



## THE CONSTRUCTION PROCESS OF THE ANGKOR MONUMENTS ELUCIDATED BY THE MAGNETIC SUSCEPTIBILITY OF SANDSTONE\*

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*The Angkor monuments in Cambodia are mainly constructed of grey to yellowish-brown sandstones. No differences in the constituent minerals and in the chemical composition of the sandstones have been confirmed among the monuments. However, we have found their magnetic susceptibility a useful parameter by which to distinguish them. The principal monuments of Angkor Wat, Ta Prohm, Preah Khan, Banteay Kdei and Bayon, constructed from the Angkor Wat period to the Bayon period (from the beginning of the 12th century to the beginning of the 13th century AD), were investigated in detail using a portable magnetic susceptibility meter. We succeeded in dividing the periods of construction into stages. This elucidated the enlargement process of the monuments and correlated their construction stages.*

**KEYWORDS:** ANGKOR MONUMENTS, SANDSTONE, MAGNETIC SUSCEPTIBILITY,  
ANGKOR WAT, TA PROHM, PREAH KHAN, BANTEAY KDEI, BAYON,  
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### INTRODUCTION

The Khmer people constructed the Angkor monuments, which are widely distributed in Cambodia and Thailand, between the ninth and the 13th centuries AD. The main monuments are concentrated around Siem Reap City, Cambodia (Fig. 1), and in 1992 UNESCO registered them on the World Cultural Heritage List. Since construction, the monuments have had to resist decay caused by the tropical climate. The École Française d'Extrême-Orient (EFEO) of France initiated the restoration of the Angkor monuments in 1907. Many teams from different countries, including the USA, Italy, Germany, India and the Republic of China, are contributing to the restoration and conservation works. The Japanese government created the Japanese Government Team for Safeguarding Angkor (JSA) in 1994. JSA finished the restoration of the Northern Library of Bayon in 1999 (Nakagawa 2000), and the restoration of Prasat Suor Prat and the Northern Library of Angkor Wat is now in progress. In a fundamental investigation of the Angkor monuments, a petrological study of the stone materials, based on detailed measurements of the magnetic susceptibility of sandstones, has succeeded in elucidating the enlargement process of the monuments that were constructed from the Angkor period to the Bayon period (from the beginning of the 12th century to the beginning of the 13th century), especially Ta Prohm, Preah Khan, Banteay Kdei and Bayon. Previous studies, based on epigraphy, art and

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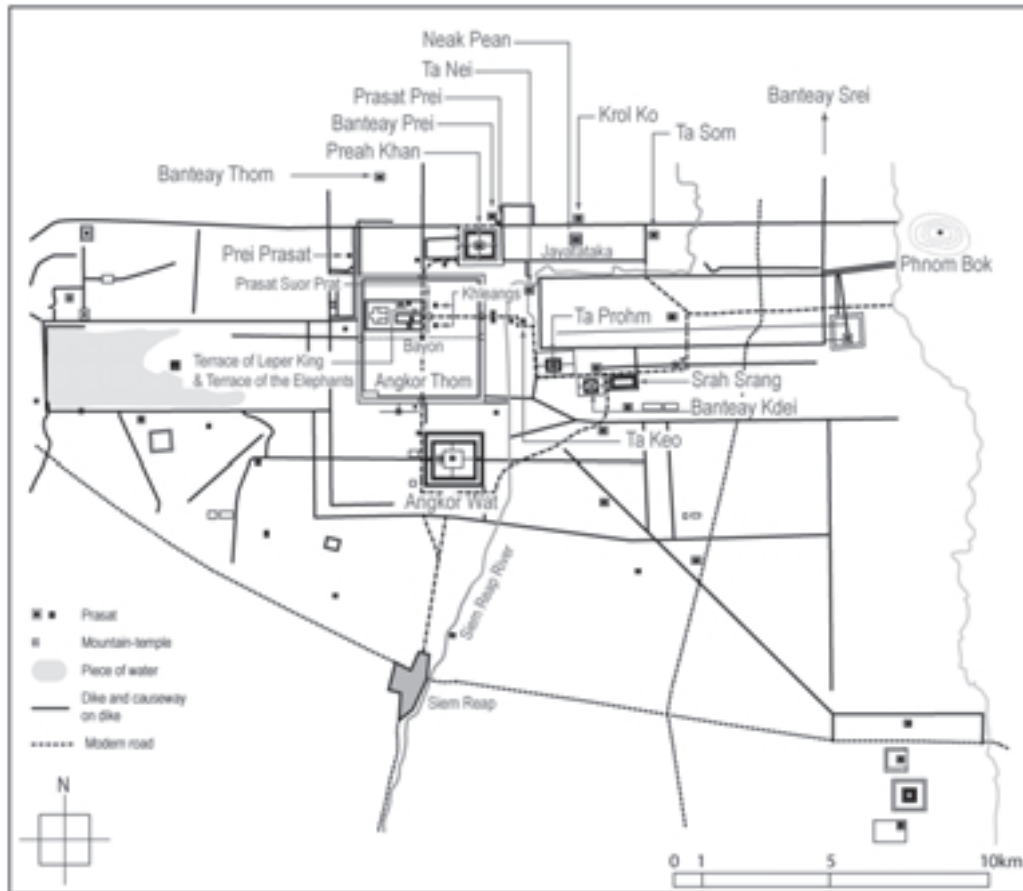


Figure 1 A map of the Angkor monuments, showing the distribution of the monuments investigated.

architectural history, have revealed that the monuments were constructed in the order of Ta Prohm, Preah Khan, Banteay Kdei and Bayon (Stern 1965; Dumarçay and Groslier 1973). The usefulness of magnetic susceptibility in the provenancing of Roman granite columns has already been shown by Williams-Thorpe and Thorpe (1993) and Williams-Thorpe *et al.* (1996).

#### THE STONE MATERIALS

The stone materials used for the Angkor monuments are sandstone and laterite. Brick is also used in the relatively old monuments constructed in the ninth and tenth centuries. We distinguished three types of sandstones on the basis of colour and constituent minerals: grey to yellowish-brown sandstone, red sandstone and greenish greywacke (Uchida *et al.* 1998). These correspond to the grey sandstone, red sandstone and green sandstone, respectively, of the classification by Delvert (1963). Red sandstone is used only for Banteay Srei and for a part of North and South Khleangs, and greenish greywacke only for the sanctuaries on the top of Ta Keo. Grey to yellowish-brown sandstone, consisting mainly of quartz, plagioclase, alkali feldspar, biotite, muscovite and rock fragments, is the main sandstone used for almost of the





monuments. No differences in the constituent minerals, and also in the bulk chemical composition for 50 elements, were recognized among the grey to yellowish-brown sandstones used for the Angkor monuments (Uchida *et al.* 1998).

As for laterite, two types can be distinguished: porous laterite and pisolitic laterite. Both types of laterite consist of the same minerals: kaolinite, quartz, hematite and goethite. However, differences in the contents of the minor elements As, Sb, V and Sr were observed between them (Uchida *et al.* 1999). Based on their contents and on their pore size, the investigated 30 main monuments were classified into five groups. This suggests that there were at least five quarries for laterites, and that the quarries changed over time (Uchida *et al.* 1999).

#### THE MAGNETIC PROPERTIES OF THE SANDSTONES

The grey to yellowish-brown sandstone is a primary stone material in the Angkor monuments and is used for almost of the monuments. This sandstone shows no variation in the constituent minerals and in its bulk chemical composition. However, we found significant differences in the magnetic susceptibility of the sandstone. Biotite is one of the main constituent minerals of the sandstone, but because biotite shows extremely low magnetic susceptibility compared with magnetite (Carmichael 1982), magnetite—in spite of its small quantity—is considered to be the main reason for the magnetic susceptibility of the sandstone. The magnetic susceptibility can be measured rapidly and non-destructively using a portable magnetic susceptibility meter (Geofyzika Model KT-5 and SM-20, Czech). The principle of the magnetic susceptibility measurement and the instrumentation were described in detail in Williams-Thorpe and Thorpe (1993) and Williams-Thorpe *et al.* (1996, 2000). The sandstone blocks showed a considerable variation in magnetic susceptibility from block to block, so an average value for 50 blocks was obtained at each location. For accuracy of measurement, the measurements were carried out selectively on the flat surface of the sandstone blocks. No correction was made for magnetic susceptibility, because the sandstone blocks are large (in general, larger than  $25 \times 40 \times 70$  cm). On the basis of magnetic susceptibility, Uchida *et al.* (1998) had already classified the 30 main Angkor monuments into eight groups and revealed that the sandstones were supplied from seven quarries. The sandstones of the monuments in group six are thought to have been quarried from the same two quarries as those used for the monuments in groups five and seven. Angkor Wat is a representative monument of group five, and Bayon of group seven (Fig. 1). The sandstone blocks used for the group five monuments showed an average magnetic susceptibility of more than  $3.1 \times 10^{-3}$  SI units. Those in group seven showed a lower average magnetic susceptibility, being less than  $1.3 \times 10^{-3}$  SI units. Ta Prohm, Preah Khan and Banteay Kdei (Fig. 1), in group six, all showed magnetic susceptibilities between these two values. The present detailed study of magnetic susceptibility for the sandstones used for the monuments in groups five, six and seven elucidated the enlargement process of Ta Prohm, Preah Khan, Banteay Kdei and Bayon and correlated the construction stages among them. However, we do not have enough information on the quarries, due to landmines buried during the civil war.

#### THE CONSTRUCTION PROCESS ELUCIDATED BY THE MAGNETIC SUSCEPTIBILITY OF THE SANDSTONE BLOCKS

The previous study revealed that the sandstone blocks used for the monuments of group six, Ta Prohm, Preah Kahn and Banteay Kdei, were supplied from at least two different quarries, and that the average magnetic susceptibility changes systematically from group five to group seven

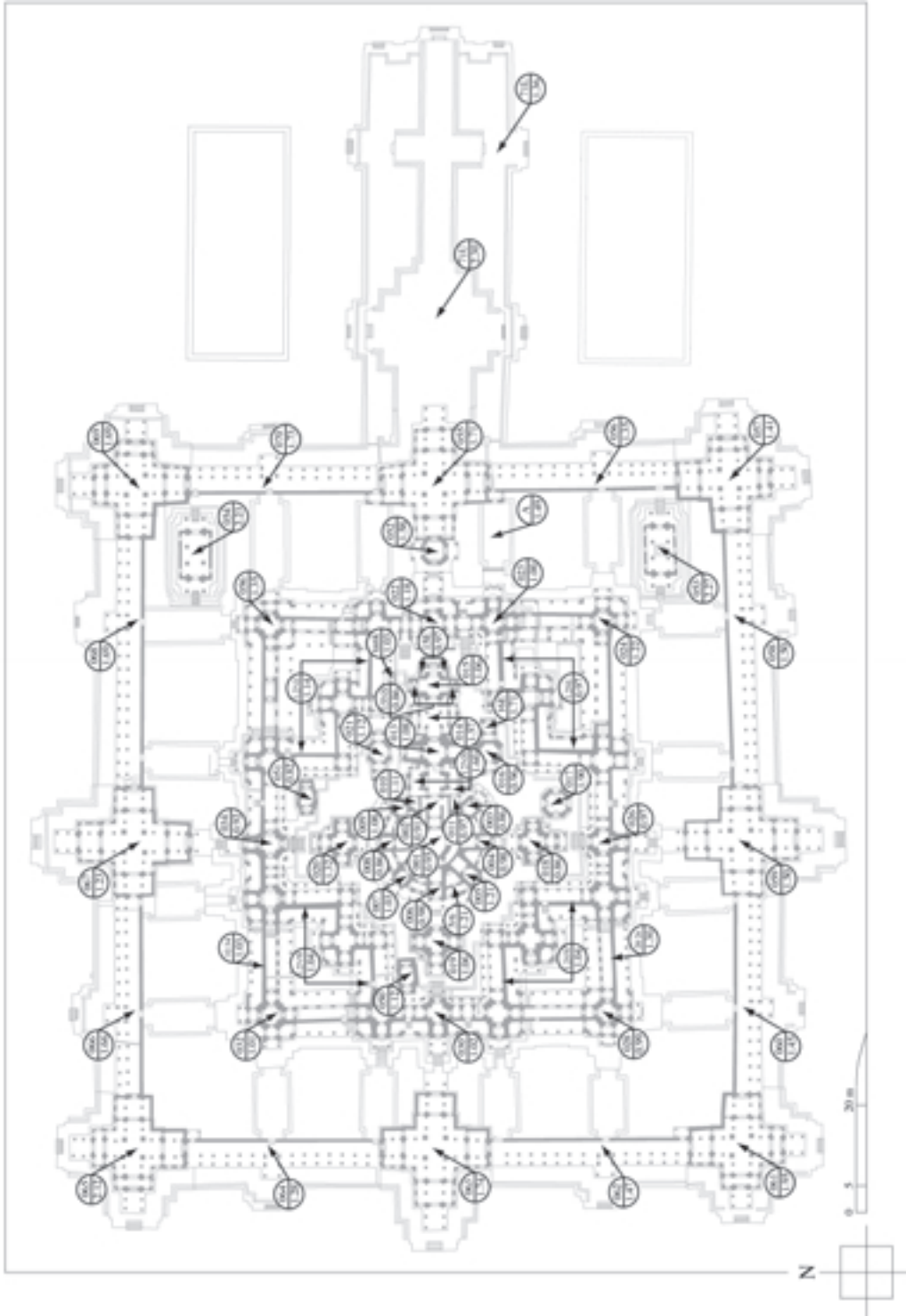


Figure 2 A plan of Bayon, showing the distribution of the magnetic susceptibilities of the grey to yellowish-brown sandstones. The upper number in the circles is the identification number of the structure and the lower is the average magnetic susceptibility in  $10^{-3}$  SI units.

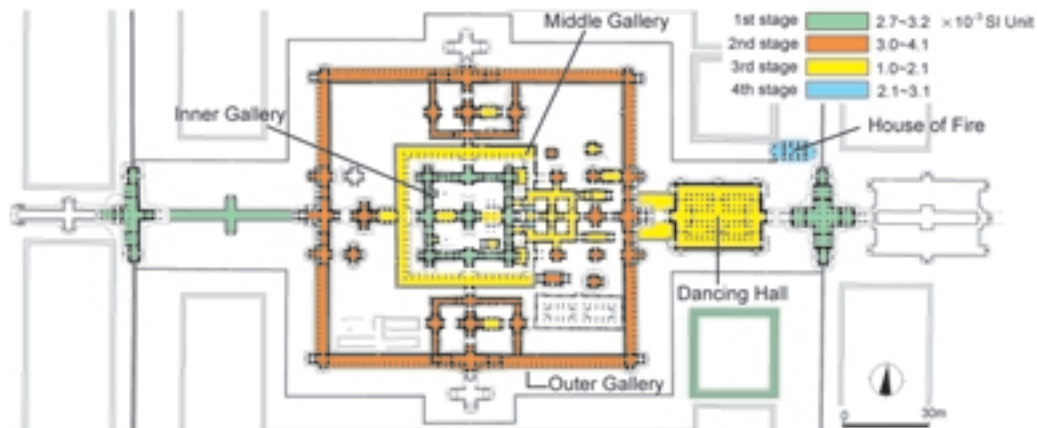


Figure 3 The construction sequence of Ta Prohm deduced from the magnetic susceptibilities of the sandstones. Four stages can be distinguished (drawn using the same colours as in Table 1).

(Uchida *et al.* 1998). These results indicate the possibility that the magnetic susceptibility is a useful parameter for elucidating the construction process of these monuments. Thus the detailed measurements of the magnetic susceptibility of the grey to yellowish-brown sandstone blocks were carried out for Angkor Wat, Ta Prohm, Preah Kahn, Banteay Kdei and Bayon. The measurements were performed at each of 28 locations in Angkor Wat, 83 locations in Ta Prohm, 128 locations in Preah Khan, 36 locations in Banteay Kdei and 77 locations in Bayon (Fig. 2). Fifty stone blocks were measured at each location and the average magnetic susceptibility was obtained for each location. The results of the stage division based on the magnetic susceptibility for Angkor Wat, Ta Prohm, Preah Khan, Banteay Kdei and Bayon are as follows.

Angkor Wat, in spite of its large scale, has a homogeneous average magnetic susceptibility ( $3.1\text{--}4.0 \times 10^{-3}$  SI units), except for the small extension in the central part ( $2.3 \times 10^{-3}$  SI units), and no systematic difference was observed. This suggests that the sandstone blocks of Angkor Wat were almost all supplied from just one quarry.

Ta Prohm differs from Angkor Wat. In Ta Prohm, the average magnetic susceptibility of the sandstone blocks showed a distinct variation from place to place. On the basis of the average magnetic susceptibility, and also taking into account architectural and ornamental evidence, it is considered that Ta Prohm was constructed in four stages (Fig. 3). The average magnetic susceptibility for 50 blocks at each location ranges from  $2.7 \times 10^{-3}$  to  $3.2 \times 10^{-3}$  SI units for the first stage, from  $3.0 \times 10^{-3}$  to  $4.1 \times 10^{-3}$  SI units for the second, from  $1.0 \times 10^{-3}$  to  $2.1 \times 10^{-3}$  SI units for the third, and from  $2.1 \times 10^{-3}$  to  $3.1 \times 10^{-3}$  SI units for the fourth stage. The average magnetic susceptibility generally decreases with time, except in the fourth stage. The Central Tower, the Inner Gate Towers, the Inner Gallery and ponds inside the Inner Enclosure were built in the first stage. The Outer Gallery and the two small galleries connected to it were constructed in the second stage. Several small towers distributed between the Middle Gallery and the Outer Gallery were built in the second or third stage. The Middle Gallery, the Dancing Hall, the Outer Gate Towers and many connecting parts are considered to belong to the third stage. The fourth stage is restricted to the House of Fire near the east Inner Gate.

Preah Khan (Fig. 4) is complex, and four stages were distinguished on the basis of the average magnetic susceptibility, taking into account architectural and ornamental evidence. The average magnetic susceptibility ranges from  $2.5 \times 10^{-3}$  to  $3.3 \times 10^{-3}$  SI units for the first stage,



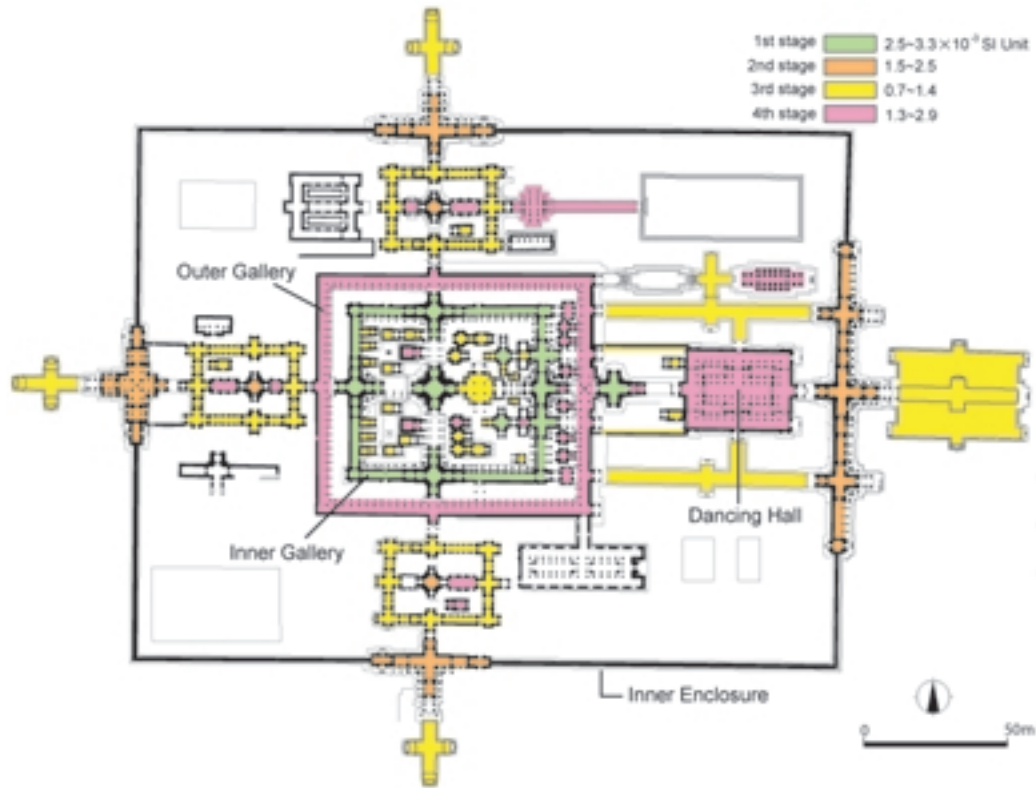


Figure 4 The construction sequence of Preah Khan deduced from the magnetic susceptibilities of the sandstones. Four stages can be distinguished (drawn using the same colours as in Table 1).

from  $1.5 \times 10^{-3}$  to  $2.5 \times 10^{-3}$  SI units for the second, from  $0.7 \times 10^{-3}$  to  $1.4 \times 10^{-3}$  SI units for the third and from  $1.3 \times 10^{-3}$  to  $2.9 \times 10^{-3}$  SI units for the fourth. As at Ta Prohm, the magnetic susceptibility decreases with time, but increases in the fourth stage. Decorations on the stone surface of Preah Khan were taken into account for its classification of stages, because the second stage had the same average magnetic susceptibility range as that of the fourth stage. Figure 5 is a frequency diagram of the magnetic susceptibility for each stage. The sandstones of the first stage have a peak between  $2.5 \times 10^{-3}$  and  $3.0 \times 10^{-3}$  SI units, and those of the third stage between  $0.5 \times 10^{-3}$  and  $1.0 \times 10^{-3}$  SI units. On the other hand, the second stage shows two peaks between  $0.5 \times 10^{-3}$  and  $1.0 \times 10^{-3}$  SI units and between  $2.5 \times 10^{-3}$  and  $3.0 \times 10^{-3}$  SI units. This suggests that the sandstone blocks of the second stage were supplied from two different quarries. The sandstones used for the first stage are homogeneous in colour (almost grey) and have almost no lamina texture, whereas those for the third and fourth stages show a colour variation from grey to yellowish-brown and frequently have lamina. The sandstones of the first stage are similar to those used for Angkor Wat. The first stage covered the Central Tower, the Inner Gallery and the two big towers inside the Inner Gallery, and the tower on the east side of the Outer Gallery. The second stage included the Inner Gate Towers and three central towers of the three small galleries between the Outer Gallery and the Inner Enclosure. The third stage included many small buildings inside the Inner Gallery, the Outer Gate Towers, the Causeways connecting the Outer Gallery to the east Inner Gate Tower, and three small galleries



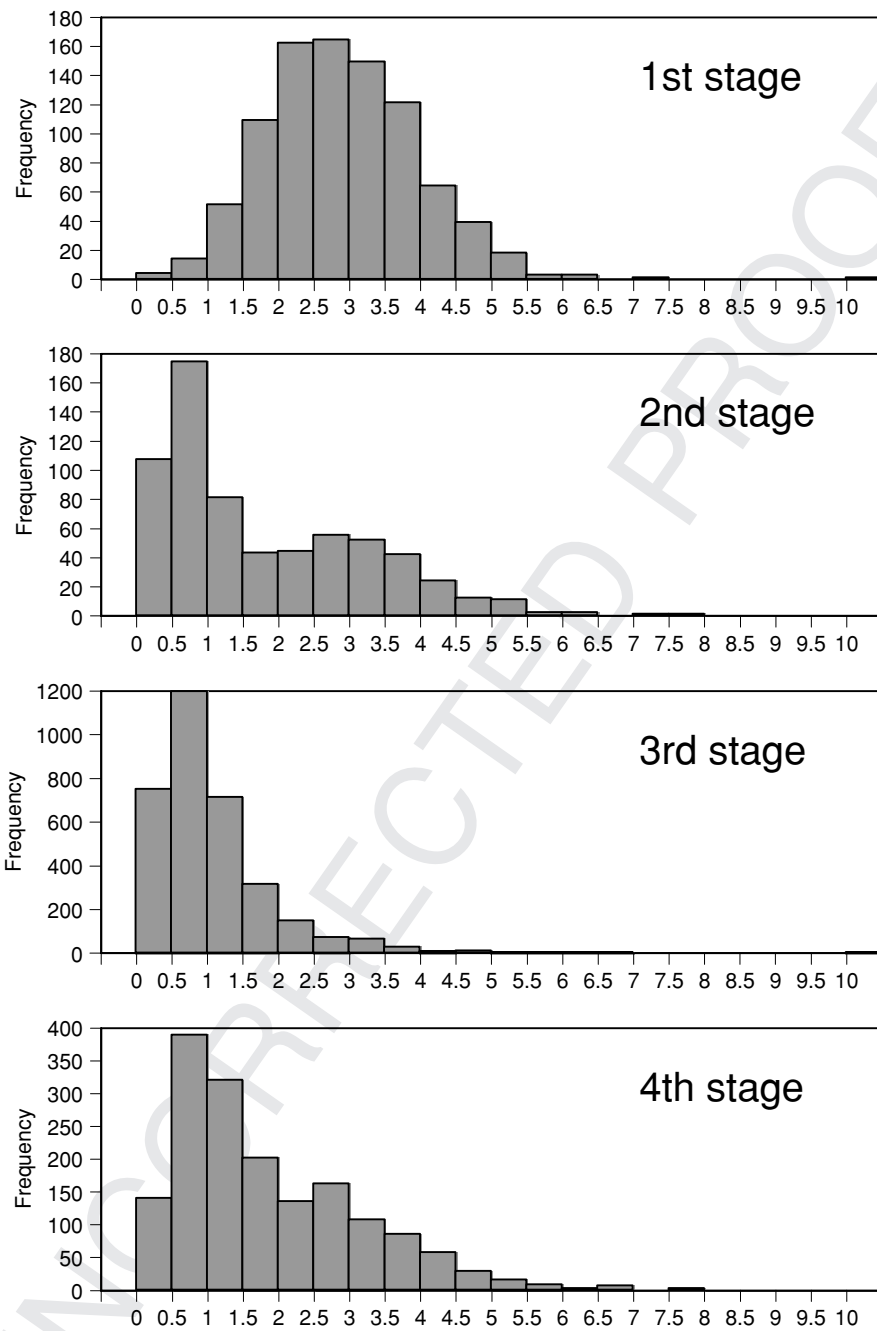


Figure 5 The frequency diagram of the magnetic susceptibilities of the sandstone blocks used for Preah Khan.



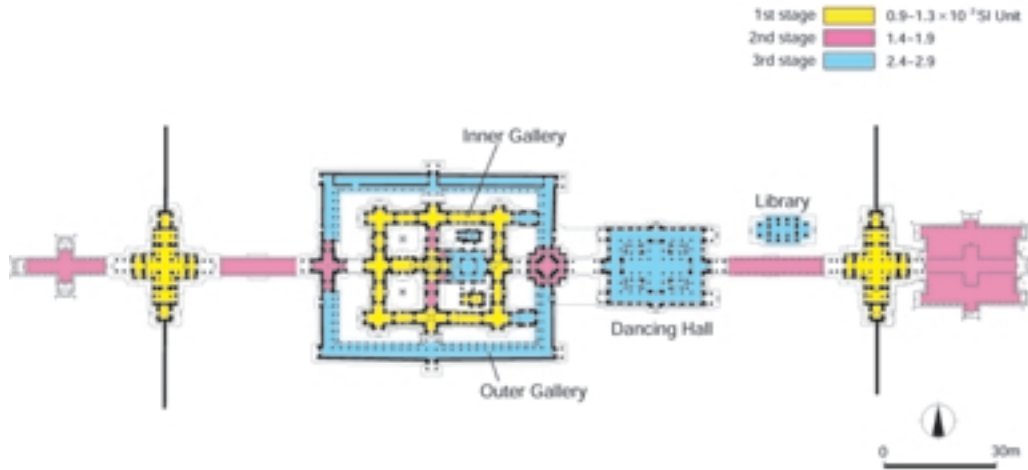


Figure 6 The construction sequence of Banteay Kdei deduced from the magnetic susceptibilities of the sandstones. Three stages can be distinguished (drawn using the same colours as in Table 1).

between the Outer Gallery and the Inner Enclosure. The Dancing Hall, the Outer Gallery and the connecting parts between the Inner Gallery and the Outer Gallery were built in the fourth stage.

Banteay Kdei is a simple case. It seems to have been constructed in three stages (Fig. 6). The Central Tower, the Inner Gallery and the Inner Gate Towers were built in the first stage ( $0.9\text{--}1.3 \times 10^{-3}$  SI units). The east and west Gate Towers of the Outer Gallery and the Causeways were built in the second stage ( $1.4\text{--}1.9 \times 10^{-3}$  SI units). The third stage included the Outer Gallery, the Dancing Hall and the Library ( $2.4\text{--}2.9 \times 10^{-3}$  SI units). The magnetic susceptibility increases with time.

Dumarçay and Groslier (1973) recognized four stages for Bayon. That does not basically contradict the present study, but our magnetic measurement revealed just three stages (Fig. 7). Except for some extended parts and the Inner Gallery, the Central Tower was built in the first stage ( $0.8\text{--}1.3 \times 10^{-3}$  SI units), which corresponds to Dumarçay and Groslier's (1973) first and second stages. The Inner Gallery seems to show a slightly higher magnetic susceptibility compared with other locations (Fig. 2). The five Gate Towers and the four Corner Towers of Angkor Thom also belongs to the first stage. The Outer Gallery, including the extended parts of the Central Tower, was built in the second stage ( $1.3\text{--}2.1 \times 10^{-3}$  SI units). The Northern and Southern Libraries and the central part of the Eastern Terrace can be assigned to the third stage ( $2.2\text{--}2.3 \times 10^{-3}$  SI unit). The magnetic susceptibility for Bayon increases with time at Banteay Kdei.

#### THE CORRELATION OF THE CONSTRUCTION STAGES AMONG THE MONUMENTS CONSTRUCTED IN THE BAYON PERIOD

The enlargement process of the monuments had not previously been established—except for Bayon, on the basis of architectural evidence, by Dumarçay and Groslier (1973)—and the correlation of the construction stages among the monuments had remained unresolved. The present study, however, has succeeded in elucidating the enlargement process, and also the correlation of the construction stages among the monuments investigated. The correlation of





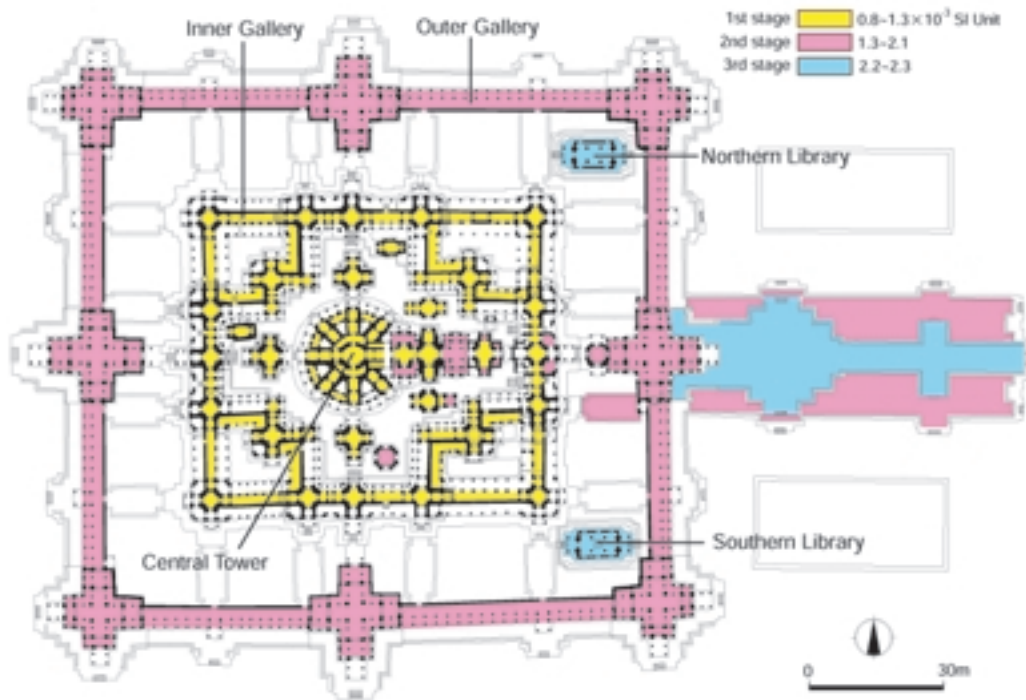


Figure 7 The construction sequence of Bayon deduced from the magnetic susceptibilities of the sandstones. Three stages can be distinguished (drawn using the same colours as in Table 1).

the construction stages based on the present study is shown in Table 1, where the same colours as used in Figs 3, 4, 6 and 7 are employed. The results suggest, for example, that the third stage of Preah Khan corresponds to the third stage of Ta Prohm and also to the first stage of Banteay Kdei and Bayon, and that Banteay Kdei was constructed in approximately the same period as Bayon. From the Angkor Wat period to the Bayon period, the magnetic susceptibility of the sandstones generally decreases from  $4 \times 10^{-3}$  SI units to  $1 \times 10^{-3}$  SI units, but then increases to  $3 \times 10^{-3}$  SI units. Table 1 also shows the results of the magnetic susceptibility measurements for other monuments with a Bayon style: Neak Pean, Ta Nei, Banteay Prei, Banteay Thom, Ta Som, Krol Ko, Prasat Prei, Prei Prasat, the Terrace of the Leper King and the Terrace of the Elephants. The construction period of their simple and small-scale structures was deduced from the magnetic susceptibility of the sandstones on the assumption that the central part was constructed first, and by taking into account architectural and decorative styles. In Neak Pean, the Central Sanctuary has an average magnetic susceptibility of  $3.0 \times 10^{-3}$  SI units except for some later additions, but the other surrounding buildings show an average magnetic susceptibility ranging from  $1.2 \times 10^{-3}$  to  $2.0 \times 10^{-3}$  SI units. In the case of Ta Nei, the average magnetic susceptibility is slightly dispersed from  $1.1 \times 10^{-3}$  to  $1.7 \times 10^{-3}$  SI units. The average magnetic susceptibility of the Central Sanctuary of Banteay Prei is  $1.5 \times 10^{-3}$  SI units, but those for the Gallery and the Gate Towers range from  $0.7 \times 10^{-3}$  to  $1.0 \times 10^{-3}$  SI units. In Banteay Thom, the two Main Towers show an average magnetic susceptibility of  $1.6 \times 10^{-3}$  SI units, but the other locations, such as the Libraries, the Gallery and the Gate Tower, range from  $0.8 \times 10^{-3}$  to  $1.3 \times 10^{-3}$  SI units. In Ta Som, all structures such as the Central Tower, the Gallery and the Gate



Table 1 The correlation of the construction stages among Angkor Wat, Ta Prohm, Preah Khan, Banteay Kdei, Bayon and the other Bayon style monuments  
(Magnetic susceptibility in  $10^{-3}$  SI unit)

Group	V	VIa	VIb	VIc	VI d	VII	VIIIa	VIIIb
Angkor Wat	1st stage 3.1–4.0							
Ta Prohm		1st stage 2.7–3.2	2nd stage 3.0–4.1			3rd stage 1.0–2.1	4th stage 2.1–3.1	
Preah Khan				1st stage 2.5–3.3 1st stage 3.0	2nd stage 1.5–2.5	3rd stage 0.7–1.4	4th stage 1.3–2.9	
Neak Pean							2nd stage 1.2–2.0	
Ta Nei					1st stage 1.1–1.7		2nd stage 1.6–1.7	
Banteay Prei					1st stage 1.5	2nd stage 0.7–1.0		
Banteay Thom					1st stage 1.6	2nd stage 0.8–1.3		
Banteay Kdei						1st stage 0.9–1.3	2nd stage 1.4–1.9	3rd stage 2.4–2.9
Bayon						1st stage 0.8–1.3	2nd stage 1.3–2.1	3rd stage 2.2–2.3
Ta Som						1st stage 0.7–1.2		
Krol Ko						1st stage 1.0–1.1		
Prasat Prei						1st stage 0.7		
Prei Prasat						1st stage 1.0		
T. Elephants							1st stage 1.4–1.7	2nd stage 1.7–2.3
T. Leper King								1st stage 1.9



Towers show a narrow range of average magnetic values, from  $0.7 \times 10^{-3}$  to  $1.2 \times 10^{-3}$  SI units. Prasat Prei and Prei Prasat show  $0.7 \times 10^{-3}$  and  $1.0 \times 10^{-3}$  SI units, respectively, in the average magnetic susceptibility. In the case of the Terrace of the Elephants, the central part has an average magnetic susceptibility of  $1.4\text{--}1.7 \times 10^{-3}$  SI units, whereas the other parts have values in the range  $1.7\text{--}2.3 \times 10^{-3}$  SI units. On the other hand, the Terrace of the Leper King is homogeneous ( $1.9 \times 10^{-3}$  SI units). Almost of the monuments except for Neak Pean, the Terrace of the Leper King and the Terrace of the Elephants have sandstone blocks with an average magnetic susceptibility of between  $0.7 \times 10^{-3}$  and  $1.3 \times 10^{-3}$  SI units. These values are representative for the Bayon-style monuments. No other monuments constructed before the Angkor Wat period used sandstone blocks with such a low average magnetic susceptibility (Uchida *et al.* 1998).

#### CONCLUSIONS AND FURTHER WORK

The magnetic susceptibility of the grey to yellowish-brown sandstone, which is the most popular sandstone used for the Angkor monuments, has been shown to be a suitable parameter for the elucidation of the construction process and the correlation of the construction stages of the monuments. The sandstone blocks of Angkor Wat show a homogeneous magnetic susceptibility in spite of its large scale. This may suggest that the sandstone blocks were supplied from one quarry. On the other hand, the sandstone blocks of Ta Prohm, Preah Khan, Banteay Kdei and Bayon show a variation in the magnetic susceptibility from place to place. On the basis of the magnetic susceptibilities, their construction process was divided into four stages for Ta Prohm and Preah Khan and into three stages for Banteay Kdei and Bayon. We succeeded in correlating the construction stages among the various monuments, including other monuments with a Bayon style.

The information obtained on magnetic susceptibility will be indispensable in identifying the quarries. The sandstone blocks are said to be derived from the south-east foot of Mt. Koulen, situated 40 km to the north-east of Siem Reap City (Boulbet 1979). Unfortunately, we could not get enough information about the quarries, because of the danger due to landmines buried during the civil war. However, there were probably multiple quarries for the investigated monuments. Future investigation of the quarries is expected to clarify the number of the quarries as well as the reason for the changes in magnetic susceptibility.

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