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Consideration on the construction process and the sandstone quarries during the Angkor period based on the magnetic susceptibility

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Abstract

Detailed magnetic susceptibility measurement was conducted on the sandstones used for the Angkor monuments constructed in the period spanning the Preah Ko and Angkor Wat styles, and the construction process of the buildings and quarries of the sandstones was considered. Combined with the previous study on the sandstones of the Bayon style [Uchida, E., Cunin, O., Shimoda, I., Suda, C., Nakagawa, T., 2003. The construction process of the Angkor monuments elucidated by the magnetic susceptibility of sandstone, Archaeometry 45, 221–232], the magnetic susceptibility measurement revealed that there were 7 sandstone quarries corresponding to Stages I, II, III, IVa, V, VII and VIIIb during the Angkor period. The sandstones used for the monuments belonging to Stage I show average magnetic susceptibility values ranging from 1.1 to 2.3×10^{-3} SI units. In the Bakheng style period (Stage II), the average magnetic susceptibility of the supplied sandstones decreased gradually from around 10 to 1×10^{-3} SI units over time. The magnetic susceptibility range of the sandstones used for the monuments of Stage III was from 2.3 to 3.0×10^{-3} SI units. In the early Angkor Wat style period (IVb), the average magnetic susceptibility of the supplied sandstones increased over time, reflecting the supply of the sandstones from two different quarries, that is, the quarry corresponding to the Khleang and Baphuon style monuments (Stage IVa), with low average magnetic susceptibilities of 1.1 to 2.4×10^{-3} SI units, and the quarry corresponding to the main Angkor Wat style monuments (Stage V), with high average magnetic susceptibilities ranging from 2.8 to more than 4.3×10^{-3} SI units. The sandstones of Stage VII show low average magnetic susceptibility around 1×10^{-3} SI unit. The sandstones of Stage VId is a mixture of sandstones of Stages V and those of Stage VII. The sandstones with high magnetic susceptibilities are found in the monuments belonging to Stage VIIIb, reflecting the supply from the new sandstone quarry.
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1. Introduction

The Angkor monuments were constructed in the 9th to 13th centuries using sandstone, laterite, and brick as construction materials. Sandstone is used more or less in almost all of them, and it is the most important construction material in the Angkor monuments. Three kinds of sandstone, that is, gray to yellowish brown sandstone, red sandstone, and greenish graywacke were used in the Angkor monuments (Delvert, 1963; Uchida et al., 1998). The use of the latter two types of sandstone was limited, whereas the gray to yellowish brown sandstone is the most popular. The gray to yellowish brown sandstone is thought to have been derived from the formation of the Middle to Upper Jurassic Period of the Mesozoic era, which is called the Grès Supérieur Formation in Cambodia and the Phu Kradung Formation in Thailand. This formation is distributed in the southeast foot of Mt. Kulen, which is located about 40 km northeast of Siem Reap City (Delvert, 1963). Several quarries used in the Angkor period have been discovered there. The gray to yellowish brown

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sandstone used in the Angkor monuments was of good quality and homogeneous until the early Bayon style period, but the color variation and lamina structure became remarkable in the later Bayon style period (Uchida et al., 2005). As no differences of the gray to yellowish brown sandstones in the bulk chemical composition, including minor elements, and in the mineral composition were found among the Angkor monuments, they can be classified petrologically into the same type of sandstone (Uchida et al., 1998). However, based on the magnetic susceptibility of the sandstones, it could be clarified that about seven quarries existed during the Angkor period (Uchida et al., 1998). Moreover, a detailed study of the magnetic susceptibility of the sandstone elucidated the construction sequence of the Bayon style monuments where large-scale modifications and additions were conducted (Uchida et al., 2003). In this study, detailed measurement of the magnetic susceptibility of the sandstones was performed for the Angkor monuments constructed before the Bayon style period (Fig. 1), and estimations of the construction sequence in addition to consideration of the quarries was carried out.

The magnetic susceptibility measurement was carried out non-destructively using portable magnetic susceptibility meters Models KT-5 and MS-20 (Geofyzika, Czech). In general, the measurement was performed on the flat surfaces of 50 sandstone blocks at each location and then the average value was obtained. The gray to yellowish brown sandstone consists mainly of quartz, feldspars, biotite, muscovite and rock fragments, being accompanied with small amounts of calcite, magnetite, zircon and garnet. The magnetic susceptibility of the sandstone is almost attributable to magnetite with strong magnetic property.

2. Magnetic susceptibility of the sandstones used for the Angkor monuments constructed before the Bayon style period

Uchida et al. (1999) carried out a general survey of the magnetic susceptibility of the gray to yellowish brown sandstone used for the main Angkor monuments and divided them into eight groups (Groups 1 to 8). In this paper, we use Stages I to VIII, corresponding to Groups 1 to 8 of Uchida et al. (1998). Further, Uchida et al. (2003) subdivided Stage VI into four Stages, VIa to VId, and Stage VIII into two Stages, VIIIa and VIIIb. In this study, we also subdivide Stage IV into two Stages, IVa and IVb. It is presumed that in Stage IVb the sandstone blocks were supplied from two different quarries, corresponding to Stage IVa and Stage V. In this paper, we elucidate the construction sequence of the monuments constructed from the Bakong to Angkor Wat style periods (Stages I to V). The construction sequence of the Bayon style monuments (Stages VIa to VIIIb) has already been reported in Uchida et al. (2003).

2.1. The monuments belonging to Stage I

The sandstones used for the monuments belonging to Stage I show average values of 1.1 to 2.3 $\times 10^{-3}$ SI units of magnetic susceptibility.

2.1.1. Preah Ko

In Preah Ko, the measurement was carried out only for the platform because the six sanctuaries were built almost completely of bricks and the use of sandstones was limited. As a result, a magnetic susceptibility value of 1.7 $\times 10^{-3}$ SI unit was obtained for the platform.

2.1.2. Bakong

In Bakong, measurement was performed at 26 places such as the sanctuaries, the platform, the gopuras, the long halls, and the buildings situated in the north and south of the long halls. The average magnetic susceptibility was distributed in a range between 1.3 and 2.3 $\times 10^{-3}$ SI units. Based on its iconography, the central sanctuary is considered as an addition in the later stage that was constructed in the Angkor Wat style period (Boisselier, 1952; Glaize, 1944). However, judging from the measured magnetic susceptibility (1.66 $\times 10^{-3}$ SI unit), flat shape, small size, and horizontal orientation of the bedding plane of the sandstone blocks, it is considered that the central sanctuary was constructed in the late Bayon style period (Stage VIIIa to VIIIb).

2.1.3. Lolei

Four sanctuaries remain in Lolei. Though built mainly of brick, sandstones were also used for the doorframes, false doors, lintels, colonettes, and other parts. The obtained average magnetic susceptibility for these sandstones was 2.1 $\times 10^{-3}$ SI unit.

2.2. Monuments mainly belonging to Stage II

In these monuments, the average magnetic susceptibilities of the sandstones vary widely from place to place, in a range of 1.0 to 9.1 $\times 10^{-3}$ SI units, and tend to decrease over time.

2.2.1. Phnom Bok

Phnom Bok is situated on the top of Mt. Bok with an altitude of 235 m. Magnetic susceptibility measurement was carried out for the platform, the three sanctuaries, and the northern and southern libraries (Fig. 2). The magnetic susceptibility of the platform is clearly different with respect to its north and south parts. The north part shows a value of 1.13 $\times 10^{-3}$ SI unit, while the south part shows a value of 9.09 $\times 10^{-3}$ SI unit. However, the basement of the south part of the platform consists of sandstone blocks with low magnetic susceptibility (1.56 $\times 10^{-3}$ SI unit), i.e., the same as those of the north part of the platform. The three sanctuaries show high magnetic susceptibilities of 6.72, 6.49, and 5.62 $\times 10^{-3}$ SI units from north to south, respectively. The northern and southern sandstone libraries show low values of 1.69 and 2.84 $\times 10^{-3}$ SI units, respectively. The sandstone blocks used for the entrance part of the southern brick library have a value of 1.36 $\times 10^{-3}$ SI unit. The magnetic susceptibility measurement for the northern brick library, however, was not performed due to its complete collapse. The low magnetic susceptibility of the north part of the platform suggests a possibility that the sandstones were supplied from the quarry used

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