5. The manner of positioning sandstone materials in the Angkor Monuments - Sedimentological aspects.

by S. Tsukawaki (1) and T. Moriai (2)

(1) Tohoku University, Faculty of Science, Institute of Geology and Paleontology
(2) Tohoku Institute of Technology, Department of Civil Engineering

I Introduction

The various structures of the Angkor Monuments are built of mainly of sandstone and laterite, the sandstone in particular having been widely used for decorating important walls and towers. This sandstone, with beautiful and precise carvings, has been quarried from Phnom Kuhlen hill, consisting of sedimentary rocks of Late Paleozoic to early Cainozoic age (Upper Indochinia Formation : US Geol. Survey, 1971), situated about 40 km to the northeast of the Angkor region, and transported by ox and horse drawn wagons (scene of carnage) and rafts to the building site of the various monuments (Ishizawa, 1989 : Hirayama et al, 1992).

The petrological features of the sandstone blocks have been clarified. The results of chemical compositions and mineral assemblages of each of the sandstone blocks have been indicated by the French School of the Far East (see Moriai, 1991). Moriai (1991) has also described the suites of rocks involved with the blocks, centreing on the sandstones and, from X-ray powder diffraction analysis of materials from Ta Prohm, Ta Kev, Banteay Kdei and East Mebon, he has indicated that the main rock-forming minerals are quartz, feldspar, mica and chlorite with small amounts of kaolin and calcite. In addition to these petrological features, many of the sandstone blocks have recognisable sedimentary structures (mentioned below) which have been briefly reported by Moriai (1991).

In this study sandstones of the various monuments were observed from a sedimentological viewpoint as necessary basic data for a future geological survey of Cambodia and a number of regularities were highlighted in the distribution of blocks which can be inferred from the sedimentary structures. So these facts are known, adding some comments,

and inviting opinions and criticisms from the various specialists were made.

In carrying out this study we have been helped in various ways by Professor Y. Ishizawa of Sophia University, leader of the 8th Angkor Survey Mission, and the members of his mission. In particular, we have had on-site consultations with Mr. Isamu Yamamoto, honorary president of the Japan Building Stone Association. Also, Mr. T. Narita of Waseda University Department of Science and Engineering who has instructed us concerning Bayon and given us on-site discussions. The personnel from the Phnom Penh Government Ministry of Information and Culture and the Angkor Monuments Preservation Office has accommodated us in connexion with the actual investigations. We wish to express here our deepest appreciation to each of them.

II Sedimentary Rocks and Sedimentary Structures

At various places on the earth's surface, accumulations of clastic materials such as gravel, the remains of living things, chemical precipitates, etc. are buried underground by structural movements, etc. and with subsequent diagenesis, the consolidated material becomes sedimentary rock. Sandstone is mainly consolidated sand and its structure, preserved in the internal and upper and lower surfaces of the strata of sedimentary rock seen in the field, can often be distinguished clearly with the naked eye. These are called internal sedimentary structures and upper and lower surface sedimentary structures. Sedimentary structures of various forms are important in geological science and are used not only as indicators of the depositional environment at the time but for determining the upper and lower directions (new and old strata) of strata which might have been reversed by foldings and for correlating strata between regions which have become separated.

There are two broad types of mechanism for forming sedimentary structures. One is the deposition of clastic material which has been transported by fluids, typified by environments such as sand hills blown by the wind or strongly flowing streams. The other is the accumulation of detritus flowing down slope under its own weight, exemplified by rock avalanches, turbidites, pyroclastic

flows, etc. In addition to these, sedimentary structures are formed which assume various forms due to primary factors such as the particle size distribution, thickness of the fluid layer, flow velocity, etc. as well as post-depositional secondary deformation, etc.

Sedimentary structures observed in the sandstone blocks of the Angkor monuments complex are mainly internal sedimentary structures. These are colour differences, grain size, orientation of the longitudinal axes, etc. of the grains of the minerals which form the deposits, which are regularly arranged horizontally or vertically and, since they have a three dimensional form within the strata, the cross section changes according to the direction from which the strata (blocks) are viewed (Fig. 1).

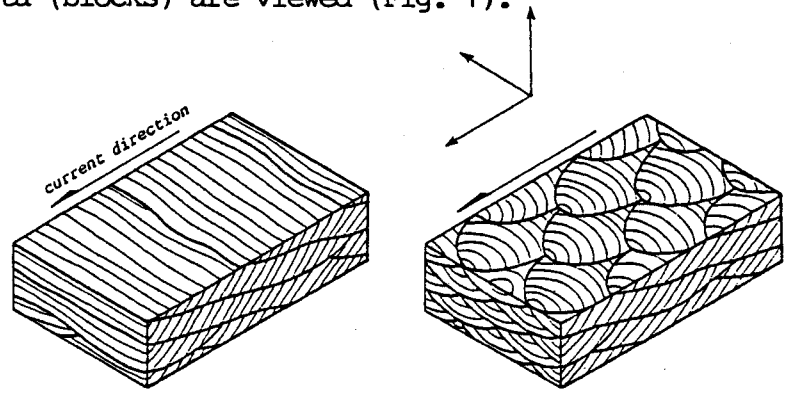

Fig. 1 Three dimensional construction of internal sedimentary structure. (simplified from Allen, 1982)

In the Bayon style of three temples (mentioned below), which are the object of this investigation, compared with earlier buildings, there is a tendency to use more blocks derived from sandstone which exhibits distinct sedimentary structure. The main structures are parellel laminations (Plate, 1a) and cross-stratification (Plate, 1b). Various forms can be observed in the cross-stratification, the front strata in particular appearing variously from straight to gentle curving and occasionally shell fossils and fine gravels appear to be aligned with the stratifications. Sandstones in which wave ripples and herringbone stratifications have been developed have been used in some places. In each case, these sedimentary structures have been formed by the transportation and deposition of the clastic materials by the flow of water and it can be inferred that the depositional environments would

include the lower reaches of a large stream, a sandy beach on the sea and a shallow shelf influences by waves and tidal flows.

III Survey and Research Methods

Observations of sandstone blocks were made mainly at Bayon, which is the central temple of Angkor Thom, and roughly the same was done at Prah Khan and Banteay Kdei. Each of these buildings is included in the Bayon complex, erected towards the end of the Angkor period in the 12th and 13th Centuries (Ishizawa, 1989). In addition, the blocks of Angkor Vat, which had been built earlier were examined for comparison with the complex of monuments mentioned above. The survey methods which were applied to the various building materials are as discussed below.

IV Angkor Thom, Bayon

In the Bayon survey, the internal sedimentary structures of each sandstone building block of the Upper Terrace and First Gallery and of the northern entrance were examined, recording their sedimentary structures as well as the part of the building in which they were used (Fig. 2). Also, the placement of the blocks with respect to their internal sedimentary structures, whether horizontal or vertical, was noted (Fig. 3). In respect of the horizontally placed blocks in particular, in cases where the geological up and down directions could be confirmed from the erosional surfaces in the sedimentary structures (Fig. 4), whether these had been placed normally or upside down were recorded.

Based on the map of the Upper Terrace by Dumarcay (1967), the number and size of the sandstone blocks were studied in the floor, and whether they had been placed horizontally or vertically. The number and placement of the blocks were confirmed, which Dumarcay had erred in assuming the blocks were uniform, paying particular attention to blocks which have deteriorated due to weathering after Bayon was built. At the First Gallery, the interior walls which are the best preserved were observed. Since it is difficult to recognise sedimentary structures in the upper parts of the walls due to weathering, plants, etc., the survey was

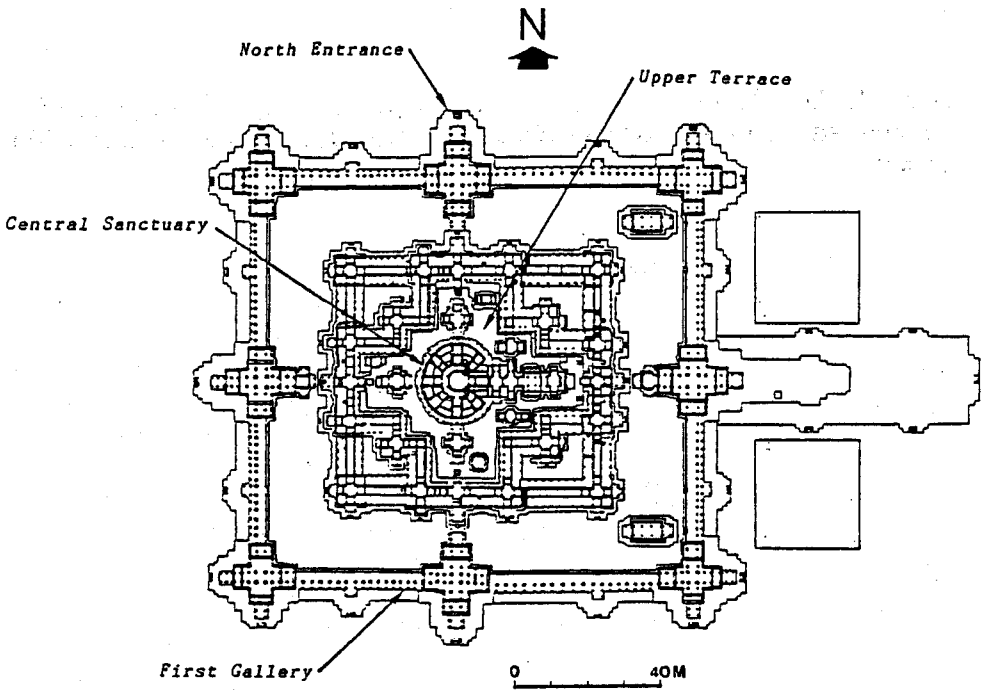

Fig. 2 Sites surveyed at Bayon. (Ishizawa, 1989 amended)

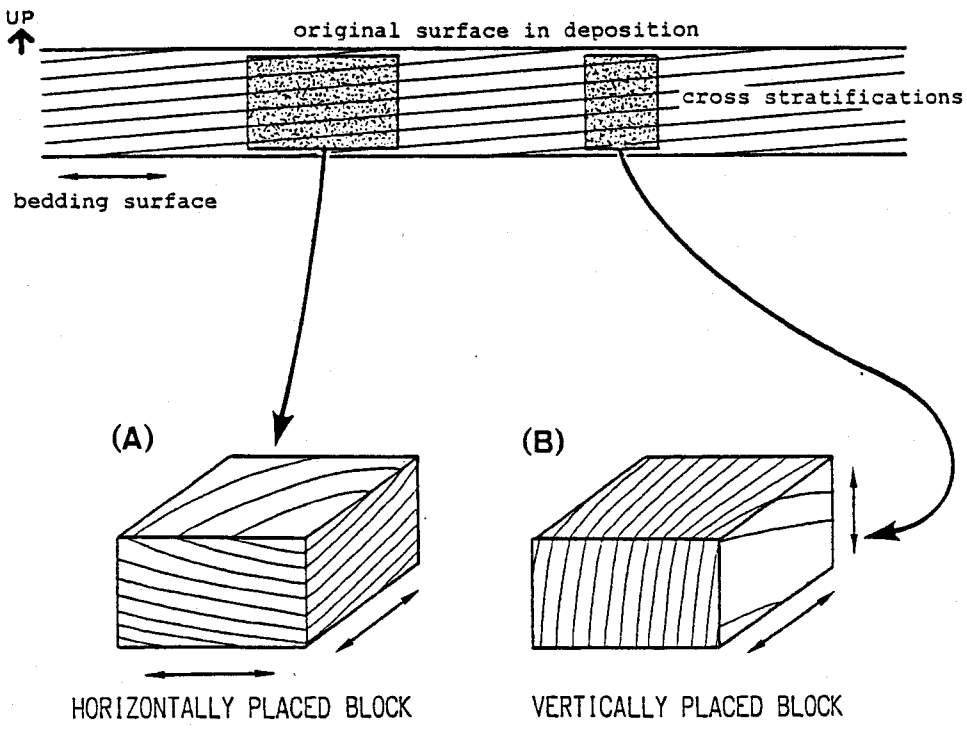

Fig.3 Vertical and horizontal placement of sandstone blocks

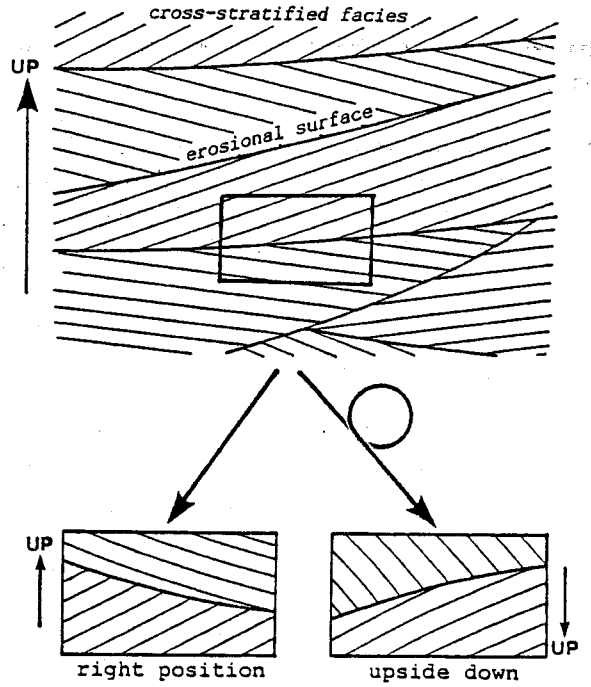

Fig. 4 Using sedimentary structure to determine geological normal or inversed placement of sandstone blocks.

limited to a height about two metres from the floor (the 8th or 9th row of blocks). The sedimentary structures which were observed were mainly parallel laminations. Since it was often difficult to distinguish the geological up and down, the observation was centred whether the stones had been placed horizontally or vertically. At the north entrance the same observations were done as for the Upper Terrace and First Gallery, investigating steps, floors and columns.

1. Upper Terrace

For convenience the Bayon Upper Terrace is divided into the northeast, southeast, southwest and northwest sections. Fig. 5 shows the positions of sandstone blocks in the Upper Terrace whose vertically placement has been confirmed, in particular those with prominent cross-stratification. Also, Table 1 shows the numbers of blocks used in the whole of the Upper Terrace and the number used in each section, as well as the numbers of stones placed vertically and those with cross-stratification, together

with the proportion of the total which is represented by each category.

2740 blocks have been laid in the whole of the Upper Terrace, 70 of which are placed vertically and 15 have cross-stratification. Each building stone is generally rectangular and has an average floor area of 0.26 m^2. The long edges of horizontally placed blocks are often about one metre long and ratio of long and short sides is about 2:1. By contrast, the vertically placed blocks with long sides which exceed 100 cm (No 39 for example) are seen rarely. In general they are markably smaller than the horizontally placed blocks, being under 50 cm long and in all cases the short sides are no more than 30 cm long. Their shape varies from nearly square to elongated with long to short side ratios which reach up to 5:1 (Plate, 1c). Places where several small blocks have been used together are particularly noticeable (for instance, Nos 18-20 in the northeast section and Nos 50-52 in the southwest section : Plate, 1d). The sizes of blocks with cross-stratification differ not greatly from those which are placed horizontally. Whereas each building stone is placed in a straight line aligned with the straight edges of the outer perimeter, from the inside edge they are placed radially, centred on the almost circular central sanctuary, and in the places where they both meet, the placement is particularly complicated.

On comparing the shapes of the east and west parts of the Upper Terrace, the two eastern sections are about 30% larger in area than the two western sections. Also, because there is one sanctuary in the northeast section and two in the southeast section, their horizontal shapes become even more complicated. On comparing south and north, the southeast and southwest sections are each about 10% larger in floor area than the northeast and northwest sections respectively.

A total of 679 blocks have been used in the northeast section, of which 25 are placed vertically. The average area of the blocks is 0.29 m^2, which is a little larger than the general average. The proportion of vertically placed blocks is about 3.7%, which tends to be more than in the other three sections but the individual blocks which are used are smaller. A large number of the vertically placed blocks are used in the particularly complicated placement of stones around the sub-sanctuary.

Only one building stone with cross-stratification was found.

ALL FLOOR	FS(m^2)	FS(%)	BN	BN(%)	SIZE(m^2)
Total	712	-	2740	-	0.26
V. block	6.3	0.9	70	2.6	0.09
CS block	3.2	0.4	15	0.6	0.21
NE FLOOR	FS(m^2)	FS(%)	BN	BN(%)	SIZE(m^2)
Total	198	-	679	-	0.29
V. block	2.0	1.0	25	3.7	0.10
CS block	0.2	0.1	1	0.2	0.18
SE FLOOR	FS(m^2)	FS(%)	BN	BN(%)	SIZE(m^2)
Total	219	-	741	-	0.30
V. block	1.6	0.7	16	2.2	0.10
CS block	2.0	0.9	8	1.1	0.25
SW FLOOR	FS(m^2)	FS(%)	BN	BN(%)	SIZE(m^2)
Total	156	-	719	-	0.22
V. block	1.7	1.1	17	2.4	0.10
CS block	0.6	0.4	3	0.4	0.20
SE FLOOR	FS(m^2)	FS(%)	BN	BN(%)	SIZE(m^2)
Total	139	-	601	-	0.23
V. block	1.1	0.8	12	2.0	0.09
CS block	0.5	0.4	3	0.5	0.17

FS : floor space
BN : number of blocks
SIZE: average size of blocks

Table 1 Number of blocks in Bayon Upper Terrace and each of its sections and number of vertically placed blocks used.

The greatest number of blocks, 741 in all, are used in the southeast section, which has the greatest floor area and a horizontal shape complicated by the presence of the two sanctuaries. Sixteen of these are placed vertically. The average area of the stones is 0.30 m^2, which is larger

than the general average. The proportion of vertically placed blocks is 2.2% which is rather less than the general average, and they are used near the steps and around the sub-sanctuary. The number of building stones with cross-stratification is eight, which is the greatest of the four sections.

In the southwest section, which has a comparatively simple horizontal shape, although the area is smaller, a comparatively large total of 719 blocks are used, giving an average area of 0.22 m^2 per building stone, which is smaller than the other three sections. 17 vertically placed blocks and three with cross-stratification were observed, which is about equal to the general averages for these features. The vertically placed blocks are frequently used near the boundary between the blocks placed radially around the central sanctuary and those aligned with the outer edges.

The northwest section, which has the smallest floor area, is constructed of the smallest number of blocks, a total of 601. The average floor area per building stone is 0.23 m^2, which is small. The proportion of vertically placed blocks used is also small, being 2%, and they are used in the same way as in the southwest section. Three blocks with cross-stratification were confirmed.

2. First Gallery internal walls

(1) Vertically placed blocks

The internal walls of the First Gallery have been divided into four sections: east, west, south and north, and each wall into east-west and south-north bounded by the central entrances. The blocks in the walls are not necessarily placed horizontally and regularly but, for convenience, the vertically placed stones are recorded as being in a rows numbered upwards from the floor level. The results are shown in Fig. 6 and Table 2.

The average size of blocks used in the internal walls is of the order of 25 cm high and 40 cm wide, stones exceeding 30 cm is height are rare. The depth of the blocks is estimated to be 40 cm. Conversely, vertically placed blocks generally have a height of 30 cm and a width of 20 cm, standing a little higher than horizontally placed stones and being about half their width (Plate, 1e). Also, whereas

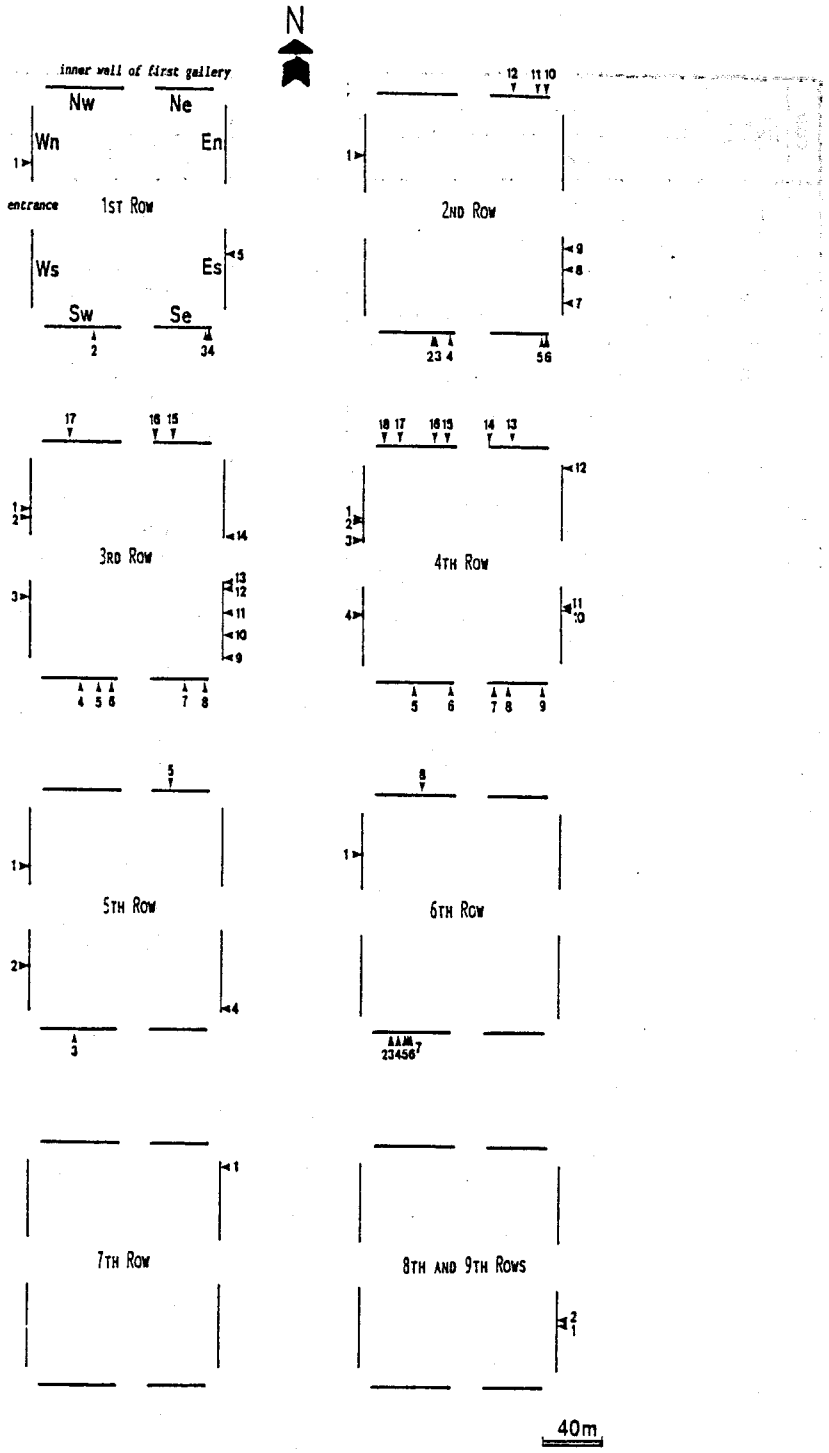

Fig. 6 Positions of vertically placed sandstone blocks in Bayon First Gallery.

row	wall	no.	size(cm)		shape*
			W	H	
1st	Wn	1	22	40	A
	Sw	2	80	30	R(P)
	Se	3	20	30	R
	Se	4	25	30	R
	Ws	5	10	25	A(P)
2nd	Wn	1	22	30	A
	Sw	2	15	40	A
	Sw	3	20	45	R
	Sw	4	30	45	R
	Se	5	30	30	R
	Se	6	20	40	R
	Es	7	15	25	A
	Es	8	20	25	R
	Es	9	15	25	A
	Ne	10	20	25	A
	Ne	11	25	35	R
	Ne	12	17	25	A
3rd	Wn	1	15	25	A
	Wn	2	15	50	A
	Ws	3	25	15	A
	Sw	4	20	20	R(P)
	Sw	5	20	28	R
	Sw	6	25	40	R
	Se	7	35	38	A
	Se	8	15	15	R
	Es	9	9	20	A
	Es	10	20	30	R(P)
	Es	11	20	25	A
	Es	12	15	20	A
	Es	13	15	25	A
	En	14	20	35	R
	Ne	15	20	25	AV
	Ne	16	15	20	A
	Nw	17	12	15	A

row	wall	no.	size(cm)		shape*
			W	H	
4th	Wn	1	15	20	R
	Wn	2	30	40	R
	Wn	3	12	40	A
	Ws	4	20	40	R(P)
	Sw	5	25	40	R
	Sw	6	20	35	A
	Se	7	15	30	A(P)
	Se	8	20	25	R
	Se	9	15	30	A
	Es	10	20	30	R
	Es	11	20	30	R
	En	12	25	32	R(P)
	Ne	13	20	25	R
	Ne	14	20	40	R
	Nw	15	25	35	R
	Nw	16	12	30	A
	Nw	17	25	35	R(P)
	Nw	18	12	20	A
5th	Wn	1	25	30	R
	Ws	2	20	25	R
	Sw	3	20	40	R
	Es	4	15	30	A
	Ne	5	20	25	AV
6th	Wn	1	22	30	A
	Sw	2	10	15	R
	Sw	3	10	25	R
	Sw	4	30	40	R
	Sw	5	20	40	R
	Sw	6	20	35	R
	Sw	7	30	30	R
	Nw	8	20	50	R
7th	Ew	1	20	25	R
8,9th	Es	1	15	25	R
	Es	2	20	30	R
	Average		20.4	30.6	

*
R : Rectoangle and Square
A : Trapezium
AV: Pentagon
(P): L-shape

Table 2 Position and shape of vertically placed blocks in Bayon First Gallery

the horizontally placed blocks in the walls exhibit a rectangular shape, about 40% of the vertically placed blocks in the wall have a trapezoidal shape, the short side of the trapezium being placed to the bottom (Plate, 1f). Furthermore, among the vertically placed blocks, about 10% were seen to be L-shaped.

On examining the number of vertically placed blocks used in each of the eight wall sections, there are 16 and 14 used respectively in the south side (W) and the east side (S), no more than three are used in each of the east side (N) and west side (S). Also, in considering the rows in which the vertically placed blocks are located, whereas the 2nd, 3rd and 4th rows have 12-18 stones, with the exception of the 6th row on the south side, the first row and rows from the fifth and higher have no more than 5 stones.

(2) Horizontally placed blocks

In each of the east, west, south and north walls, twenty horizontally placed blocks of average size with clearly developed cross-stratification are selected randomly and determined whether their placement was geologically normal or inverse (Plate, 1g) The results are shown in Table 3. In each wall, 40 to 60% of the stones had been placed inversely and no clear regularity could be recognise. Also, in cases where a succession of several horizontally placed blocks with prominent parallel laminations had been placed sideways, usually they had been cleverly placed with the sedimentary structures continuously aligned (Plate, 1h).

WALL	North	West	South	East
Total number of examined blocks	20	20	20	20
Number of inversely placed blocks	8	7	14	10

Table 3 Number of blocks normally and inversed horizontally placed blocks in Banteay Kdei and Prah Khan.

3. Northern Entrance

All the blocks used in the steps at the northern entrance have been placed horizontally. By contrast, several vertically placed blocks in the floor are noticed, two small vertically placed blocks with exposed parts

measuring about 20 x 30 cm, which are used in the part of the floor closest to the steps, are particularly noticeable. On the other hand, not confined to the northern entrance but in all places in the Bayon, there are two main methods of using sandstone building stone for columns. For columns up to 40 cm wide, a sandstone monolith is placed vertically (upright). By contrast, several pieces of horizontally placed blocks are piled up for columns of 40 cm or more. These two types of columns are frequently used in pairs in the passage ways of the gallery (Plate, 2a).

V Banteay Kdei and Prah Khan

At Banteay Kdei and Prah Khan, centred on the galleries and No 2 perimeter wall, no more than describe the sedimentary structures were done which could be recognized in the sandstone blocks and look at their placement directions in summary. In each of the monuments prominent sedimentary structures could be recognised in more than half of the sandstone blocks, nearly all of them being parallel laminations and cross-stratification, similar to the Bayon features but, at Banteay Kdei main sanctuary, the upright parts of the window frames were herringbone stratified sandstone (Plate, 2b) and wave ripple patterned sandstone has been used for the bottom parts of the same windows (Plate, 2c).

Except for the cases where they have been used to construct window frames and entrances, hardly any vertically placed blocks can be recognised in either of the monuments. As to whether horizontally placed blocks have been placed geologically normal or inverse, the same method as was used in Bayon was applied to 40 stones selected at random from each site. The results are shown in Table 4. In both monuments, the number of upside down stones was extremely low.

	Banteay Kdei	Prah Khan
Total number of examined blocks	40	40
Number of inversely placed blocks	3	5

Table 4 Number of blocks normally and inversed horizontally placed blocks in Banteay Kdei and Prah Khan.

VI Discussion

1. Factors controlling the size of sandstone blocks

Horizontally placed blocks seen in the walls of the Bayon First Gallery all seem to have a uniform height of about 25 cm. The sedimentary structures observed in these blocks, cross-stratification in particular, often exhibit the sort of complete form seen in field strata, the upper and lower parts seldom being cut off (Fig. 7). Multiple

Fig. 7 General form of cross-stratification seen in field strata and complete and incomplete sections seen in sandstone blocks.

cross-stratification in one building stone is also seldom noticed. The same sort of thing can be seen in the Bayon North Entrance and First Gallery columns, etc. These facts suggest the possibility that when the blocks were quarried, a single stratum of sandstone (a layer of field stone demarcated by prominent upper and lower erosion surfaces or primary depositional surfaces) was cut out and used for building blocks. In other words, each block was not cut out of a huge lump of sandstone, but the constant thickness of the layer of sandstone was the factor which determined the size of the blocks and this thickness might be used as a standard measure.

On looking at the strata in the field, sandstone strata with well developed parallel laminations and cross stratification often have thin intercalated mudstone layers which are generally some centimetres thick. Actually at Phnom Bakheng such sections are exposed along the approach road (Plate, 2d). Such mudstones encased in sandstone can be observed in the sandstone blocks of the Bayon First

Gallery (Plate, 2e). Consideration of these matters seems to confirm the existence of thin mudstone layers in the sandstone quarries. Thin mudstone layers such as those seen in the outcrop at Phnom Bakheng are frangible and easily separate into thin flakes which not only renders them unsuitable as building block material but also means that if they are enclosed within the block they form a line of weakness which makes the whole block prone to failure. However, the Phnom Bakheng mudstones form a flat smooth surface and, if similar mudstone strata were to occur in the quarry, that surface would not only be suitable as a reference surface but its brittleness would make it effective as a cutting plane for obtaining building blocks from the sandstone above and below. The local craftsmen at the time would have been aware of these facts and they would have put these features displayed by the mudstone layers to practical use as reference surfaces and cutting planes for quarrying the blocks.

As discussed above, the size of the blocks used at Bayon was not controlled by the transportation and building technology at the time but the local craftsmen at the time placed a high value on making the best use of the various features of the sandstone strata which were in the quarry.

2. Vertically placed blocks in Bayon

(1) Purpose of vertically placed blocks

Vertically placed blocks in the Bayon Upper Terrace, which was constructed of blocks laid horizontally, were frequently used near the borders between the different placements of blocks from outside and inside the terrace and around the sub-sanctuaries where the block placement was particularly complicated. In general they are smaller than the horizontally placed blocks. This is also the case with the North Entrance and the steps. On the other hand, in the inner wall of the First Gallery, where blocks are piled vertically, 0-5 vertically placed blocks are used in the rows of each wall and, as in the Upper Terrace, they are generally smaller than the horizontally placed blocks and the number used varies with the height of the wall.

In cases where sandstone with prominent parallel laminations and cross stratification is used for flat blocks in floors and walls, the load on each block is mainly

vertical compression and it will be stronger if the stratified face, which is physically more likely to break, is parallel to the ground. This difference is particularly significant in weakly consolidated sandstones and it is for this reason that the blocks have been placed horizontally in nearly all parts of Bayon. Also, as discussed above, assuming that the sandstone strata in the quarry had a uniform thickness in the ground, the fact that it would be easy to obtain blocks of uniform thickness was also a probable reason for using them horizontally. However, when the floors and walls were being constructed by laying the blocks side by side and there were final gaps to be closed, vertical placement, which makes the sedimentary structure (parallel lamination in particular) parallel to the cut surface, would provide the advantage of easy fine adjustment. This is supported by the facts that the vertically placed blocks in the Bayon Upper Terrace and walls are generally smaller than the horizontally placed blocks and that they nearly all have well developed parallel laminations. Also, almost half the vertical blocks observed in the walls are trapeziums was to close gaps and also to act as wedges to give greater strength to the wall.

(2) Number of vertically placed blocks used in the walls of the Upper Terrace and First Gallery

On looking at the Upper Terrace in four sections, there are clear differences in the numbers of blocks, including vertically placed blocks, which are used in each section. Nearly 20% more blocks are used in the southwest section than in the northwest section which has almost the same area and this number is also clearly greater than those for the northeast and southeast sections which have a greater area. This means that the blocks in the southwest section are smaller than in the other three sections. It be thought that blocks of adequate size were difficult to obtain, in other words, good quality blocks were unobtainable because the final construction work was in the Upper Terrace, or perhaps the transportation of large blocks was impossible because of the onset of the dry season (Hirayama et al, 1992) and this is supported by the large number of vertically placed blocks used to fill gaps between the blocks in this section. On the other hand, in the northeast section there is a tendency for more vertically placed blocks to have been used than in the southeast section almost the same area but a more difficult flat

shape. Any obvious difference in the size of blocks used both these sections is not observed and the reason for this difference in the number of vertically placed blocks used may be that, at the time Bayon was constructed, the techniques in each section were different because of different people in charge or different groups of workmen, or the work was done in different seasons.

Even though some parts of the upper walls were unobservable due to collapse and plant overgrowths, the liberal use of vertically placed blocks in the internal walls of the First Gallery is quite clear, in the 2nd to 4th rows in particular. Considering that when one section of wall was constructed, the blocks were placed one row at a time from the bottom, if the blocks were placed either to the left or to the right, or in both directions, it should have been possible to close the gaps with one or less vertically placed blocks in each row. The fact that few vertically placed blocks are used in the first row, which is the base for constructing the wall, implies that this is a valid working method. By contrast, the use of several vertically placed blocks in the 2nd to 4th rows indicates that the blocks began to be laid in several places. The 2nd to 4th rows (30 cm to 1 m above the floor) are at a convenient height for a man to stand and work and, since the blocks used for wall construction have an average weight of 40-60 kg each, they could be lifted into place by two men. Consequently, at the time the walls were constructed, after the first row of blocks had been placed precisely, the 2nd to 4th rows were made by several workers laying the blocks by hand at several places along the wall. Then for the 5th and higher rows, where hand work only would be difficult, therefore equipment such as scaffolding would be used (Ishizawa, 1989) to lift up the blocks one at a time at a certain place along the wall and place them horizontally from that place.

3. The incidence of geologically normal or inversed orientation of horizontally placed blocks in the three monuments

In the study of the various monuments, mainly the First Galleries, when the geologically normal or inversed orientation of horizontally placed blocks was examined, a significant difference was noticed between the Banteay Kdei and Prah Khan monuments and Bayon, the former two having

almost all blocks laid normally. By contrast, at Bayon, almost half the blocks were laid normally and half were laid inversely which means they were laid without regard to top and bottom.

Ignoring for the moment the differences in physical strength due to placing blocks normally or inversely and considering the fact that at Phnom Kuhlen where the blocks were quarried, the sandstone strata are flat or gently dipping (US Geol. Survey, 1971; Workman, 1975), the normal placement of so many of the blocks at Banteay Kdei and Prah Khan had some artificial or natural cause. Artificial causes might include the quarry master and the construction site supervisor being the same person, or of the same group, and when the blocks which were transported to the construction site were distributed to each section as construction materials, care was taken that the sandstone strata exposed in the quarry could be restored at the construction site, in other words that it would look natural. As a natural cause on the other hand, it is possible that the material remained horizontal throughout the processes of quarrying, subsequent transportation and delivery to the construction site where the blocks were cut. The fact that horizontally placed blocks were used at Bayon without regard to orientation means that perhaps such care was not taken or a different method of transportation was used.

4. Internal sedimentary structures in the blocks at the three monuments

At Banteay Kdei and Prah Khan, blocks can be seen which have sedimentary structures such as herringbone cross stratifications and wave ripples in addition to the parallel lamination and cross stratification observed in the blocks at Bayon. In each case, the depositional environment indicated by these sedimentary structures is a shallow shelf or estuarine which are conducive to the formation of parallel laminations and cross stratification. However, the fact that the sedimentary structures which are observed in the blocks at Banteay Kdei and Prah Khan are not discovered at Bayon suggests that the blocks were taken from a different quarry or at a different period.

5. Comparison with pre-Bayon style buildings

Compared with the three Bayon style temples, the blocks used at Pre-Bayon style buildings such as Angkor Vat are often larger and made from sandstone whose internal structure is unclear (Plate, 2f). Internal sedimentary structures are displaced surface properties leading to lines of weakness which invite breakage, so it is clear that sandstones in which these are developed are unsuitable for building blocks. At Bayon also, sandstones with sedimentary structures which are unclear are frequently used for dynamically important components such as columns constructed from single sandstone blocks. In other words, the frequent use of blocks with well developed sedimentary structures in the three Bayon style temples which are the subject of this study, as has been indicated up to now (for instance Ishizawa, 1986), indicates a scarcity of good quality blocks at that time and the good quality blocks were probably specially selected for use in important parts of the buildings such as columns and gables.

Vertically placed blocks were also found among the blocks laid in the west access road leading to the front of Angkor Vat (Plate, 2g). These blocks were laid for the same reasons as similar blocks in the Bayon Upper Terrace, etc.

6. Were the walls of the Bayon First Gallery painted?

On looking at two or more continuously aligned, horizontally placed blocks in the walls of Bayon First Gallery, they are usually placed so that the sedimentary structures of the left and right blocks appear continuous. It could be thought that this is primarily for reasons of appearance but no necessity for this if, as has been indicated up to now (Ishizawa, 1989), the walls were coloured after the blocks were set in place. The fact is that at least a part of the walls of the Bayon First Gallery were bare sandstone and it is possible that at the time of construction of the First Gallery, it had already been decided that the walls would be unpainted.

VII Subjects for the Future

Due to restricted time, in this survey no more than observations were done in respect of Bayon, Banteay Kdei and

a part of Prah Khan. However, from a sedimatological viewpoint, a number of rules could be made concerning the method of placement of the blocks in the various temples and the discovery of these would give a handle to clarifying temple construction methods and the sequence of construction of the parts of the temples. There, in the future, firstly a detailed survey of the size, placement method, and sedimentary structure of each block in these three temples, statistical processing of the results, has the potential for making these discoveries more objective and detailed. Then, since the same block placement was carried out at Angkor Vat also, by comparing the results of the same sort of survey carried out on various temples of another period could be expected to throw some light on the dynastic changes.

On the other hand, of the investigated three temples certain sedimentary structures are observed in the Banteay Kdei and Prah Khan blocks which are not recognised at Bayon. This suggests that the quarries for the blocks were different or different periods of extraction from the same quarry. In order to clarify this point a future field study of the Phnom Kuhlen hill is needed to investigate the geological structures and internal sedimentary structures of the sandstone strata.

VIII Conclusions

1. Internal sedimentary structures of sandstone blocks are described at the Bayon Upper Terrace, First Gallery and North Entrance and at Banteay Kdei and Prah Khan, and the placement directions of the blocks are studied which derive from the descriptions.
2. About 2.6% of the total number of blocks in the Bayon Upper Terrace have been placed vertically to fill gaps and there are differences in the frequency of usage in various parts of the terrace.
3. Vertically placed blocks in the Bayon First Gallery have been used in the same manner as in the Upper Terrace, often being used in the 2nd to 4th rows in particular.
4. The sizes of blocks in the three Bayon style temples are controlled by the thickness of sandstone beds in the quarry.
5. It is possible that the blocks for Banteay Kdei and Prah Khan and the blocks for Bayon were derived from different quarries or from different quarrying periods.
6. It is possible that the blocks for Banteay Kdei and Prah

Khan and the blocks for Bayon were transported by different methods or by different groups of workers.
7. The abundant use at the three Bayon style temples of sandstone with well developed sedimentary structures suggest a shortage of good quality building blocks.
8. There is a possibility that at least a part of the walls of the Bayon First Gallery were not painted.

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Fig. 1 : Three dimensional construction of internal sedimentary structure. (simplified from Allen, 1982)

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a: Block with well developed parallel laminations (height 35 cm) in Banteay Kdei Main Temple wall.
b: Block with well developed cross stratification (height 20 cm) in Bayon First Gallery inner wall.
c: Vertically placed block (15x30 cm : arrow) in Bayon Upper Terrace floor.
d: Several consecutive vertically placed blocks (from arrow) in Bayon Upper Terrace floor.
e: Vertically placed block (centre : height 20 cm) in Bayon First Gallery inner wall.
f: Trapezoidal vertically placed block (centre : height 20 cm) in Bayon First Gallery inner wall.

g: Upside down horizontally placed block in Bayon First Gallery inner wall (height 25 cm. Arrow shows erosional surface).
h: Example of continuous sedimentary structure (cross stratification) in horizontally placed blocks in Bayon First Gallery inner wall (particularly noticeable near arrow).

Plate 2

a: Group of columns near Bayon North Entrance (one vertical sandstone monolith and one composed of several horizontally placed blocks).
b: Well developed herringbone cross stratifications (arrow) in a block (width 40 cm) in Banteay Kdei main temple.
c: Well developed wave ripples (arrow) in a block in Banteay Kdei main temple. Coin diameter 22 mm.
d: Exposed strata at Phnom Bakheng east side approach road (the flat white patch is the upper surface of a mudstone layer).
e: Mudstone enclosed by sandstone, seen in a sandstone block in Bayon First Gallery inner wall (arrow : enclosed mudstone length 15 cm approx.).
f: Angkor Vat Central Sanctuary sandstone block with uncertain stratification (width 50 cm approx.).
g: Vertically placed blocks in Angkor Vat western approach road (center : width 30 cm approx.).