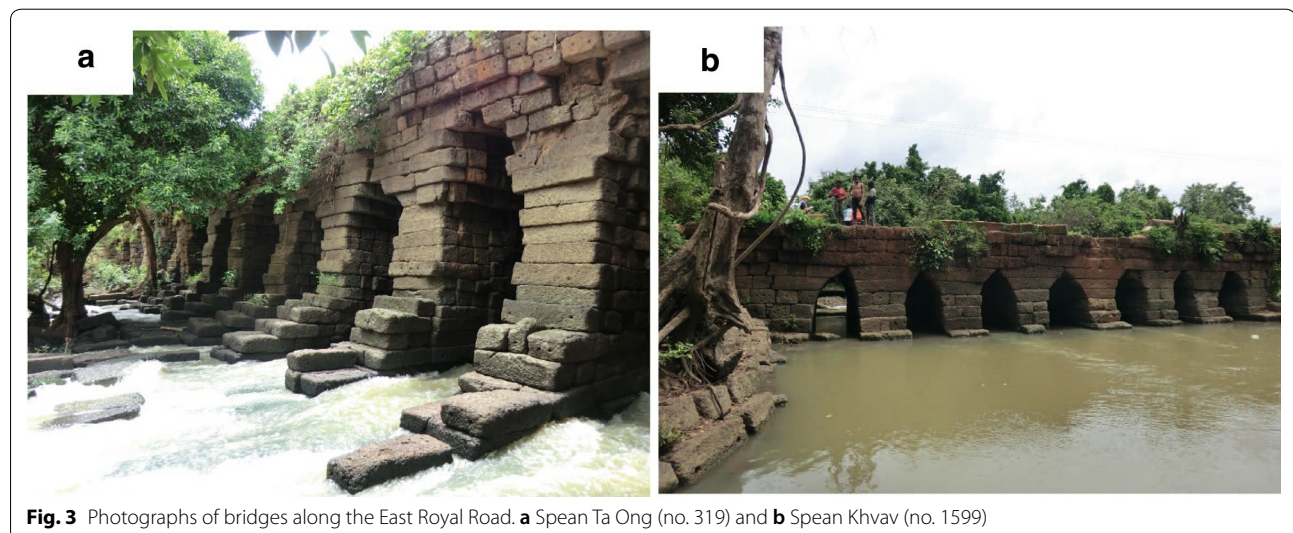
Thailand) of the Late Jurassic to Early Cretaceous [22], and was one of the most commonly used construction materials of the Angkor monuments. The sandstone was supplied from the southeastern foothills of Kulen Mountain, approximately 30 km northeast of the Angkor monuments [12]. Sandstone blocks were transported to the Angkor area using canals and rivers [12]. This is almost the shortest route from the quarry sites to the Angkor area, with a total distance of 34 km.

Previous studies

Bridge construction ages along the East Royal Road

Judging from the decorative style of the sandstone balustrades, Boisselier [23] considered that all the bridges along the East Royal Road were built during the reigns of Suryavarman I (1002–1049 CE) and Suryavarman II (1113–ca.1150 CE), that is, in the Khleang period and the Angkor Wat period, respectively. Groslier [16] suggested that the Naga balustrades were added by Jayavarman VII (1182–ca.1218 CE), and the bridges themselves predated that, except for a few. Bruguier [24] suggested that previously existing wooden bridges were burned by the Cham in 1177 CE and then rebuilt with stone blocks by Jayavarman VII. Based on a combination of node-networks, epigraphy, and architectural information, Hendrickson [8] inferred that the region along the East Royal Road was of great importance through the 12th century, and that the road system, including the bridges, was completed perhaps centuries before Jayavarman VII.

Decorations in various places, such as short pillars on the balustrades, are certainly similar to the Bayon style. In the Bayon period, it was common for Garuda to be engraved on the front of multi-headed Naga figures, but this composition is not found on the bridges along the



East Royal Road. Therefore, there is doubt in specifying this style. Furthermore, Buddha statues were engraved at the center of the hoods of multi-headed Naga, which are confirmed on bridge nos. 318, 319, and 1599 (CISARK; <http://cisark.mcfa.gov.kh/>). They are clearly due to modifications in the subsequent iconoclasm.

Magnetic susceptibilities of sandstone blocks used in Temples d'Étape, Fire Shrines and Preah Khan of Kompong Svay along the East Royal Road

Magnetic susceptibility measurements of sandstone blocks used in the construction of Temples d'Étape and Fire Shrines along the East Royal Road were carried out previously by Uchida et al. [25].

Preah Khan of Kompong Svay is located on the eastern end of the East Royal Road. Sandstone blocks with relatively high magnetic susceptibilities, ranging from 1.4 to 2.0×10^{-3} SI units, and some with low magnetic susceptibilities, ranging from 0.3 to 0.6×10^{-3} SI units, were used in this temple complex. Sandstone blocks with high magnetic susceptibilities were used in Prasat Kat Kdei, which is the oldest temple in Preah Khan of Kompong Svay, constructed in the late Khleang period (the early 11th to middle 11th centuries) as suggested by the inscription K.161, and also in the buildings in the central part of Preah Khan of Kompong Svay such as the Central Sanctuary, Gopuras of the Inner Gallery, and the Northern and Southern Libraries. This finding suggests that sandstone blocks with high magnetic susceptibilities were used for construction in the early period, and then sandstone blocks with low magnetic susceptibilities began to be used later. Because the average magnetic susceptibility of sandstone blocks used in Prasat Kat Kdei is 1.60×10^{-3} SI units, and the magnetic susceptibilities of sandstone blocks used in the Angkor monuments from the same period (the late Khleang period) range from 1.1 to 2.4×10^{-3} SI units (Uchida et al. [5]), it is inferred that sandstone blocks with high magnetic susceptibilities in Preah Khan of Kompong Svay came from quarries in the southeastern foothills of Kulen Mountain. The buildings in the central area where the high magnetic susceptibility sandstone blocks were used are inferred to have been constructed in the Angkor Wat period because the cross section of the sandstone blocks is close to square in shape, the orientation of the bedding planes is almost horizontal, and the sandstone blocks were stacked with coursed ashlar [26, 27]. Because the magnetic susceptibilities of the sandstone blocks from the Angkor Wat period in the Angkor region were initially low and increased over time from 1.1 to 5.6×10^{-3} SI units [5], it is inferred that these buildings were constructed in the early Angkor Wat period (Fig. 2). Sandstone blocks with low magnetic susceptibilities ranging from 0.3 to 0.6×10^{-3} SI units

were not used in the Angkor monuments, and are not found in the ancient quarries in the southeastern foothills of Kulen Mountain [12]. Therefore, it is inferred that sandstone blocks with low magnetic susceptibilities were supplied from somewhere near Preah Khan of Kompong Svay. We confirmed that sandstone with similar low magnetic susceptibilities is distributed in the southern foothills ($13^\circ 38' 24''$ N, $105^\circ 01' 11''$ E) of Tbeng Mountain, approximately 30 km northeast of Preah Khan of Kompong Svay [25]. The average magnetic susceptibility of sandstone blocks measured in the modern sandstone quarry along the road on the east side of Tbeng Mountain was as low as 0.5×10^{-3} SI units. This value is concordant with the magnetic susceptibility of sandstone blocks in the later period of Preah Khan of Kompong Svay. Because sandstone blocks with high as well as low magnetic susceptibilities are found in the Inner and Outer Galleries, and because even the sandstone blocks from the Angkor Wat period with high magnetic susceptibilities have relatively low values, ranging from 1.2 to 2.0×10^{-3} SI units, it is presumed that the change from the sandstone quarry with high magnetic susceptibilities to that with low magnetic susceptibilities occurred in the early Angkor Wat period [5].

Along the East Royal Road, there are six Temples d'Étape (from west to east, Prasat Banteay Ampil, Prasat Chrei, Prasat Toap Chey, Prasat Pram, Prasat Supheap Tbong, and Prasat Trapeang Chambok), which are thought to have been constructed in the Angkor Wat period [25]. The magnetic susceptibilities of the sandstone blocks in these buildings increased from west to east (from 2.84 to 4.48×10^{-3} SI units) [25]. In contrast, the magnetic susceptibilities of sandstone blocks from Prasat Trapeang Chambok at the eastern end are low (0.39×10^{-3} SI units), similar to those with low magnetic susceptibilities in Preah Khan of Kompong Svay. The change in magnetic susceptibilities of the sandstone blocks from Prasat Banteay Ampil to Prasat Supheap Tbong is similar to that in the magnetic susceptibilities of sandstone blocks in the early Angkor Wat period [5]. This finding suggests that Temples d'Étape were constructed eastwards and that sandstone blocks were supplied from the southeastern foothills of Kulen Mountain (Fig. 8 in Uchida et al. [25]). In contrast, it is inferred that the sandstone blocks of Prasat Trapeang Chambok, at the eastern end, were supplied from a sandstone quarry near Preah Khan of Kompong Svay (Fig. 2).

Along the East Royal Road, there are seven Fire Shrines (from west to east, Fire Shrine of Ta Prohm, Fire Shrine of Preah Khan, Prasat Kansaeng, Prasat Trapeang Khnar, Prasat Ta En, Prasat Supheap Chueng, and Prasat Kuk) which are considered to have been constructed in the Bayon period [25]. The two westernmost Fire Shrines

of Ta Prohm and Preah Khan are located in the Angkor region. Similar to the Temples d'étape, the magnetic susceptibilities of the sandstone blocks used for the Fire Shrines increased from west to east (Fig. 9 in Uchida et al. [25]). The magnetic susceptibilities of the sandstone blocks used in the Angkor monuments tend to increase gradually from 0.7 to 3.1×10^{-3} SI units in and after the main Bayon period (the end of the 12th to early 13th centuries) [5]. It is inferred from this finding that, similar to the Temples d'étape, the Fire Shrines were also constructed from west to east, and the sandstone blocks used for construction were supplied from the southeastern foothills of Kulen Mountain. However, it is inferred that the Fire Shrines at Prasat Supheap Cheung (0.36×10^{-3} SI units) and Prasat Kuk (0.40×10^{-3} SI units) are made of low magnetic susceptibility sandstone blocks supplied from a quarry near Preah Khan of Kompong Svay (Fig. 2).

As described previously, at the beginning of the Angkor Wat period sandstone blocks were transported from the southeastern foothills of Kulen Mountain to Preah Khan of Kompong Svay along the whole length of the East Royal Road, around 60 km. In the early Angkor Wat period, sandstone blocks were supplied to Prasat Supheap Tbong from Kulen Mountain, but by the late Bayon period, they were only supplied as far as Prasat Ta En (Prasat Pram) (Fig. 2). This confirms that the supply ranges of sandstone blocks from Kulen Mountain became narrower over time.

Methods

In this study, non-destructive chemical composition analyses were carried out on laterite blocks used for bridge construction along the East Royal Road using a portable X-ray fluorescence analyzer equipped with a silicon drift detector and a 4 W, 50 kV Rh X-ray tube configuration (Type DP-4000-C, Innov-X Systems Delta Premium, Waltham, MA, USA). The measurements were carried out in a soil mode for precise analysis of minor heavy elements (using three different beams, beam 1: 40 kV, 100 μ A, beam 2: 40 kV, 100 μ A, beam 3: 15 kV, 200 μ A). Measurement time was 20 s for each beam, and total measurement time was fixed at 60 s. Before measurement, the instrument was calibrated using 10 reference rocks from the Geological Survey of Japan (JA-1, JA-2, JB-1b, JB-2, JB-3, JG-1a, JG-2, JGb-1, JR-1, and JR-2) [28]. Analytical precisions were summarized in Table 1. The measurements were made on flat and non-deteriorated surfaces of stone blocks not covered with algae or lichens. The measuring surfaces were cleaned with a brush. For each bridge, measurements were made on flat surfaces of 10 different laterite blocks selected randomly, and the median values were obtained.

In addition, we measured non-destructively magnetic susceptibilities of laterite blocks of the bridges and sandstone blocks of the balustrades using a portable magnetic susceptibility meter (ZH instruments SM 30, Brno, Czech Republic) with a reading surface of 5 cm \times 5 cm. Measurements were made on randomly selected 40 flat and non-deteriorated laterite block surfaces in total for each bridge. Although most of the sandstone blocks have disappeared, possibly due to reuse by local people, measurements were made on up to 20 sandstone blocks selected randomly for each bridge. For four bridges, nos. 2498, 3701, 1600, and 3705 (CISARK; <http://cisark.mcfa.gov.kh/>), no sandstone blocks remained, so we could not measure magnetic susceptibilities. Magnetic susceptibility measurements were performed on flat surfaces not deteriorated physically and/or chemically, and also not covered with algae or lichens, and the median values were obtained. The magnetic susceptibilities of sandstone depend on the content of magnetite (Fe_3O_4), which is a minor mineral in the sandstone. Because magnetite is a heavy mineral compared with major rock-forming minerals such as quartz, feldspar and micas, it concentrates in specific place. In addition, the content of magnetite in sandstone depend on source rocks. These factors determine the horizontal and vertical difference in magnetic susceptibility of sandstone layer. Conversely, the magnetic susceptibilities of laterite are due to large amounts of goethite ($\text{FeO}(\text{OH})$) and hematite (Fe_2O_3), as well as minor amounts of maghemite (Fe_2O_3). Maghemite is a highly magnetic mineral, like magnetite [29].

Thicknesses were measured for 25 laterite blocks of each bridge and the median values were obtained. The thicknesses of both sandstone and laterite blocks decreased over time in the Angkor monuments, from around 45 cm before the Angkor Wat period, to around 25 cm in the late Bayon period. The cross section of stone blocks was square until the Bapuon period, but changed to rectangular after that [30]. We can see stone blocks with both square and rectangular cross sections in the Angkor Wat period. In addition, the orientation of bedding planes was random before the Baphuon period, but almost horizontal in the Angkor Wat period and later [4].

To compare with laterite blocks used for bridge construction, laterite blocks used in temples at Chau Say Tevoda, Prasat Suor Prat, Thommanon, Angkor Wat, and Banteay Samre constructed in the Angkor Wat period, and also Ta Prohm, Angkor Thom, and Banteay Kdei constructed in the Bayon period, were subjected to chemical composition analyses, magnetic susceptibility measurements, and thickness measurements. According to Uchida et al. [7], there were no clear differences in chemical compositions or magnetic susceptibilities between the laterite blocks used for the buildings

Table 1 Median values of chemical compositions, magnetic susceptibilities and thickness of laterite blocks used for bridge construction along the East Royal Road

Grouping	CISARK no.	Monuments	Cr (ppm)	Co (ppm)	Cu (ppm)	Y (ppm)	Zr (ppm)	Ti (ppm)	Sr (ppm)	Fe (ppm)	V (ppm)	As (ppm)	Zn (ppm)	M.S.*	Thickness (cm)
Precision			8.5	7.5	1.6	0.3	1.4	2.22	1	1084	8.6	1.6	1.4	0.001	0.5
Group A	2494	Sp. O Chungruk	252	124	163	8	159	6924	40	409642	1161	208	61	0.50	36.5
	3708	Sp. O Chattrrea	318	135	140	14	131	8490	41	517535	1426	99	49	0.44	28
	3706	Sp. Khmeng	257	167	68	24	186	10232	89	400229	1382	44	89	0.44	34.5
Group B	213	Sp. Khmeng	230	159	287	8	152	6557	37	494871	1416	67	62	0.53	29
	7397	Sp. O Phdar	526	180	36	8	141	10752	67	497275	1814	39	28	1.29	31
	7081	Sp. Khmeng	425	230	110	7	130	11416	170	515340	1732	53	29	1.28	34.5
Group C	2495	(no name)	589	225	94	7	126	11448	67	493618	1611	53	19	1.14	30
	2496	(no name)	648	246	131	9	110	11796	62	490763	1716	46	19	1.23	28
	3705	(no name)	498	124	91	13	217	8447	141	316576	1058	27	57	0.52	27.5
Group D	3707	Sp. Rontadev	489	133	93	14	237	9787	143	301240	1391	57	58	0.46	29.5
	1600	Sp. Phum O	245	99	85	21	265	12295	141	235661	978	52	63	0.45	34
	3701	Sp. Tradaev	298	102	84	13	228	7102	125	244007	840	45	46	0.50	29
	1599	Sp. Khvav	470	108	87	14	245	11525	152	323235	1472	108	183	0.48	34.5
	225	Sp. Touch	910	179	46	16	275	9627	160	559457	2123	166	107	0.44	32
	319	Sp. Ta Ong	587	215	57	19	219	10936	217	472045	1709	166	84	0.44	34
	318	Sp. Khmeng	454	171	60	12	163	8161	168	422228	1394	135	60	0.50	30.5
	2498	Sp. Toap Chey	621	205	79	4	138	11617	26	585268	2544	34	29	1.01	28
	3703	Sp. Yea Pun	394	190	84	4	162	8911	20	466086	2192	26	26	0.75	35
	3702	Sp. Khmeng	370	128	65	9	137	9175	30	328955	1740	20	32	0.84	31
Group E	306	Sp. Khmeng	534	205	80	9	200	10613	47	535771	2424	67	72	1.21	27
	1974	Sp. Khmeng	311	187	42	9	158	8577	42	315716	1328	26	53	0.80	30
	5426	Sp. Khmeng	424	187	39	7	113	10237	33	376840	1420	49	46	0.39	36
	1025	Sp. Thmor Bay Kream	260	266	34	5	95	9528	10	450687	1411	29	18	0.80	29.5
	2695	(no name)	672	208	68	8	128	9977	22	555617	1921	38	31	0.55	29

Table 1 (continued)

Grouping	CISARK no.	Monuments	Cr (ppm)	Co (ppm)	Cu (ppm)	Y (ppm)	Zr (ppm)	Ti (ppm)	Sr (ppm)	Fe (ppm)	V (ppm)	As (ppm)	Zn (ppm)	M.S.*	Thickness (cm)
Group E	466	Sp.Thmor Ste- ing Touch	346	167	57	12	144	6928	136	298551	768	152	56	0.30	29.5
		Angkor monu- ments	274	136	44	17	124	5304	214	260241	604	326	41	0.22	30.5
		Prasat Suor Prat (S2,N3)	401	125	67	17	110	6759	132	281670	802	208	28	0.29	42
		Banteay Samre (outer enclo- sure)	472	144	52	19	132	6973	231	338433	1044	310	54	0.38	40
		Banteay Samre (inner enclo- sure)	165	138	73	17	111	4717	206	265561	562	275	85	0.30	32.5
		Chau Say Tevoda (outer enclosure)	392	168	89	11	120	6431	128	383051	851	178	58	0.45	24
		Ta Prohm (inner enclosure)	381	154	66	19	128	5637	190	297714	864	337	42	0.35	33
		Banteay Kdei (inner enclo- sure)	490	172	71	56	141	7029	177	233858	1393	176	47	0.36	36
		Thommanon (foundation)	365	199	72	19	116	7373	156	396912	1082	217	28	0.45	31
		Chau Say Tevoda (foun- dation)	357	201	83	15	129	6411	151	427471	686	198	74	0.53	N/A
		Angkor Wat (outer enclo- sure)	193	146	82	51	117	4235	180	137270	763	134	60	0.30	35

Chemical composition and magnetic susceptibility data used to group the bridges are surrounded by bold rectangular frames. The sequence of the bridges from top to bottom corresponds to positions from east to west
 *Magnetic susceptibility (10^{-3} SI units)

constructed in the Angkor Wat period and those built in the Bayon period in the Angkor monuments. This finding suggests the strong possibility that they were supplied from the same quarrying area. However, their source is still unknown.

To infer the supply range of laterite blocks used for the bridges, hierarchical cluster and principal component analyses were conducted. The median concentrations of each element and magnetic susceptibility (Table 1) standardised to a constant total were used in the cluster and principal component analyses (Additional file 1) [31–33]. T-tests were performed to examine the confidence of the deduced groupings of the bridges using chemical compositions and magnetic susceptibility of laterite and sandstone blocks. R (ver. 3.5.3) was used for the cluster and principal component analyses and t-tests [34].

Results

Chemical composition

The major components of laterite used in the Angkor monuments were Fe_2O_3 , Al_2O_3 , and SiO_2 [7]. The portable X-ray fluorescence analysis in soil mode revealed 16 elements across all laterite blocks: K, Cr, Co, Cu, Zn, As, Y, Zr, Ti, Sr, P, S, Ca, Mn, Fe, and V. Silicon (Si) and aluminum (Al) were not detectable by the portable X-ray fluorescence analyzer in soil mode. Five elements (K, P, S, Ca, and Mn) that exhibited large variations or no systematic variations were excluded; then, the bridges were classified into at least five groups based on contents of the other 11 elements (Table 1 and Additional file 2), Group A to Group E, from east to west (Figs. 2 and 4). The laterite blocks of Group A are relatively depleted in Cr, Co, Ti, Sr, and V, but are enriched in Cu, Y, and Zn compared with those of Group B. The laterite blocks of Group B are depleted in Y, Zr, Sr, and Zn, but are enriched in Co and V compared with those of Group C. The laterite blocks of Group C are enriched in Y, Sr, and As compared with those of Group D. The laterite blocks of Group D are depleted in Y, Sr, and As compared with those of Group E. These facts suggest that the laterite blocks were supplied from five different quarrying areas. Only the laterite blocks used for bridge no. 466 (CISARK; <http://ciskark.mcf.gov.kh/>) in Group E, near the western end of the East Royal Road closest to the Angkor monuments, are similar in chemical composition to the laterite blocks used for the Angkor monuments from the Angkor Wat period to the Bayon period. It is possible that these blocks came from the same quarrying area.

In the Angkor monuments, gray to yellowish brown sandstone was used as a main construction material, but there is no difference in the chemical composition between the temples. Our preliminary surveys have also revealed that the gray to yellowish brown sandstone used

in the temples along the East Royal Road is not different from the sandstone in the Angkor monuments in terms of chemical composition. In this study, therefore, the chemical composition analysis of sandstone used in the bridges of the East Royal Road was not conducted.

Magnetic susceptibility

The median magnetic susceptibilities of the laterite blocks in the bridges range from 0.30 to 1.29×10^{-3} SI units (Table 1, Fig. 4, and Additional file 3). The same groupings as those based on the chemical compositions were obtained: the median magnetic susceptibilities of the laterite blocks of Group A are low, ranging from 0.44 to 0.53×10^{-3} SI units; those of Group B are high, ranging from 1.14 to 1.29×10^{-3} SI units; those of Group C are low, ranging from 0.44 to 0.52×10^{-3} SI units; those of Group D range from 0.39 to 1.21×10^{-3} SI units; and the median magnetic susceptibility of the laterite blocks of Group E is as low as 0.30×10^{-3} SI units (Table 1 and Fig. 4). The magnetic susceptibilities of laterite blocks in Group E, closest to the Angkor monuments, are in the same range as those of the laterite blocks in the Angkor monuments from the Angkor Wat period to the Bayon period (0.22 to 0.53×10^{-3} SI units), and it is inferred that they were supplied from the same quarrying area.

The median magnetic susceptibilities of the sandstone blocks used for the bridge balustrades range from 0.23 to 3.43×10^{-3} SI units (Fig. 5 and Additional file 4). The number of sandstone blocks is small and they are widely dispersed. No sandstone blocks remained for bridges nos. 2498, 3701, 1600 and 3705 (CISARK; <http://ciskark.mcf.gov.kh/>). Sandstone blocks of the four bridges nos. 213, 3706, 3708, and 2494 near Preah Khan of Kompong Svay on the eastern side of the East Royal Road have low median magnetic susceptibilities, ranging from 0.23 to 0.51×10^{-3} SI units, averaging 0.31×10^{-3} SI units. Sandstone blocks of the bridges on the western side have higher median magnetic susceptibilities, ranging from 0.75 to 3.41×10^{-3} SI units, averaging 1.73×10^{-3} SI units.

Thickness of laterite blocks

The laterite blocks used in construction of the bridges have rectangular ends, not square ends, and their median thickness ranges from 27.5 to 36.5 cm (Table 1 and Additional file 5). These results are almost concordant with those obtained by Uchida and Ando [30] for the laterite and sandstone blocks used for temples in the Angkor monuments from the Angkor Wat period to the Bayon period, not before the Angkor Wat period.

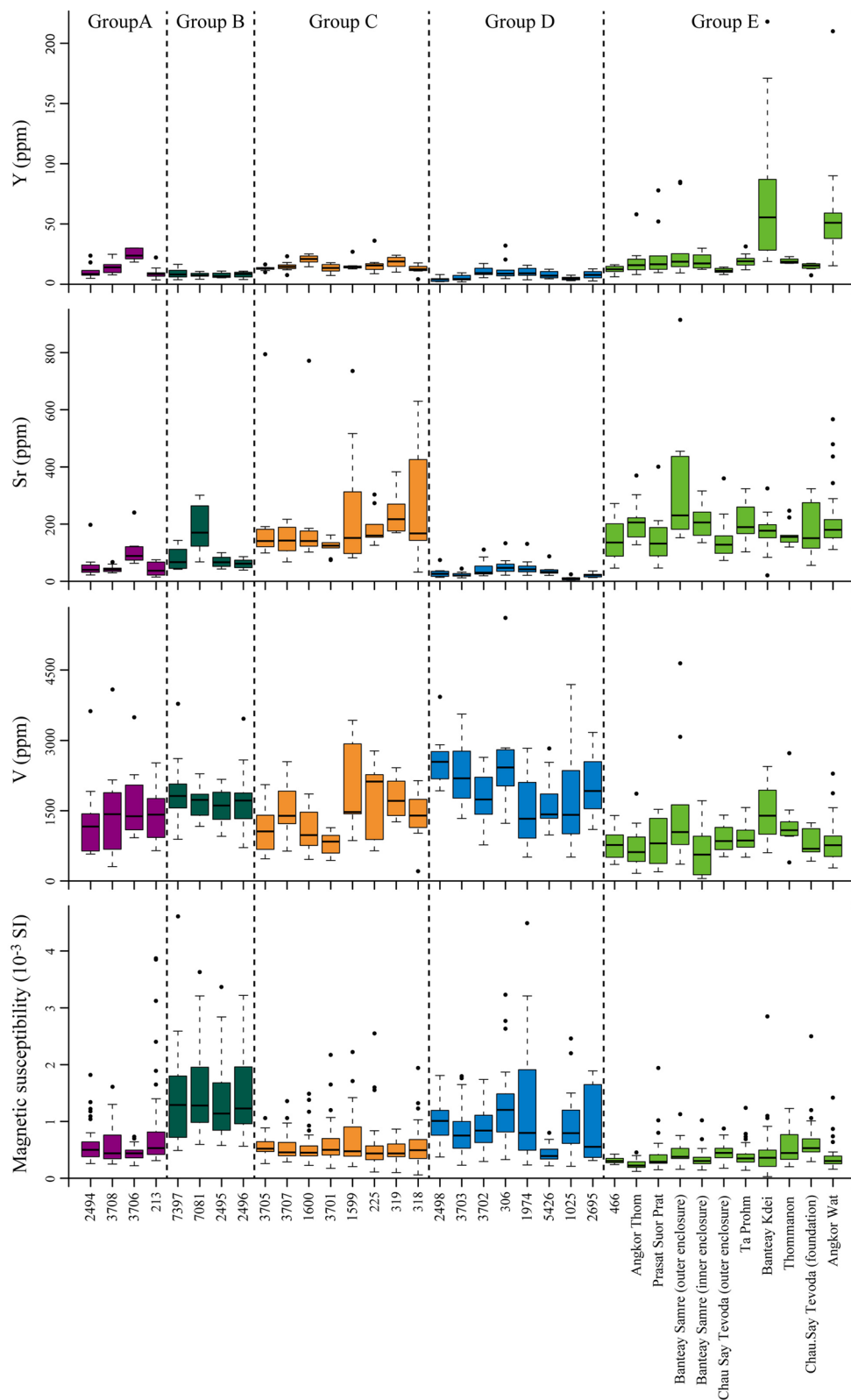
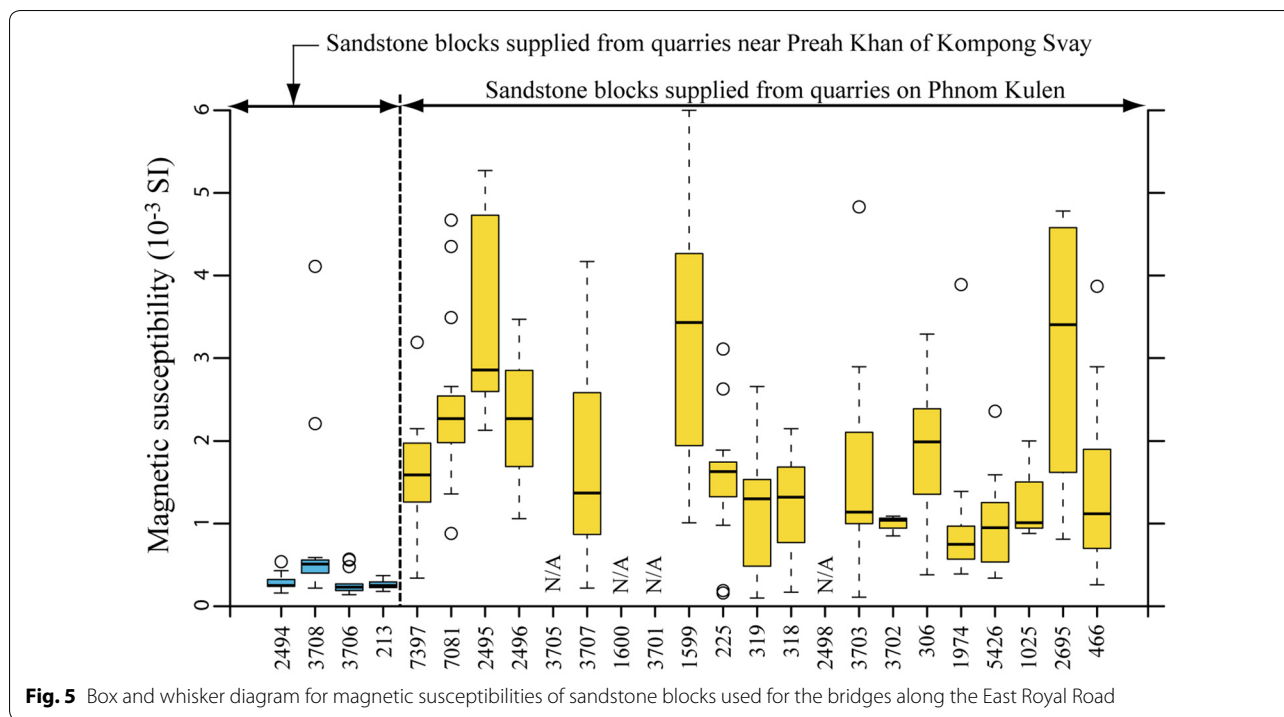


Fig. 4 Box and whisker diagrams for contents of Y, Sr and V, and magnetic susceptibility of laterite blocks used in the bridges along the East Royal Road. Five groups (Group A to Group E) can be distinguished



Hierarchical cluster analysis of laterite blocks

We performed hierarchical cluster analyses using single linkage, complete linkage, group average, centroid, median, and Ward’s methods (Additional file 6), but the analysis result by Ward’s method with a squared Euclidean distance gave the result most consistent with the hypothesis presented in this paper compared to other methods. In other words, Ward’s method classified the laterites used in the Angkor Wat to Bayon periods into one group (Fig. 6), while the other methods split them into at least two groups. Ward’s method gave almost the same groupings (Group A to Group E) as those obtained from the chemical composition and magnetic susceptibility data shown in Table 1 and Fig. 4. However, bridge no. 318 (CISARK; <http://cisark.mcfa.gov.kh/>) was reclassified from Group C (Table 1) to Group E in the cluster analysis, and bridge no. 3706 was reclassified from Group A to Group C.

Principal component analysis of laterite blocks

Results of the principal component analysis are shown in Fig. 7 as principal components 1 vs. 2 and principal components 1 vs. 3 diagrams. In the former, the area of Group A classified in Table 1 and Fig. 4 slightly overlaps with the area of Group C, but in the latter, the area of Group A does not overlap with the area of Group C at all. In both diagrams, the area of Group B is completely

included in the area of Group D. In both diagrams, the area of Group A is separated completely from the area of Group B, the area of Group B from the area of Group C, the area of Group C from the area of Group D, and the area of Group D from the area of Group E. The laterite blocks of Group A are enriched in Cu; those of Group B and D are enriched in Co, V, and Fe and have higher magnetic susceptibilities; those of Group C are enriched in Zn and Zr; and those of Group E are enriched in Sr, As, and Y. These facts suggest that the laterite blocks of each group (Group A to Group E) were supplied from different quarrying areas.

Bridge no. 3706 (CISARK; <http://cisark.mcfa.gov.kh/>) was classified as both Group A and Group C in the principal components 1 vs. 2 diagram, but was classified as Group A, not Group C, in the principal components 1 vs. 3 diagram. Bridge no. 318 was classified as both Group A and Group C in the principal components 1 vs. 2 diagram, but was classified as Group C in the principal components 1 vs. 3 diagram. These results are concordant with the results obtained by grouping based on chemical composition and magnetic susceptibility data in Table 1 and Fig. 4.

Studies on laterite blocks in the Angkor monuments [7] revealed that Fe, V and magnetic susceptibility have a positive correlation to each other, and that Sr, Y and As also have a positive correlation. It is, however, clarified

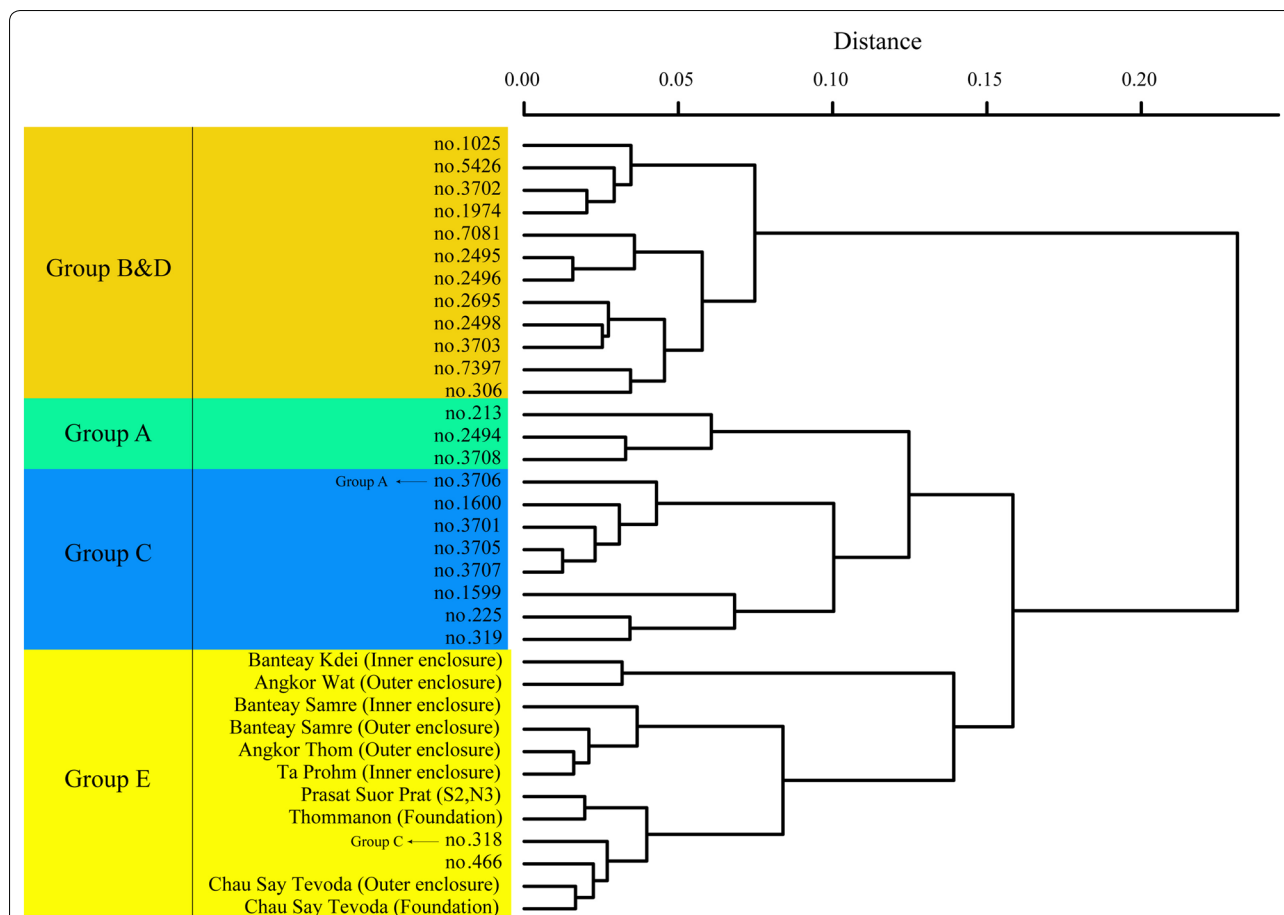


Fig. 6 Dendrogram obtained from hierarchical cluster analysis using Ward’s method for the bridges along the East Royal Road, based on median chemical composition and magnetic susceptibility data for laterite blocks listed in Table 1. The median concentrations of each element and magnetic susceptibility standardised to a constant total were used in the analysis

that there is a negative correlation between the former and the latter. These results are in a good agreement with those of the principal component analysis.

T-tests to examine the confidence of the grouping of the bridges

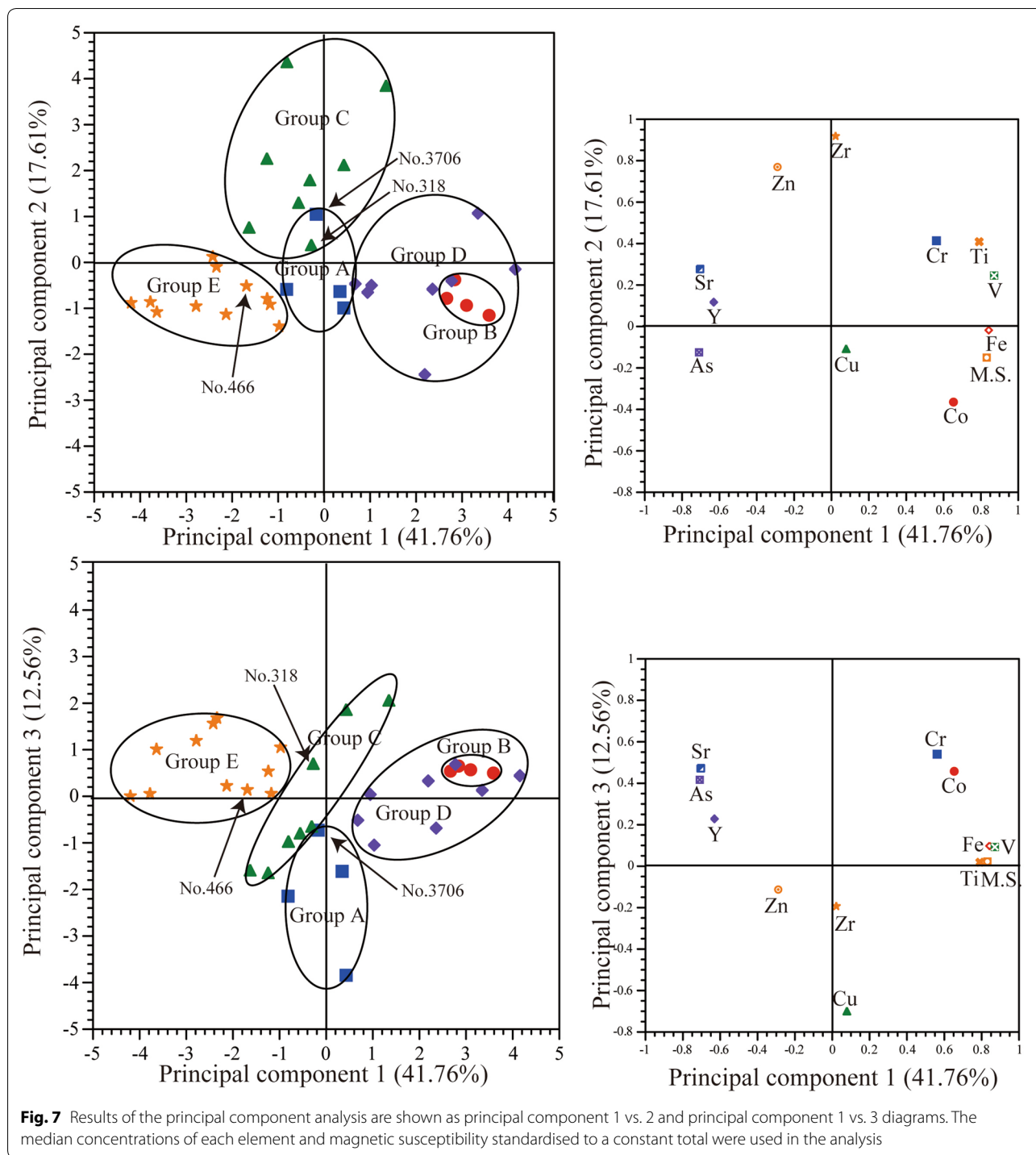
We conducted t-tests to examine the confidence of the groupings of the bridges based on magnetic susceptibility of laterite and sandstone blocks (Additional files 2 and 3), and p values were calculated. As a result, p values for magnetic susceptibility of laterite blocks between Group A and Group B, Group B and Group C, Group C and Group D, and Group D and Group E, were all extremely low (less than 2.65×10^{-18}) (Table 2). These results revealed that laterite blocks of Group A and Group B, Group B and Group C, Group C and Group D, and Group D and Group E were supplied from different quarrying areas, respectively. In addition, p value for magnetic susceptibility between the sandstone blocks used in the bridges 2494 to 213 and

those in the bridges 7397 to 466 was extremely small (4.45×10^{-28}). This result suggests a clear difference in provenance.

The t-tests were also conducted to examine the confidence of the grouping of the bridges based on Y, V, and Sr contents of laterite (Additional file 1). As a result, p values were less than 0.05 with one exception (p value for V: 0.136 between Group A and Group B) (Table 2). These results clearly support that laterite blocks of Group A and Group B, Group B and Group C, Group C and Group D, and Group D and Group E were supplied from different quarrying areas, respectively.

Discussion

Based on the results for magnetic susceptibilities of sandstone blocks and those for chemical compositions, magnetic susceptibilities and thicknesses of laterite blocks, presented in the previous chapter, we discuss here the stone block supply range and construction period for the bridges along the East Royal Road.



Sandstone blocks

The same tendency as Temples d'étape and Fire Shrines is observed for the magnetic susceptibilities of sandstone blocks used in the balustrades of the bridges along the East Royal Road; that is, median magnetic susceptibilities on the west side are high (0.75 to 3.41×10^{-3} SI

units), whereas the four bridges on the east side (nos. 213, 3706, 3708, and 2494; CISARK; <http://cisark.mcf.gov.kh/>) have low median magnetic susceptibilities (0.23 to 0.51×10^{-3} SI units). This finding suggests that the sandstone blocks for the bridges on the western side were supplied from Kulen Mountain, but that those for

Table 2 P values obtained by t-tests to examine the confidence of the grouping of the bridges along the East Royal Road based on magnetic susceptibility and chemical compositions of laterite blocks

	Groups A and B	Groups B and C	Groups C and D	Groups D and E
Magnetic susceptibility	3.06×10^{-25}	4.05×10^{-33}	2.65×10^{-18}	1.52×10^{-34}
Y content	4.61×10^{-6}	7.11×10^{-20}	1.55×10^{-19}	3.76×10^{-12}
Sr content	6.96×10^{-4}	2.10×10^{-6}	2.14×10^{-15}	8.04×10^{-33}
V content	0.136	0.0151	5.29×10^{-6}	2.26×10^{-16}

the bridges on the eastern side were supplied from the quarry near Preah Khan of Kompong Svay (Fig. 2). The boundary between high and low magnetic susceptibility sandstone blocks is consistent with the boundary for sandstone blocks used for Temples d'étape, but is different from the boundary for sandstone blocks used for Fire Shrines. Judging from the supply ranges of the sandstone blocks used for the balustrades of the bridges, it is inferred that the bridges were constructed from the early Angkor Wat period to the early Bayon period. Regarding the magnetic susceptibilities of sandstone blocks used for the balustrades of the bridges, if we assume construction occurred in the early Angkor Wat period, contradictions do not arise with magnetic susceptibilities of sandstone blocks used in the Angkor monuments. Judging from these facts, it is highly likely that the balustrades of the bridges along the East Royal Road were constructed in the early Angkor Wat period.

Laterite blocks

Based on chemical compositions and magnetic susceptibilities of laterite blocks, the bridges were classified into five groups (Group A to Group E) (Table 1 and Fig. 4). Sr, V, and Y contents, and magnetic susceptibilities are good indicators for grouping the laterite bridges (Tables 1 and 2). Analysis revealed that only bridge no. 466 (CISARK; <http://cisark.mcfa.gov.kh/>), classified as Group E, was constructed from the same laterite blocks as those used from the Angkor Wat period to the Bayon period. This finding indicates that the laterite blocks used in the construction of the Angkor monuments were supplied from the area west of bridge no. 2695. The supply ranges of the laterite blocks used for the construction of the other laterite bridges are also narrower than those of the sandstone blocks. This result suggests that laterite occurs in many areas along the East Royal Road, and that procurement of laterite blocks was easier than that of sandstone blocks.

Sandstone blocks were supplied from the southeastern foothills of Kulen Mountain to Preah Khan of Kompong Svay in the beginning of the Angkor Wat period, and were transported approximately 60 km. Because canals have not been confirmed in the area between Kulen

Mountain and Preah Khan of Kompong Svay, stone blocks may have been transported over land. Transportation of stone blocks by canal would have been difficult because the altitude is the highest in the area around bridge no. 7081 (about 90 m above sea level), between Kulen Mountain (about 80 m above sea level in Beng Mealea) and Preah Khan of Kompong Svay (about 65 m above sea level). The lowest altitude is near bridge no. 319 (around 40 m above sea level). This represents a difference in elevation of around 50 m. As mentioned above, it is inferred that sandstone blocks were transported from Kulen Mountain to Preah Khan of Kompong Svay in the beginning of the Angkor Wat period, so it is reasonable to infer that the East Royal Road, as well as the masonry bridges, were already constructed at the time. The facts that the boundary between Group A and Group B for the laterite bridges coincides with the supply boundary of the sandstone blocks used for the balustrades, and that it also coincides with the supply boundary of the sandstone blocks used in Temple d'étapes, support the idea that the bridges along the East Royal Road were constructed in the early Angkor period. In addition, the facts that rectangular cross section laterite blocks instead of square ones were used for the bridge construction, that they were stacked with coursed ashlar, and that the orientation of bedding planes is almost horizontal, suggest that the bridges were constructed in the early Angkor Wat period, not before the Angkor Wat period [27].

Conclusions

Sandstone and laterite blocks used in the 25 bridges along the East Royal Road connecting the capital city of Angkor to Preah Khan of Kompong Svay were investigated to clarify the supply range of stone blocks and the construction period of the bridges.

There are marked geographical differences in magnetic susceptibilities of sandstone blocks used for the balustrades of the bridges along the East Royal Road. Based on these magnetic susceptibilities, it was inferred that sandstone blocks in the bridges east of bridge no. 213 (CISARK; <http://cisark.mcfa.gov.kh/>) were supplied from a sandstone quarry near Preah Khan of Kompong Svay, and that those west of bridge no. 7397

were supplied from the southeastern foothills of Kulen Mountain. This result is concordant with that obtained from the sandstone blocks used for the Temple d'étapes along the East Royal Road [25].

The laterite blocks, which were the main bridge construction materials, are presumed to have been supplied from five different quarrying areas, and the supply ranges were much narrower than those of the sandstone blocks. This finding indicates that laterite is widely distributed along the East Royal Road, and that the procurement of laterite blocks was easier than that of sandstone blocks. However, these ancient laterite quarries have not yet been found.

Judging from the median magnetic susceptibilities, supply ranges, and characteristics of laterite blocks, such as cross sectional shapes and the orientations of bedding planes, the construction of the masonry bridges along the East Royal Road is highly likely to have occurred in the early Angkor Wat period (the late 11th to early 12th centuries).

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s40494-020-00383-2>.

Additional file 1: Data used for the cluster and principal component analyses. The median concentrations of each element and magnetic susceptibility data listed in Table 1 were standardised to a constant total.

Additional file 2: Raw data of chemical composition analysis of laterite blocks used for the bridge construction along the East Royal Road by a portable XRF.

Additional file 3: Raw data of magnetic susceptibilities of laterite blocks used for the bridge construction along the East Royal Road.

Additional file 4: Raw data of magnetic susceptibilities of sandstone blocks used for the bridge construction along the East Royal Road.

Additional file 5: Raw data of thickness of laterite blocks used for the bridge construction along the East Royal Road.

Additional file 6: Results of cluster analyses using single linkage, complete linkage, group average, centroid, median, and Ward's methods.

Abbreviations

EFEQ: École Française d'Extrême-Orient; CISARK: Carte Interactive des Sites Archéologiques Khmers.

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Authors' contributions

EU conceived and coordinated this research. EU, YSak, RC and IS conducted the field investigation. EU and YSai performed multivariate analyses, EU carried out the interpretation of the results, and drafted the manuscript. EU, YSai and IS made all figures and table. All authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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