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TOWARDS A QUANTITATIVE PETROGRAPHIC DATABASE OF KHMER STONE MATERIALS—KOH KER STYLE SCULPTURE*

F. CARÒ

Department of Scientific Research, The Metropolitan Museum of Art, New York, NY 10028-0198, USA

J. G. DOUGLAS

Department of Conservation and Scientific Research, Freer Gallery of Art and Arthur M. Sackler Gallery,
Smithsonian Institution, Washington, DC 20013-7012, USA

and S. IM

APSARA Authority, Siem Reap, Cambodia

A comprehensive quantitative petrographic database of sandstones used by the Khmers for sculptural purposes would be a helpful tool for archaeologists, museum curators and others interested in pursuing research on early stone usage, geological source and provenance. Towards that end, this paper presents quantitative petrographic analysis of stone materials used in the production of some free-standing sculptures and architectural elements in the Koh Ker style of the 10th century from the collections of the National Museum of Cambodia and The Metropolitan Museum of Art. These materials are compared to samples from the quarry of Thmâ Anlong near the foothills of the Phnom Kulen, Sieam Reap province. Primary and secondary detrital modes and key grain-size parameters are used to identify three sandstone types. The free-standing sculptures are carved from feldspathic arenite and feldspato-lithic to litho-feldspathic arenite. Finely carved lintels are worked from a quartz arenite, which is significantly richer in quartz grains and of a finer grain size. The geological source of the two other lithotypes will have to await detailed geological survey of the Koh Ker area accompanied by petrographic study of selected samples from documented quarries. The significance and potentiality of quantitative petrographic study of Khmer stone materials are shown in supporting and integrating archaeological investigations in South-East Asia.

KEYWORDS: SANDSTONE, PETROGRAPHY, PROVENANCE, CAMBODIA, SCULPTURE, POINT COUNTING

INTRODUCTION

Petrographic characterization of stone material used in Khmer sculpture has been shown recently to be an important source of information about trends of stone usage in Khmer art and may eventually be useful in the identification of the location of main sources of raw materials (Douglas 2004; Douglas and Sorensen 2007). The current study focuses on the petrography of the sculptural production of Koh Ker style, dating to the 10th century. New samples from

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sculptures and sandstone outcrops have been obtained during an ongoing project at The Metropolitan Museum of Art to study the South-East Asian stone sculpture collection. Thus, seven Khmer sculptures have been added to a group of four Koh Ker style sculptures from the National Museum of Cambodia (Douglas 2004) and to two sandstone samples taken from an abandoned quarry located in the province of Siem Reap, 45 km south-west of Koh Ker. The enlarged group of Koh Ker style sculptures therefore includes both well-provenanced materials from the National Museum of Cambodia and those materials of unknown provenance from The Metropolitan Museum of Art, which have been the subject of detailed art-historical and related technical study.

Several published studies present overviews of Khmer stone petrography: the study of stone materials of Angkor Wat (Delvert 1963), which integrates an earlier work of Saurin (1954); the study of the building materials of the Angkor complex by the Japanese research team headed by Etsudo Uchida, which has been presented in several publications (e.g., Uchida *et al.* 1998); the survey of about 50 sculptures from the Musée Guimet collection (Baptiste *et al*. 2001); and the study of 29 sculptures from the National Museum of Cambodia (Douglas 2004; Douglas and Sorensen 2007). Additionally, petrographic descriptions of Khmer stone sculptures have been published as appendices in broader art-historical studies of South-East Asian art (Woodward 1994/5; Newman 1997).

The study of stone materials from this selection of Koh Ker sculptures is aimed at enlarging the existing database of Khmer stones by adding quantitative petrographic data, which will provide useful insight into the question of stone usage and geological source of sandstone used by the Khmers during the development of Koh Ker as capital of the Khmer empire. A quantitative approach to the study of stone sculptural material from Cambodia, which allows us to describe some distinctive petrographic characteristics, can be used in art-historical studies of sculptures of unknown provenance, and well as for the development of guidelines for the identification of the most probable sites of material provenance.

GEOLOGICAL BACKGROUND

Koh Ker, the primary political centre of the Khmer empire at the beginning of the 10th century (Jacques and Lafond 2004), is located in northern Cambodia, in the province of Preah Vihear. The region lies between the Khorat plateau at the Thailand border to the north and the Tonle Sap Lake to the south. The topography in the Koh Ker area is marked by notable highlands (the Khmer word for highland is 'phnom'), which arise abruptly from the vast Quaternary sediment deposits of the Mekong and the Tonle Sap rivers. These isolated buttes have variable extensions, but generally their surface does not exceed a few square kilometres.

In the considered area, the plateaus are constituted by Lower–Middle Triassic volcano-sedimentary units, Lower–Upper Jurassic sedimentary units and by smaller Pliocene–Pleistocene basalts and related sedimentary deposits (Fig. 1). The volcano-sedimentary units are exposed in moderate relief 30 km south of Koh Ker and in smaller buttes 20 km north. North of Koh Ker, the Upper Carboniferous unit is represented by greyish black limestone, while southward they are mostly constituted by intermediate extrusive rocks overlain by Triassic rhyolitic tuffs.

Jurassic sandstones constitute the main subhorizontal tablelands of northern Cambodia. The Khorat Plateau in the north, the Phnom Kulen in the south and the Phnom Tbaeng east of Koh Ker are the broadest outcrops of sedimentary rocks in the area (Tien *et al*. 1991; United Nations 1993; Sotham 1997).

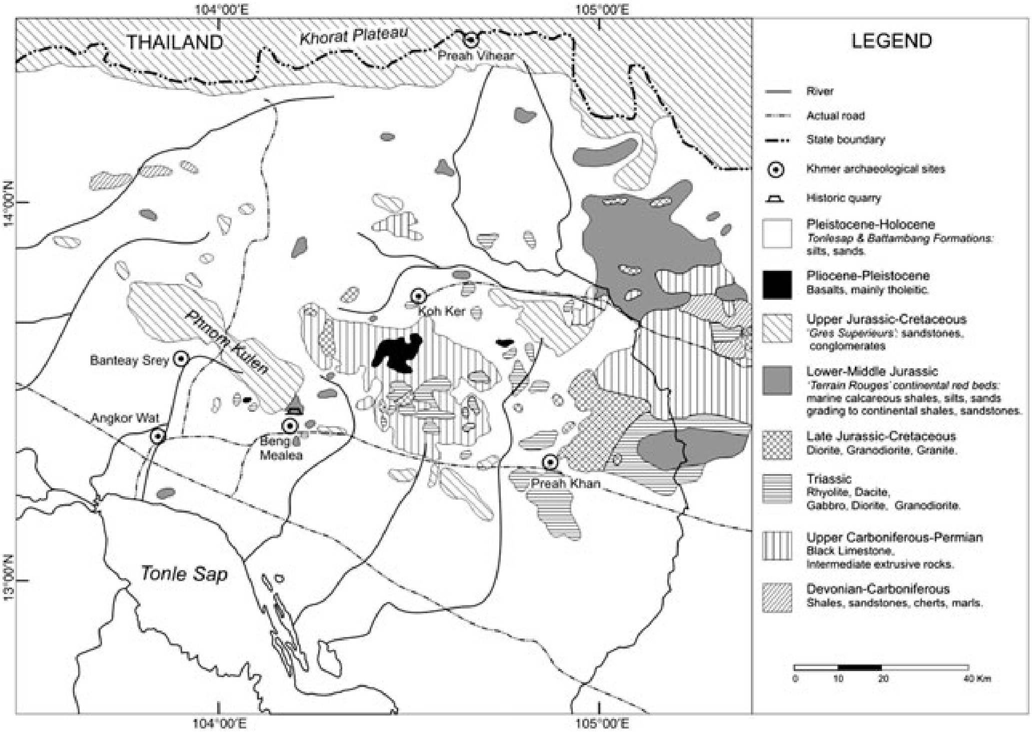

Figure 1 *A schematic geological map of the area around Koh Ker, with the location of the Thmâ Anlong quarry and the major Khmer archaeological sites (modified after United Nations 1993).*

Lower–Middle Jurassic rocks mostly occur in isolated outcrops and comprise conglomerates, sandstones and siltstones of continental origin, which are known under the name of *Terrain Rouge* or Red Sandstone (Tien *et al*. 1991; United Nations 1993; Sotham 1997). In northern Cambodia, this Lower–Middle Jurassic unit is covered by shallow Quaternary sediments. As a consequence, sandstone also crops out horizontally in numerous river beds and other natural cuts in Siem Reap and in Preah Vihear provinces, and all over the site of Koh Ker (Parmentier 1939; Delvert 1963; Moriai *et al*. 2002; Jacques and Lafond 2004). However, this occurrence is not mapped in detail in the published geological maps (Tien *et al*. 1991; United Nations 1993; Sotham 1997). A generalized survey of the geology of the area surrounding Koh Ker is given by Moriai *et al*. (2002), who report a schematic east–west geological section where Jurassic sandstone is found 2–3 m below a residual soil that originated from the weathering of the bedrock.

Upper Jurassic conglomerates and sandstones, known as *Grès supérieures* or Upper Sandstone because of their occurrence in mountain crests, constitute the south margin of the Khorat Group, the Phnom Kulen and other isolated outcrops in the Siem Reap and Preah Vihear provinces, playing an important role in the geomorphology of northern Cambodia (Tien *et al*. 1991; United Nations 1993; Sotham 1997).

The upper horizons of the Lower to Middle Jurassic units and the Upper Jurassic units are thought to have provided much of the building and sculptural material in the area during the whole Khmer empire (Uchida *et al*. 1995; Baptiste *et al*. 2001; Douglas 2004). Evidence of multiple episodes of quarrying is present near Beng Mealea at the foot of Phnom Kulen and in the bed of the Mealea River, where the upper horizons of Lower to Middle Jurassic arkosic arenite are cropping out in horizontal layers (Delvert 1963). Previous studies of Khmer stone material suggest that other sources have been exploited through time, both from Triassic and Jurassic units (Delvert 1963; Uchida *et al.* 1995, 1996; Uchida and Maeda 1998; Uchida and Ando 2001; Douglas 2004).

In Koh Ker, the rock carvings on the sandstone outcrop known as Ang Khna are thought to be realized on the vertical surfaces of an abandoned and partially buried quarry (Jacques and Lafond 2004). Moriai *et al.* (2002) report an important pit quarry in the river bed of the O'Talik, about 8 km north of Koh Ker, where massive sandstone monoliths 5 m long are still present on the ground. Although quarried from strata close to the surface, this sandstone shows good mechanical properties compared to similar lithologies from northern Cambodia (Moriai *et al*. 2002). In a recent field survey, we counted at least two other quarries in addition to the two above-mentioned sites, and multiple sandstone outcrops having similar attitudes scattered in the surroundings of Prasat Thom.

The Lower to Middle Jurassic sandstone represents here a massive stone source that potentially could have provided an adequate supply for both building and sculptural purposes in Koh Ker.

SCULPTURE AND QUARRY SAMPLES

The samples from sculpture from the National Museum of Cambodia were generated during ongoing conservation work at the museum headed by Bertrand Porte, École Française d'Extrême-Orient (EFEO) (see Porte 2001, 2002).

The samples from sculpture at The Metropolitan Museum of Art were obtained within the framework of an ongoing project aimed at the characterization of the stone materials used in Khmer sculpture within The Metropolitan's collections. Free-standing sculptures have been sampled from areas affected by previous breaks or loss of material, generally located at the back of arm or leg joints. Lintels have been sampled from the bottom edges adjacent to existing surface losses. Table 1 reports the description of the studied Koh Ker sculptures, while Figure 2 shows a selection of the studied sculpture from the collection of The Metropolitan Museum of Art.

Samples from the Lower–Middle Jurassic continental unit were collected from a quarry located near the village of Trapeang Russei, in the commune of Beng Mealea, 45 km east of Angkor (Fig. 1). This site comprises two main quarries known by the names of Thmâ Anlong and Veal Vong, and, together with O Thmâ Dap and Phnom Bei, forms a well-known quarrying district in the Kulen area (Delvert 1963). The sandstone is exposed over a vast area, which shows remains of ancient open quarrying near the foothills of Phnom Kulen, 2 km west of O Thmâ Dap. The quarry remains suggest that stone blocks, about 1 m in height, were removed with chisels following the horizontal bedding of the sandstone terraces (Fig. 3). Our samples have been taken directly from the quarried outcrop, in such a way that both weathered and fresh stone are present in a single fragment.

ANALYTICAL METHOD

Standard thin sections with a nominal thickness of 30 µm have been prepared from stone fragments embedded in epoxy resin. For each sample, the maximum number of detrital grains was counted and each grain classified and measured by means of a micrometric eyepiece, using a Zeiss Axioplan II polarized light microscope. Counts varied according to the dimension of samples and on the grain size and sorting of the rock, but usually at least 300 points have been counted.

Table 1 *Descriptions of the studied Koh Ker sculptures*

Sample	*Object description*	*Provenance*	*Sample location*
Sculpture from the National Museum of Cambodia			
K890	Head of Siva	Prasat Kraham, Koh Ker	–
K1807	Lion	Prasat Thom, Koh Ker	–
K1667	Siva	Prasat Chrap, Koh Ker	–
K1817	Siva	Prasat Chrap, Koh Ker	–
Sculpture from The Metropolitan Museum of Art			
1987.308	Guardian Figure	Unknown provenance probably Koh Ker, Preah Vihear Prov.	Proper left leg break at lower front edge
1989.100	Head of Kneeling Male Attendant or Guardian (now attached to body, 1992.390.2)	Unknown provenance probably Koh Ker, Preah Vihear Prov.	Back of proper right ear lobe, at edge of break
1992.390.1	Kneeling Male Attendant or Guardian Figure (with head, 1987.410)	Unknown provenance probably Koh Ker, Preah Vihear Prov.	Bottom outer edge of proper right leg, at ankle
1992.390.2	Kneeling Male Attendant or Guardian Figure (with head, 1989.100)	Unknown provenance probably Koh Ker, Preah Vihear Prov.	Outside proper right ankle near underside of upper leg
2003.605	Standing Female Deity	Unknown provenance probably Koh Ker, Preah Vihear Prov.	Inside of proper right ankle
36.96.6	Lintel with carved figures	Unknown provenance probably Koh Ker, Preah Vihear Prov.	Front of left bottom edge
1994.111	Lintel with Kala Head	Unknown provenance probably Koh Ker, Preah Vihear Prov.	Front of left bottom edge

Figure 2 *Sculptures and a lintel from The Metropolitan Museum of Art: (a) Kneeling Male Attendant or Guardian Figure, 1992.390.1; (b) Kneeling Male Attendant or Guardian Figure, 1992.390.2 and Head, 1989.100; (c) Standing Female Deity, 2003.605; (d) Guardian Figure, 1987.308; and (e) Lintel with Kala Head, 1994.111 (courtesy of The Metropolitan Museum of Art).*

Figure 3 *Views of the quarry of Thmâ Anlong near Beng Mealea showing: (a) the sandstone terrace, where the bedding is almost parallel to the surface; (b) the remains of one extraction site; and (c) detail of the tool marks left on the outcrop.*

In order to obtain the most information from the samples, the analyses were performed according to two different methods: the Pettijohn (Pettijohn 1975) and the Gazzi–Dickinson (Gazzi 1966; Dickinson 1970) classification methods. This allows us to study better the grain distributions from the differing perspectives of these two classification systems, and allows easier comparisons for samples studied by other researchers. The Gazzi–Dickinson method of point counting assigns sand-sized crystals within larger polymineralic fragments to the category of the single crystal or grain, rather than to the category of the larger rock fragment to which they belong. With this counting method, only rock fragments having a fine-grained texture are assigned to the class of the lithic grains (L*) (Ingersoll *et al.* 1984). This approach reduces the effect of grain size on modal composition due to the existing direct correlation between the size of grains and the amount of coarse-grained lithic fragments, minimizing the compositional variations among samples of different grain size caused by the physical disaggregation of polymineralic grains (Gazzi 1966; Dickinson 1970).

The Pettijohn method, however, classifies the terrigenous polymineralic grains by their origin only (volcanic, plutonic, metamorphic and sedimentary rock fragments) without dimension criteria. This criterion does not distinguish between fine or coarse minerals belonging to rock fragments. The differences between these two criteria increase as coarse polymineralic rock fragments increase (Di Giulio and Valloni 1992).

Key petrographic parameters according to both of the above-mentioned methods, as well as the grain-size distribution and key textural parameters, were derived by means of computer software modified after Balsillie *et al.* (2002). The nature of the grains and the size of the shorter and longer axes passing through the centre of mass of the each grain encountered at grid intersections along random directions were recorded using a micrometric eyepiece. The mean size is used to build up the frequency and cumulative grain-size distribution. Key grain-size parameters are presented according to Tucker (1991).

PETROGRAPHIC DATA—STONE TEXTURE AND COMPOSITION

All the analysed rock samples from the in Koh Ker style sculptures are fine, moderately well-sorted, mostly matrix-free sandstones, where the bulk of framework grains are formed by, in order of abundance, quartz, feldspar and rock fragments. The relative abundance of these three fractions and the type of the rock fragments are the key parameters that allow identification of three types of detrital sandstone. According to the Gazzi–Dickinson classification, the analysed sandstones are quartz arenite, feldspathic arenite and feldspato-lithic to litho-feldspathic arenite (Fig. 4 (a)). According to Pettijohn's classification, the sandstones are sublithic arenite, arkosic arenite and lithic arenite (Fig. 4 (b)). The texture is typical of moderately well-sorted, fine-grained sandstone, and shows little variation (Fig. 4 (c)).

Table 2 and Table 3 report primary and secondary detrital modes and key textural parameters of the studied samples, while Figure 4 graphically reports the framework compositional and textural classification diagrams.

Sculptures from the National Museum of Cambodia

Two samples from sculptures of known provenance (Head of Siva, K890; and Lion, K1807) are fine, moderately well-sorted feldspathic arenites according to the Gazzi–Dickinson classification, and correspond to arkosic arenite in Pettijohn's classification field (Fig. 4). The texture is variably laminated and shows evidence of diagenesis in the form of interlocking grains and quartz and

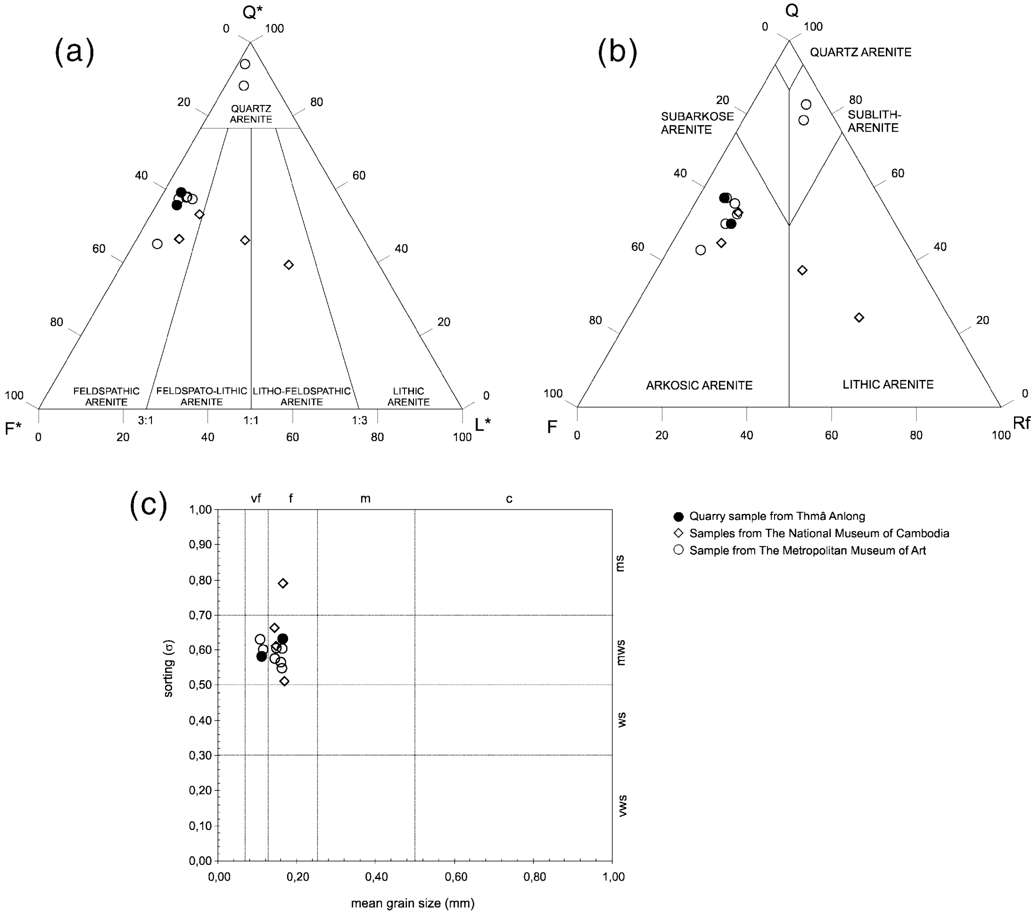

Figure 4 *A graphical representation of the key petrographic data: (a) the framework composition according to the Gazzi–Dickinson classification; (b) the framework composition according to the Pettijohn classification; and (c) a plot of mean grain size versus sorting.*

feldspar overgrowths. The dominant mineral is sub-rounded to angular mono- and polycrystalline quartz ($Q^* = 49.8 \pm 4.8\%$). Non-undulose quartz prevails over undulose quartz. Alkali feldspar ($31.4 \pm 1.3\%$) exceeds plagioclase ($5.6 \pm 3.7\%$), while rock fragments constitute $10.7 \pm 1.0\%$ of the entire framework volume. The lithic fraction reflects mostly a metamorphic source, and comprises, in order of abundance, microcrystalline quartz, phyllite, micaceous schist, elongated quartzite, siltstone, shale and basaltic to rhyolitic volcanoclasts. Both muscovite and biotite are present ($2.2 \pm 0.4\%$) in the form of oriented and bent flakes. Chlorite is also common in small flakes. The heavy mineral fraction ($3.0 \pm 2.1\%$) is represented by hematite, epidote, zircon, green and brown hornblende, small pyroxene crystals, sphene, ilmenite and garnet. The framework grains are primarily cemented by chlorite.

Samples from the two Siva, K1667 and K1817, both from Prasat Chrap, differ from the other samples from the National Museum of Cambodia in their textural and compositional features. In particular, the framework is less sorted ($0.7 < \sigma < 0.8$) and richer in rock fragments compared to the other feldspathic arenites, where the abundance of rock fragments

Table 2 *The primary detrital grain parameters and textural characteristics of Koh Ker style stone sculptures and quarry samples from Thmâ Anlong: rock names are given in both the Gazzi–Dickinson* and Pettijohn† sandstone classification systems*

Sample	*Q** *(%)*	*F** *(%)*	*L** *(%)*	*Rock name (Gazzi–Dickinson classification)*	*Q* *(%)*	*F* *(%)*	*Rf* *(%)*	*Rock name (Pettijohn classification)*	*Mean (mm)*	*Median (mm)*	*Sorting, σ*	*Cement type*	*Cement (%)*	*Matrix (%)*
Sculpture from the National Museum of Cambodia														
K890	46.4	43.6	10.0	Feldspathic arenite	44.8	43.6	11.6	Arkosic arenite	0.14	0.15	0.62	C	0.3	8.2
K1807	53.1	35.4	11.5	Feldspathic arenite	47.4	35.4	17.2	Arkosic arenite	0.17	0.17	0.52	C	0.9	3.8
K1667	46.1	28.2	25.7	Feldspato-lithic arenite	37.3	28.2	34.4	Lithic arenite	0.14	0.14	0.66	C	5.3	5.0
K1817	39.4	21.3	39.4	Litho-feldspathic arenite	24.5	21.3	54.3	Lithic arenite	0.16	0.17	0.78	C	1.9	4.7
Sculpture from The Metropolitan Museum of Art														
1987.308	45.1	49.5	5.5	Feldspathic arenite	42.9	49.5	7.7	Arkosic arenite	0.15	0.16	0.61	C	6.5	2.8
1989.100	57.9	36.0	6.1	Feldspathic arenite	52.6	36.0	11.4	Arkosic arenite	0.15	0.16	0.58	C	0.8	6.8
1992.390.1	57.4	38.0	4.7	Feldspathic arenite	52.7	38.0	9.3	Arkosic arenite	0.16	0.16	0.63	C	4.4	8.2
1992.390.2	55.6	37.5	7.0	Feldspathic arenite	54.2	37.5	8.3	Arkosic arenite	0.16	0.17	0.55	C	10.9	4.3
2003.605	57.3	35.0	7.7	Feldspathic arenite	55.6	35.0	9.4	Arkosic arenite	0.16	0.16	0.57	C	2.6	11.0
Decorative lintels from The Metropolitan Museum of Art														
36.96.6	94.1	4.2	1.7	Quartz arenite	83.1	4.2	12.7	Sublitharenite	0.12	0.12	0.60	K	11.0	2.1
1994.111	88.2	7.5	4.3	Quartz arenite	78.3	7.5	14.3	Sublitharenite	0.11	0.11	0.63	K	15.9	2.3
Quarry samples from Beng Mealea														
1C	59.1	36.8	4.1	Feldspathic arenite	57.0	36.8	6.2	Arkosic arenite	0.11	0.11	0.58	C	18.3	2.5
2C	55.6	39.5	4.8	Feldspathic arenite	50.0	38.7	11.3	Arkosic arenite	0.16	0.17	0.63	C	16.9	3.0

* Gazzi–Dickinson classification system: Q*, mono-, poly- and microcrystalline quartz grains + quartz (>62 µm) in rock fragments; F*, feldspars + feldspars (>62 µm) in rock fragments; L*, fine-grained lithic fragments.

† Pettijohn classification system: Q, mono- and polycrystalline quartz grains; F, feldspar grains; Rf, total rock fragments (including chert); C, chlorite; K, kaolinite.

Table 3 *Secondary detrital grain parameters of Koh Ker style stone sculptures and quarry samples from Thmâ Anlong*

Sample	*C/Q**	*Q_O/Q*	*P/F*	*V/L*
Sculpture from the National Museum of Cambodia				
K890	0.17	0.23	0.20	0.36
K1807	0.21	0.13	0.09	0.41
K1667	0.32	0.23	0.12	0.15
K1817	0.54	0.16	0.20	0.24
Sculpture from The Metropolitan Museum of Art				
1987.308	0.17	0.26	0.23	0.80
1989.100	0.14	0.58	0.15	0.43
1992.390.1	0.11	0.47	0.20	0.67
1992.390.2	0.15	0.46	0.13	0.60
2003.605	0.16	0.51	0.17	0.33
Decorative lintels from The Metropolitan Museum of Art				
36.96.6	0.18	0.16	0.00	0.00
1994.111	0.18	0.42	0.00	0.14
Quarry samples from Beng Mealea				
1C	0.13	0.24	0.10	0.33
2C	0.19	0.19	0.11	0.00

*C/Q, ratio of polycrystalline and cryptocrystalline quartz (C) to total quartz (Q); Q_O/Q, ratio of quartz with undulatory extinction (Q_O) to total quartz (Q); P/F, ratio of plagioclase (P) to total feldspar (F); V/L, ratio of volcanic lithic fragments (V) to total lithic fragments (L).

is directly proportional to the decrease of sorting. The framework is composed of sub-rounded to angular mono-, poly- and microcrystalline quartz (39.4% < Q* < 46.1%) and by plagioclase and alkali feldspar and lithic fragments in similar proportions (21.3% < F* < 28.2; 25.7% < L* < 39.4%). The undulose to non-undulose quartz ratio and alkali feldspar to plagioclase ratio are similar to those of the other feldspathic arenite. The lithic fraction is dominated by fragments of phyllite and muscovite schist of variable dimension (Figs 5 and 6), microcrystalline and polycrystalline elongated quartz, smaller siltstone and shale fragments, and basaltic to rhyolitic rock fragments. Micas are accessory (2.6 ± 2.2%), while the heavy mineral fraction (2.7 ± 1.0%) is represented by epidote, zircon, garnet and by scattered opaque iron and titanium oxides. Grains are primarily cemented by chlorite, while secondary calcite is abundant, both as pore filling and replacement of detrital grains and matrix.

Sculptures from The Metropolitan Museum of Art

Five of the seven sculptures from The Metropolitan Museum of Art are feldspathic arenites or arkosic arenite, respectively, according to the Gazzi–Dickinson and Pettijohn classifications. The framework grains are sub-rounded to angular, fine and moderately well-sorted (Table 2) and are cemented by chlorite. Secondary quartz overgrowth and authigenic feldspar are also common. Thin sections reveal a laminated structure with evident compaction causing pressure-solution phenomena and plastic deformation of micas and sedimentary rock fragments. Mono-, poly- and microcrystalline quartz are the most abundant framework grains (Q* = 53.4 ± 6.0%). The

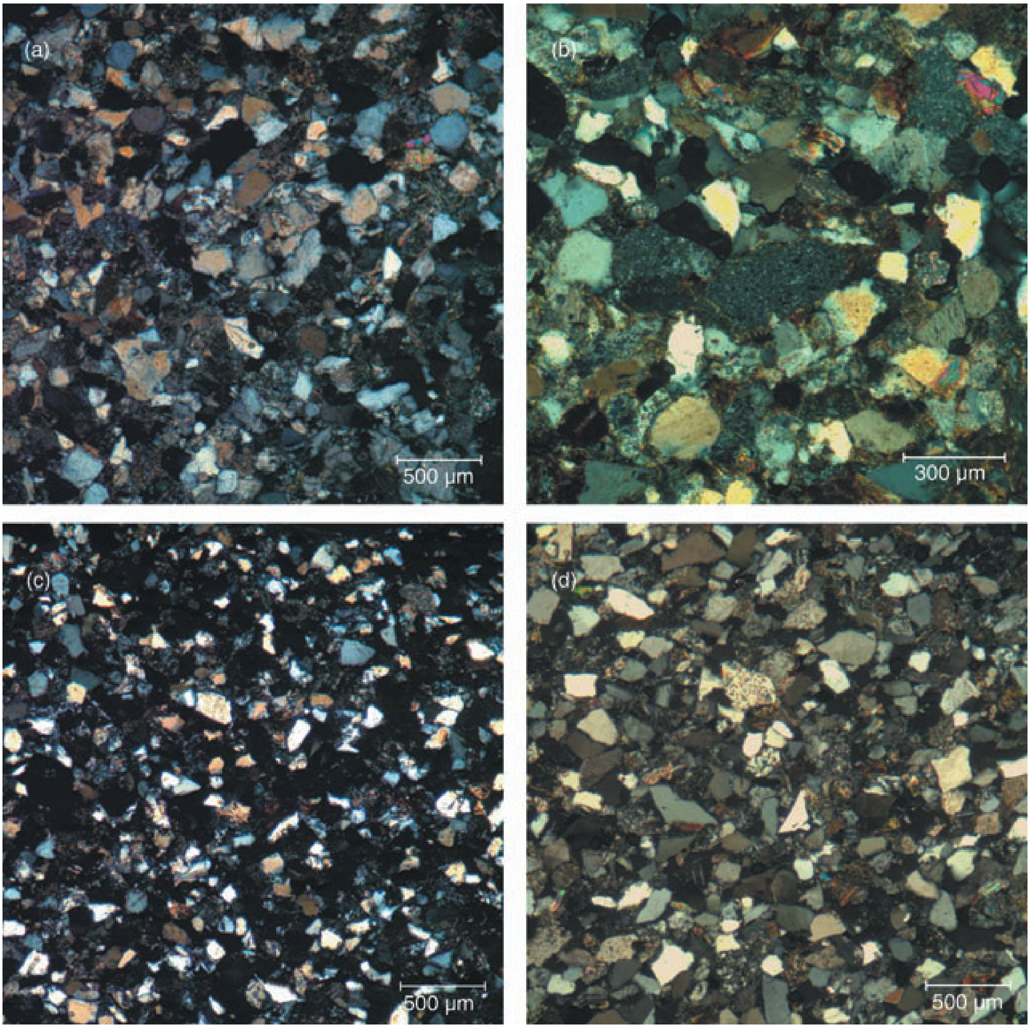

Figure 5 *Micrographs (crossed polars) showing the overall composition and texture of: (a) feldspathic arenite (Kneeling Male, 1992.390.2); (b) feldspato-lithic arenite (Siva, K1667); (c) quartz arenite (lintel, 36.96.6); and (d) the quarry sample from Thmâ Anlong (1C).*

mean ratio between non-undulose and undulose quartz is close to one. Feldspar is mostly alkali feldspar (30.5 ± 5.8%), while plagioclase is 6.8 ± 1.9% of the entire framework volume. Rock fragments (6.2 ± 0.9%) are represented by microcrystalline quartz, quartzite, phyllite, micaceous schist, siltstone, shale and basaltic to rhyolitic volcanoclasts, suggesting a mixed provenance influenced by a strong metamorphic source. Micas (1.8 ± 1.3%) and detrital chlorite are present as flakes bent between the framework grains. The heavy mineral fraction (2.4 ± 1.6%) comprises mostly hematite, magnetite, ilmenite, rutile, sphene, epidote, zircon, apatite and rare amphiboles.

The sandstone samples from the lintels 36.96.6 and 1994.111 are identified as quartz arenite or sublitharenite according to the Gazzi–Dickinson and Pettijohn classifications, respectively, in contrast to the sculpture samples described above. It has very fine, moderately well-sorted

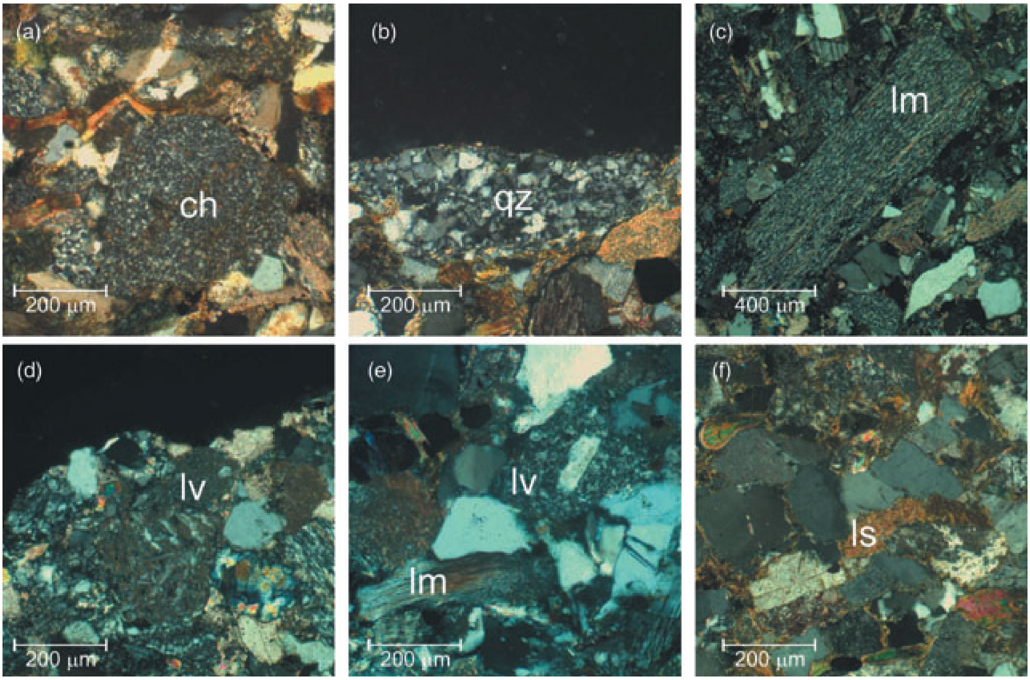

Figure 6 *Micrographs (crossed polars) showing characteristic lithic fragments: (a) chert (ch); (b) polycrystalline quartz (qz); (c) quartz–muscovite schist (lm); (d) andesitic rock fragment (lv); (e) a rhyolitic rock fragment (lv) and chlorite schist (lm); and (f) a sedimentary rock fragment (ls).*

detrital grains displaying a laminated structure (Fig. 5). The framework grains are mostly composed of sub-rounded to angular mono- and microcrystalline quartz ($88\% < Q^* < 94\%$), showing incipient overgrowth and cementation by kaolinite. Other accessory minerals are altered alkali feldspar ($4.2\% < F^* < 7.5\%$), muscovite flakes ($2.5\% < M < 3.5\%$), which tend to lie parallel to the lamination and are bent by the pressure of adjacent grains, and layered opaque minerals, mostly represented by ilmenite and fine-grained hematite. If microcrystalline quartz grains, which can reach 9.8% of the total rock volume, are excluded, the rock fragments are poorly represented ($1.7\% < L^* < 4.3\%$), only by small, elongated grains of micaceous schist. The heavy mineral fraction is almost absent. A diffuse film of hematite coating the grains and the interstices is responsible for the pink to reddish coloration of this stone.

The quarry samples of Thmâ Anlong

The sandstone samples from Beng Mealea are feldspathic arenites according to the Gazzi–Dickinson classification, and arkosic arenites according to Pettijohn (Fig. 4). The framework of this sandstone is composed of very fine to fine, moderately well-sorted, sub-angular to rounded grains, which show an evident laminated structure. In both of the samples, grains are well-packed and frequently show pressure-solution phenomena and plastic deformation, the latter mostly affecting rock fragments and micas (Fig. 5). The sandstone is cemented by a combination of chlorite and calcite, while quartz and feldspar partial overgrowths are also frequent.

Mono- and polycrystalline quartz is the most abundant fraction (57.4 ± 2.4%), followed by alkali feldspar (30.8 ± 0.6%) and by plagioclase (3.7 ± 0.3%) and occasional microcline. Non-undulose quartz prevails over undulose quartz. The rock fragment fraction (L*) is 4.5 ± 0.5% of the entire framework volume and is represented, in order of abundance, by microcrystalline quartz, quartzite, siltstone, phyllite, micaceous schist and basaltic to rhyolitic volcanoclasts. Sedimentary grains are usually rounded and deformed. Large micas are accessory (2.2 ± 0.0%) and usually parallel to the lamination and bent between adjacent grains. The heavy mineral fraction (3.5 ± 0.4%) is mostly represented by opaque hematite, magnetite and pyrite, and by rare epidote, zircon, garnet, hornblende, olivine and sphene. Occasional detrital chlorite flakes have been found.

DISCUSSION

The study of the Koh Ker sculptures and the samples from the site of Thmâ Anlong allows us to identify three main sandstone types, which can be distinguished by means of petrographic analysis. The key petrographic and textural characteristics of all the studied samples are reported in Table 2, and Figure 5 shows micrographs of the three lithotypes compared to the quarry samples of Thmâ Anlong.

The first sandstone type comprises the majority of the studied Koh Ker sculptures, and consists of feldspathic arenite. The framework is composed of very fine to fine, moderately well-sorted, subangular to rounded grains cemented by chlorite, and exhibits lamination and compaction textures (Fig. 5). Detrital grains are mostly composed of quartz, feldspar and rock fragments in a mean ratio of $Q_{53}F_{39}L_8$. Similar characteristics are found in the quarry samples of Thmâ Anlong.

A second type was identified in two sculptures from Prasat Chrap, which are composed of feldspato-lithic to litho-feldspathic arenite. This type of sandstone is composed of less well-sorted grains and is richer in rock fragments, in comparison to the other feldspathic arenites (Fig. 4). The average proportion of quartz, feldspar and rock fragments is $Q_{43}F_{25}L_{33}$. The rock fragments are of the same nature of the feldspathic arenite; that is, in order of abundance, microcrystalline and polycrystalline elongated quartz, phyllite and micaceous schist, siltstone and shale, and basaltic to rhyolitic rock fragments.

The third type of stone is a quartz arenite, which contains very fine, moderately well-sorted detrital grains displaying a laminated structure (Fig. 5). The framework grains are mostly composed of mono- and microcrystalline quartz cemented primarily by kaolinite.

According to the compositional and textural data, the first type of sandstone, feldspathic arenite, is consistent with the feldspathic arenite described by other authors (Delvert 1963; Uchida *et al.* 1998; Baptiste *et al.* 2001; Douglas 2004) (Tables 2, 3 and 4). This lithotype has also been called *grey or green sandstone*, *arkose*, or *grey to yellowish brown sandstone*, depending on the author (Table 4). It occurs extensively in architectural elements of the Angkor period (Delvert 1963; Uchida *et al.* 1995), but has also been identified in several sculptures of collections of similar age of the Musée Guimet (Baptiste *et al.* 2001), the National Museum of Cambodia (Douglas 2004) and now in the collections of The Metropolitan Museum of Art.

Although most of the published data are qualitative only, it is possible to identify common distinctive textural and compositional characteristics, such as: the grain size, which varies from fine to medium (Fig. 4); the structure, which shows clear grain orientation and evidence of compaction (Fig. 5); and the characterizing relative abundance of quartz, feldspar and rock fragments (Tables 2 and 3). The comprehensive published petrographic and geochemical data

Table 4 *A resumé of existing petrographic data about stone materials used during the Khmer empire*

Author	*Adopted rock name*	*Composition*	*Texture*
Saurin (1954)	Sandstone from Banteay Srei	Quartz and rare quartzite in abundant clay cement rich in iron oxides (hematite); the colour of this sandstone can vary depending on the content of iron oxides	Fine-grained (0.1–0.2 mm), angular grains
	Green sandstone—arkose	Quartz, plagioclase, biotite often altered to magnetite, muscovite, magnetite and hematite. Quartzite, chert and schists are the main rock fragments. Accessory minerals are zircon, corundum and tourmaline. The cement is argillaceous with abundant chlorite. Calcite is also present as cement	Fine-grained (0.05–0.15 mm), well sorted, angular grains
	Green-grey sandstone from Ta Keo	Quartz, K-feldspars and plagioclase, biotite and muscovite. Together with quartzite, chert and schist, volcanic rock fragments (andesite) are common. Accessory minerals are pyrite, tourmaline and sphene	Less sorted and fine grained than the arkose, with micro-conglomeratic texture
Delvert (1963)	Pink sandstone	Monocrystalline quartz in a kaolinite cement	Fine-grained (0.1–0.2 mm), angular grains
	Grey sandstone	Quartz, feldspars (sericitized), biotite, muscovite in a chlorite cement. Accessory minerals are iron oxides, epidote, chlorite, sphene and zircon	Fine-grained (0.05–0.15 mm), well sorted, angular grains
	Green sandstone	Quartz, abundant K-feldspars and plagioclase, altered biotite, muscovite, quartzite, schist and volcanic rock fragments in a chlorite cement	Medium-grained (0.2–0.6 mm), poorly sorted grains
Uchida *et al.* (1998)	Red sandstone—quartz arenite	Quartz with small amount of rock fragments (mainly chert). Hematite and pyrite as accessory minerals	Fine-grained (0.1–0.2 mm) and well sorted
	Grey to yellowish brown sandstone—feldspathic arenite	Quartz, feldspars, biotite, rock fragments and muscovite. Magnetite, calcite, kaolinite, garnet, epidote, zircon and tourmaline as accessory minerals	Fine- to medium-grained (0.1–0.3 mm) and well sorted
	Greenish greywacke— feldspathic wacke	Feldspars, quartz, rock fragments, biotite and muscovite	Medium-grained (<0.5 mm) and poorly sorted
Baptiste *et al.* (2001)	Quartz arenite	Quartz (>90%) and accessory micas in a kaolinite cement	Well sorted
	Arkose	Quartz (<60%), feldspars, biotite and muscovite. Epidote, sphene, zircon, pyrite, iron oxides and hydroxides as accessory minerals. Chlorite and illite cement	Variable sorting
	Greywacke	Quartz, plagioclase, calcite and chlorite. Chlorite and illite cement	Fine-grained
Douglas (2004)	Feldspathic litharenite to litharenite (sandstone from mixed parent rock source)	Quartz (34%), feldspars (26%) and rock fragments (40%). Detrital grains from igneous, metamorphic and sedimentary sources	Medium-grained, submature with 5% matrix, to coarse-grained, immature with about 20% matrix
	Feldspathic litharenite to litharenite (sandstone from calcareous mixed parent rock source)	Quartz (26%), feldspars (12%) and rock fragments (62%). High proportion of limestone grains and carbonate cement	Medium- to coarse-grained
	Lithic arkose to feldspathic litharenite (sandstone from igneous parent rock source)	Quartz (28%), feldspars (37%) and rock fragments (35%). High proportion of igneous rock fragments and fine feldspar microliths and vitreous material in the matrix	Coarse- to very coarse-grained and immature

confirm the noticeable homogeneity of this lithotype (Delvert 1963; Uchida *et al*. 1995; Uchida and Maeda 1998).

Conversely, little attention has been given in previous studies to the nature of the rock fragments, with the exception of the early study of Saurin (1954). The nature and composition of rock fragments, however, can be a key characteristic in the determination of the geological provenance. All the studied samples have a distinctive nature of lithic fragments, although present only in small amounts (7.6 ± 2.3%). The simultaneous presence of microcrystalline quartz, phyllite and micaceous schist and accessory intermediate to basic volcanic rock fragments can be used as an additional discrimination criterion in relating unknown arenite samples to this specific sedimentary unit (Fig. 6). The strong similarity of the nature of rock fragments seen in the feldspathic to litho-feldspathic arenite series suggests that these lithotypes have a similar parent rock source. The ratio of the primary detrital grain parameters (Q + F/L) can discriminate between sandstones with different source rock of similar plutonic–metamorphic nature or between different portions of the same sedimentary unit.

Because little is known about the variation of the petrographic and textural characteristics of the considered lithotype in the natural environment, we can only deduce that a different horizon, which probably reflects different areas of the same sandstone formation, has been quarried to provide the stone material for Prasat Chrap.

In our study, the quartz arenite is found in Koh Ker style lintels only. This result is in agreement with the occurrences found in the Musée Guimet collection, where the quartz arenite is used in architectural elements, lintels and columns of different periods (Baptiste *et al*. 2001). According to these data and unpublished petrographic data on nine other lintels from The Metropolitan Museum of New York, the hypothesis that this particular lithotype was used only for architectural elements that involved intricate detail is strengthened.

Furthermore, the data collected on Khmer architectures by Uchida and his co-workers corroborate this hypothesis, as the quartz arenite, called by the author *Red Sandstone* (Table 4), has been found in the finely carved architectural elements of Banteay Srey and in the pillars of South Khleang (Uchida *et al*. 1995).

The correlation of the studied samples to specific rock formations exposed in the areas near Koh Ker continues to be a challenge due to the lack of a specific petrographic database of present-day outcrops and ancient quarrying sites. However, comparison of the existing geological data, petrographic data and archaeological evidence can help in identifying the most probable sources of stone material used for the studied Koh Ker style sculptures. According to the existing field data (United Nations 1993; Uchida *et al.* 1995, 1996; Uchida and Maeda 1998; Uchida and Ando 2001) and the analysis of the Thmâ Anlong quarry samples, the feldspathic arenite can be correlated to the Lower–Middle Jurassic unit known as *Terrain rouge*, while the quartz arenite can be correlated to the younger Upper Jurassic–Cretaceous *Grès supérieures* (Saurin 1954; Delvert 1963; United Nations 1993).

As shown in a geological map of Cambodia (United Nations 1993), the identified lithotypes are easily accessible in various areas surrounding Koh Ker in a radius of 50 km. In particular, the Lower–Middle Jurassic clastic units are exposed in isolated headlands west of Koh Ker, along the ideal line that connects Preah Vihear to Beng Mealea (Fig. 1). Among these, the outcrop located north-west of Beng Mealea, in the foothills of Phnom Kulen, provided and still provides feldsphatic arenite for sculptural and architectural purposes (Delvert 1963; Uchida and Ando 2001).

East of Koh Ker, Jurassic sandstone is exposed in a small promontory about 10 km from the archaeological site, while more extended outcrops are located 50 km eastward (Fig. 1). The

Cretaceous quartz arenite is similarly distributed around Koh Ker in the upper section of the numerous mesas and buttes, with two major outcrops, westward on Phnom Kulen and eastward on Phnom Tbêng.

Unfortunately, less is known about the petrographic characteristics of the various sandstone outcrops documented in the river beds of seasonal streams that flow around the archaeological site of Koh Ker (Delvert 1963; Jacques and Lafond 2004). Although sandstone can be reasonably quarried from river beds to obtain building and sculptural material, these outcrops are not mapped and no publications exist about their distribution, geology or petrography (Moriai *et al*. 2002). Similarly, no quantitative petrographic data have been obtained on the sandstone outcrops that have been carved *in situ* in the form of massive *linga*, east of the great temple of Prasat Thom and in other shrines scattered across the area (Jacques and Lafond 2004).

Thus, if the documented presence of vast sandstone terraces in the archaeological area itself (Delvert 1963; Jacques and Lafond 2004) could explain the use of a specific stone material to produce Koh Ker style sculptures, it would be imprudent to ascribe these outcrops to the mentioned Lower–Middle Jurassic unit, or portions of it, without a detailed geological survey and petrographic study of selected samples from individual outcrops.

The similarity of the sandstone used in Koh Ker sculpture to the building material of Angkor Wat and other temples in Siem Reap province is to be ascribed to the presence of similar lithotypes in both the Koh Ker and Angkor areas. The published data, concerning stone materials from a wide range of temples of various periods, suggest that this sedimentary unit of feldspathic arenite has a very homogeneous petrographic composition.

The tectonic history of Cambodia endorses this hypothesis, as the Jurassic continental sedimentation, which followed the early Triassic Indosinian Orogeny, resulted in a thick molasse-facies sedimentary unit covering broad areas of the subcontinent (United Nations 1993; Sotham 1997).

CONCLUSION

Quantitative petrographic analysis is an effective method of studying Koh Ker style sculptures and lintels dating to the 10th century. The texture and composition of the framework grains constituting the sandstones can be used as discriminating characteristics. Feldspathic and feldspato-lithic to litho-feldspathic arenites with metamorphic, volcanic and sedimentary rock fragments are the sandstones identified among the studied free-standing sculptures. Variations in the abundance, but not in the nature, of the fine-grained metamorphic and volcanic rock fragments can occur, depending on the provenance of the considered rock.

Finely carved lintels are realized with a different lithotype, quartz arenite, which is significantly richer in quartz grains and of a finer grain size. This lithotype has also been identified in lintels and columns of the Angkor period (Uchida *et al*. 1995; Baptiste *et al*. 2001), suggesting that specific stone was selected for these fine, intricate architectural elements.

Comparison of sculptural samples with samples from the Thmâ Anlong quarry suggests that the stone used was quarried from these Lower–Middle Jurassic sandstone outcrops, or their equivalents elsewhere within the same formation. This sedimentary unit covers large areas in Siem Reap and Preah Vihear provinces, and forms the shallow bedrock of the Koh Ker group. This abundance of massive feldspathic arenite in the site could justify the use of local monumental stone blocks for building and sculptural purposes.

Conversely, less is known about the abundance and location of quartz arenite in the vicinity of Koh Ker, although some authors mention the presence of light grey sandstone in the area (Moriai *et al*. 2002).

Recent studies suggest that quarries located in various areas within the same Lower–Middle Jurassic sedimentary unit could have different petrographic characteristics (Uchida *et al*. 2007). Similarly, the primary detrital grain parameters of stone material from Prasat Chrap suggest that other types of sandstone were available in the surroundings of Koh Ker.

The possibility that multiple quarries in the Koh Ker area have similar petrographic characteristics needs to be verified through detailed petrographic study of individual outcrops.

A quantitative approach applied to the petrographic and geochemical study of sandstone outcrops and quarries can help to characterize and differentiate them, and to detail the stratigraphy of the Jurassic–Cretaceous units, at least close to areas of archaeological relevance. This information, together with the petrographic characteristics of well-provenanced sculptures, could offer valuable support to the ongoing archaeological investigations in South-East Asia.

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