STONE MATERIALS USED IN KHMER SCULPTURE FROM THE NATIONAL MUSEUM OF CAMBODIA

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Introduction

Architectural sandstone of Khmer culture has been the subject of study, but little focus has been given to the characterization of the sandstone materials used for ancient Khmer sculpture. Petrographic methods typically used in geological research promise to lead to a richer understanding of the stone materials used by early Khmer as well as provide a tool for the study of unprovenanced sculptures. The present study has been made possible as the result of ongoing conservation work headed by Bertrand Porte, École Française d'Extrême-Orient (EFEO), at the National Museum of Cambodia that began in 1997 (see Porte 2001 and 2002). Some of the sculptures in the museum's collection were severely damaged and required major conservation treatments so that they could continue to be exhibited. The stone samples used in this study were obtained during these treatments, and all come from important well-provenanced sculptures dating to the three major periods of Khmer culture (Table 1): the pre-Angkor Period from the beginning of the Christian era to the end of the 8th century, the Angkor Period from the 9th century to the 13th century, and the post-Angkor Period from the 15th century onwards.

Potential sources of sandstone for sculptural purposes used by the ancient Khmers are numerous as indicated by the regional geology of Cambodia (Crea et. al. 1999; ESCAP 1993). Cambodia is composed of three general geologic features: 1) the Triassic shales, calcareous sandstones, and marls in the East, 2) the Jurassic-Cretaceous continental shelf sandstones in the West, and 3) the central Quaternary basin which comprises a broad plain of sediments relating to the Mekong valley and the Tonle Sap Lake region (see Mineral Deposits of Cambodia; Atlas of Mineral Resources). Most of the Precambrian and Cambrian formations underlie most of the sedimentary overburden, and include igneous and high-grade metamorphic rocks. The sedimentary formations range from the Silurian in the lowermost layers to the Cretaceous in the uppermost layers. The whole sequence of these sedimentary rocks has been affected by successive tectonic and volcanic activities. A wide range of igneous rocks occurs in Cambodia including intrusive granite, diorite and gabbro, and extrusive volcanic rocks such as rhyolite, dacite, andesite and basalt.

Cambodia is part of the Indochina platform, a block of continental crust which was raised through mountain building culminating in the Late Triassic period. From the Jurassic to the Paleogene, the exposed areas of this crust were subjected to erosion and weathering which resulted in the sediments present primarily in the central basin and eastern region today.

Figure 1 shows the major geotectonic units of Cambodia constituting a simplified version of the geology of the area. The primary areas of sandstone include the Cardamom Highland and surrounding fold belts, some parts of the Siem Reap - Stung Treng Volcano-Sedimentary Fold Belt, the Battambang Plain, the Terrains Rouges Plateau and the Southeast (Dalat) Fold Belt, as well as the Khorat Plateau, which occurs in northernmost Cambodia and Thailand. Given the regional geology, sandstone occurs throughout much of Cambodia, and would have been a widely available material in ancient times for architectural and sculptural purposes. Provenance studies will need to address the wide availability of these raw materials, and will need to take into account detailed petrographic analysis and possibly more sophisticated analyses of geological materials to compare to the sculpture.

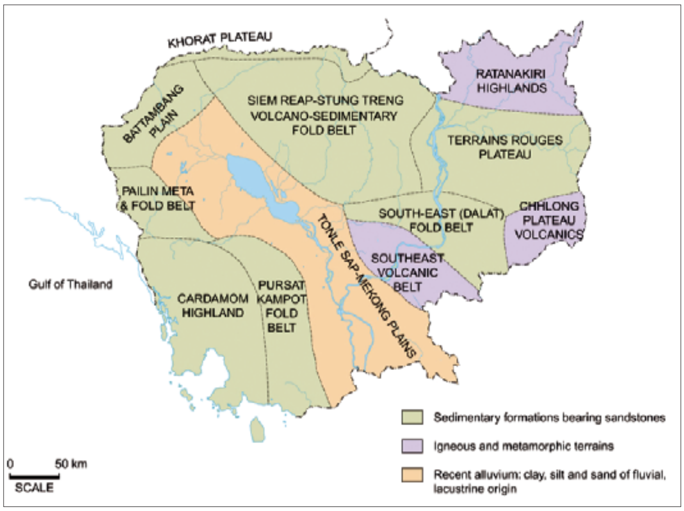

Figure 1: Major geotectonic units of Cambodia, which constitute a simplified version of the geology of the area.

The Kulen Mountains, about 50 km north of Siem Reap, are thought to have been one of the major sources of stone for architectural and sculptural purposes used by the Khmers at Angkor (Sanday 1997: 86). According to geological reports, these sandstones dating to the Jurassic-Cretaceous periods are sometimes referred to as "Grès Supérieurs," and are considered the same or similar formations as the sandstones of the Khorat Plateau (mainly in northeast Thailand), and the Cardamom Highland (in southwest Cambodia). The Kulen Mountains are a likely source for stone used at Angkor because of their proximity; and recent radar mapping has provided evidence of extensive water movement from the Kulen Mountains to Angkor during these early times (Roland Fletcher, pers. comm.). Other sandstone sources for sculpture, however, have to be considered in the case of more remote temple locations such as Phnom Chisor and Preah Vihear as other nearby sandstone formations would have been more accessible. Clearly architectural stone was quarried locally in locations remote from Angkor, such as Phnom Chisor, which most likely used the local sandstone, and Asram Maha Rosei, which is built, at least in part, from locally available basalt (analysis in unpublished report, Douglas 2003).

Previous work on classification of Khmer architectural and sculptural sandstone

Although parallels between architectural and sculptural stone have yet to be explored, sandstone building materials at Angkor have been classified into three types (Uchida, et.al. 1999):

1. *Quartzarentite (red sandstone)* – This sandstone consists primarily of fine-grained quartz (0.1 to 0.2 mm in diameter), and a minor amount of rock fragments (mainly chert and other microcrystalline quartz). Fine-grained hematite and pyrite are present in the interstices of the detrital grains.
2. *Feldspathic arenite (gray to yellowish brown sandstone)* – This sandstone is fine- to medium-grained (0.1 to 0.3 mm in diameter), and contains quartz, feldspar (plagioclase and alkali feldspar), biotite, rock fragments, muscovite, and minor amounts of magnetite, calcite, kaolinite, garnet, epidote, zircon and tourmaline. Detrital grains are angular to subangular and well-sorted. Biotite and muscovite show preferred orientation.
3. *Feldspathic wacke (greenish sandstone)* – This sandstone consists mainly of feldspar (plagioclase and alkali feldspar), quartz, rock fragments, biotite and muscovite. The detrital grains are angular and poorly sorted (<0.55 mm).

Reported colors of these sandstones are presumably of the weathered surface, which is influenced by the grain content of the sandstone as well as the weathering environment. The fresh sandstone, however, can be a very dark gray color. The first type, red sandstone, was used at Banteay Srei, and parts of North Khleang and South Khleang. The second type, gray to yellowish brown sandstone, is the most common and was used at all monuments. The third type, greenish sandstone, is limited to Ta Keo at Angkor. Instrumental methods including inductively coupled plasma emission spectrometry and instrumental neutron activation method were used to attempt to further characterize these sandstones. No systematic compositional differences were seen in samples of the gray to yellowish brown sandstone. The greenish sandstone (graywacke) was found to be compositionally similar, although the red sandstone was rich in $Si0_2$ (84 to 94% versus 66 to 72%). Plagioclase feldspars in samples from all three sandstone types were found to be albite (composition of $Ab_{80} – An_{20}$ to $Ab_{100} – An_0$). Most garnets were found to be almandine, which is derived from high-grade metamorphic rocks.

To date, the sandstone characterization study undertaken at the Musée Guimet is the most comprehensive study of Khmer sandstone in sculpture. This work was carried out on stone samples generated during the conservation treatments undertaken during the renovation of the museum (Baptiste et. al. 2001). Three broad types of stone were identified through the petrographic analysis of about 50 samples:

1. *Quartzarenite* (pinkish to cream colored sandstone) – This stone contains about 90 percent quartz grains. The cement is primarily kaolinite with traces of illite.
2. *Arkose* (gray to green colored sandstone) – This sandstone contains a variety of sedimentary, metamorphic and igneous grain types. This rock type was identified in about 70 percent of the sculpture studied.
3. *Graywacke* (dark colored sandstone) – This sandstone contains a large amount of rock fragment grains that are particularly weathered; these rocks contain well crystallized chlorite and illite, which were produced through the natural alteration (or weathering) of feldspars and micas contained in the original rock.

Six Khmer sculptures from the Alexander B. Griswold Collection of the Walters Art Gallery were analyzed through petrographic methods (Newman 1997: 261-65), although the presented data do not allow exact comparisons with the results of this current study. The sandstones were found to be rich feldspar and quartz, but also include a variety of rock fragments. Two sculptures from current-day Thailand were identified as particularly quartz-rich sandstones, including a standing Buddha, 8th cent. (Woodward 1997: no.8) and a Buddha head from Lopburi, 13th cent. (Woodward 1997: no. 34).

Petrographic analysis of sculptural sandstones from sculpture at the National Museum of Cambodia

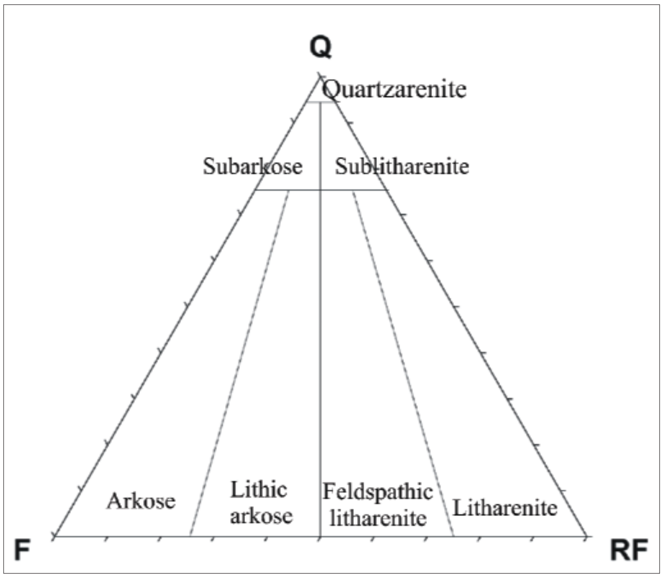

Figure 2: Classification scheme of sandstones after Folk 1974.

Twenty-nine sculpture samples in this study were thin-sectioned, and examined using the petrographic methods outlined in Appendix I. Some of the results of this work are summarized in Table 2. Rock names were assigned to the sculptural samples using a widely accepted sandstone classification system established by Robert L. Folk (Folk 1974). This classification system is based on the determination of the relative amounts of three types of detrital grains which can be plotted on a ternary diagram (see Figure 2). Detrital grain compositions are plotted along three poles of the ternary diagram as follows:

1. Q-pole: includes all types of quartz grains (mono- and polycrystalline), except chert.
2. F-pole: includes all types of alkali and plagioclase feldspar grains (mono- and polycrystalline), as well as granite and gneiss rock fragments.
3. RF-pole: includes all other rock fragments: chert, limestone, basalt, slate, volcanic, shale, etc. (does not include granite and gneiss).

As shown in the ternary plot in Figure 2, the Folk classification system has seven sandstone divisions based on grain composition:

1. *Quartzarenite* – 95% or greater quartz.
2. *Subarkose* – quartz ranging from 75 to 95%; feldspar to rock fragments ratio is greater than 1:1.
3. *Sublitharenite* – quartz ranging from 75 to 95%; feldspar to rock fragments ratio is less than 1:1.
4. *Arkose* – quartz less than 75%; feldspar to rock fragments ratio greater than 3:1.
5. *Lithic arkose* – quartz less than 75%; feldspar to rock fragments ratio between 1:1 and 3:1.
6. *Feldspathic litharenite* – quartz less than 75%; ratio of feldspar to rock fragments is between 1:1 and 1:3.

7. *Litharenite* – quartz less than 75%; ratio of feldspar to rock fragments less than 1:3.

The Folk classification system does not take into account the fine-grained matrix of a sandstone, its natural cement or any weathering or metamorphic changes. The term, "graywacke" (or "greywacke") is absent in the Folk classification system, as it has been largely abandoned due to confusion on its exact meaning.[1] Given the ambiguity associated with this term the name "graywacke" should be not used as a proper rock name.

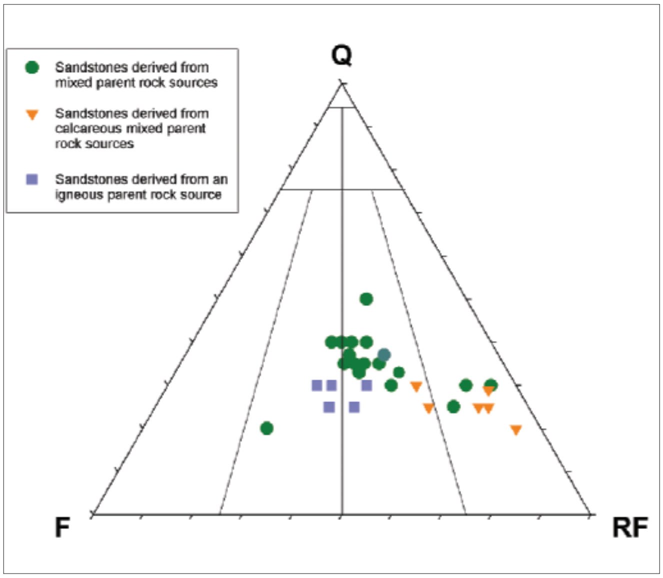

Figure 3: Classification data of sandstone samples from Khmer sculpture.

Detrital grain compositions of the Khmer sculpture samples are plotted on a ternary diagram in Figure 3, and the proper rock name for each sample is assigned based on its location in the diagram. All sculptural samples were found to be sandstones with relatively equal proportions of quartz, feldspar and rock fragments, some with a higher proportion of rock fragments. The majority of these samples are feldspathic litharenites, with a smaller number of lithic arkoses and litharenites. No quartzarenites, or quartz-rich sandstones, were identified in the current study, as have been identified in previous studies, however this may simply reflect the particular samples included here. More work will need to be done to determine the extent of the use of pink or rose-colored quartz-rich sandstone for sculpture in ancient Khmer times.[2] The samples of the current study are most like the feldspathic arenite, arkose, feldspathic wacke, and greywacke categories of the studies discussed above.

The sculptural samples varied in color and texture due to weathering and various surface deposits. The color of the fresh sandstone of the entire group, however, was an unusually uniform dark greenish gray color, ranging from 5GY 4/1 to 5GY 6/1.[3] This is significant because color is often described as a characteristic of a stone, while the color on the surface of an ancient sculpture is due to a combination of factors[4] such as the grain and matrix composition of the stone, the environment of natural weathering,

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1 Khmer sandstones have been sometimes referred to as "graywacke," a term that originally referred to a "hard, dark, semi-metamorphosed sandstone that is rich in rock fragments and chloritic clay matrix" (Folk, 1974). Various other "graywacke" definitions include reference to grain mineralogy, composition of the matrix material, and/or sedimentary structures present in the rock. The use of the term, "graywacke" has been largely debated, and as a result, Folk suggests using it exclusively as an unspecific field term rather than a proper rock name.

2 A pink or rose-colored sandstone used to make modern replicate sculptural works was analyzed through the methods outlined in this study, and was identified as a quartz-rich sublitharenite (similar to a quartzarenite). In 2003, a local stone craftsman at Artisans D'Angkor, Siem Reap, reported that this material was being quarried at Phnom Chonching, Banteay Meanchey Province, about 80 km northeast of Siem Reap. The red color of the sandstone is due to small spherical grains of hematite.

3 The Munsell system of color notation identifies three color attributes: hue, value and chroma. These attributes are arranged into a scale that can be used to accurately describe color. The color designation is written as hue value/chroma as in the example, 10Y 8/4. Munsell color notations can be determined by comparing the sample with small color chips from the Munsell Book of Color under the conditions of average daylight, 45^o illumination and normal viewing.

4 Sandstone color is due to various factors, however iron-rich minerals that occur as detrital grains or within the matrix through weathering can have a significant contribution. The colors produced by iron oxides and hydroxides through weathering of stone are as follows (adapted from Schwertmann and Taylor, 1977):

1. Goethite, α-FeOOH – yellowish brown
2. Lepidocrocite, γ-FeOOH – orange
3. Hematite, α-Fe_2O_3 – red
4. Maghemite,α-Fe_2O_3 – reddish brown
5. Ferrihydrite, $Fe_5HO_8 . 4H_2O$ or $Fe_5(O_4H_3)_3$ – reddish brown

Chlorite, which occurs as detrital grains and in the matrix as well as due to weathering or metamorphism, can add a greenish color to sandstone.

deposition of foreign material, and cleaning or other surface treatments in recent times. Although stone surfaces are important to study and understand, it would be inaccurate to assign rock types and sources to sandstone based on its surface color alone. Observations of this type should be limited to fresh surfaces.
Although it is important to assign the proper rock name to the material of each sculpture, the Folk classification is limited because it does not adequately include a mechanism to differentiate sandstone types based on grain compositions of the rock fragments, and other features such as matrix composition and weathering phenomena. Therefore, three further groups have been identified based on further petrographic analysis:

1. Sandstones with detrital grains originating from a mixed parent rock source (18 samples)

The majority of these sandstones contain varying amounts of detrital grains from igneous (plutonic and volcanic), metamorphic, and to a lesser extent, sedimentary sources. The medium-grained sandstones in this category tend to be submature, while the coarse-grained sandstones are immature and typically display poor sorting of grains (refer to Appendix 1 for definitions) and contain more matrix material. These characteristics are due to the depositional micro-environment in which the sandstone formed rather than being indicative of a particular sandstone deposit. In nature, sandstones commonly vary in particle size and sorting, layer by layer within a given deposit.

The matrix of these sandstones is typically a mixture of fine-grained clay, iron oxides and hydroxides. The fine-grained clay in the matrix is composed primarily of illite, and to a lesser extent, montmorillonite, as indicated by SEM microanalysis. Chlorite is also common in these rocks as detrital grains, as well as weathering products or secondary growth due to low grade metamorphism. The finer-grained sandstones tend to contain approximately 5% matrix as compared to the courser-grained sandstones, which contain a matrix of up to about 20%. Two sculptures, the bas-relief K2859 and the Siva K1817, along with micrographs of their sandstone samples, are shown in Figure 4.

2. *Sandstone with detrital grains originating from a calcareous mixed parent rock source* (6 samples)

These sandstones are fairly similar to the first group, but have a relatively high proportion of limestone grains and interstitial calcareous material in the cement. The sandstones can be easily confused with limestones due to their similarity to limestone in appearance and fracture, but can be recognized as sandstone through petrographic analysis. This group includes six of the earlier Khmer sculptures: the pre-Angkorian male torso K1762, Durga Mahisasuramardini K2927, Rama K1638, Harihara K1607, Visnu body K1805, and the early Angkor period Visnu K1634. Sandstones from these sculptures contain a high proportion of rock fragments, and are therefore categorized as feldpathic litharenite and litharenite. Most of the sandstones in this group are extremely weathered, due at least in part to their calcareous composition and porosity. Weathering in both grains and matrix is typified by the integration of a diffuse and fine mixture of clays and iron hydroxides. The Visnu K1805 is an excellent example belonging to this group as shown in Figure 5 along with a micrograph of this calcareous sandstone. It is not possible to conclude that the material of these sculptures is from the same or similar source as calcareous sandstones beds can be interlaminated with less calcareous sandstones.

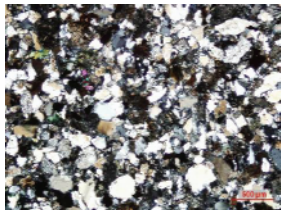

Figure 4A: micrograph

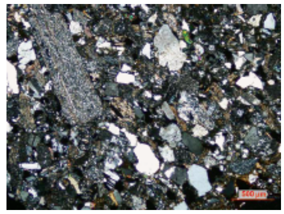

Figure 4B: micrograph

Two Khmer sculptures carved from sandstones composed of grains derived from a mixed parent source: A. Bas-relief K2859 - medium-grained, submature, feldspathic litharenite; B. Siva K1817- very coarse grained, immature, feldspathic litharenite.

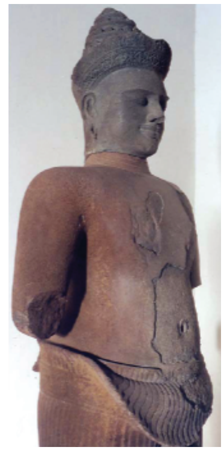

Figure 4A: K2859

Figure 4B: K1817

All photographs of statuary from the National Museum of Phnom Penh are courtesy of B. Porte.

3. Sandstones with detrital grains originating from an igneous parent rock source (5 samples)

These sandstones contain a high proportion of igneous (plutonic and volcanic) rock fragments and fine feldspar microliths and vitreous material in the matrix. They contain a relatively high proportion of feldspar grains, and are therefore categorized as feldspathic litharenite and lithic arkose. Interestingly, this type of sandstone was identified only in sculpture of the Bayon group, late 12th to 13th century, which were worked at the height of the Khmer empire during the reign of King Jayavarman VII. These sandstones most likely originate from the erosion of a nearby shallow igneous intrusion and/or volcanic source. The parent rock source would be a granodiorite or diorite, or their extrusive equivalents rhyolite or andesite. This type of sandstone was probably deposited as a diamictite,[5] which typically includes a matrix of silt and clay sized particles in a framework of sand and coarser material.

Table 3 shows some of the petrographic features these sandstones have in common. They contain most varieties of quartz as do most of the other sandstones in this study. The feldspars, however, are quite distinctive, occurring as fine microliths as well as larger grains with exsolved features. With the exception of the Lokesvara K1695 all contain significant amounts of amphibole (variety: hornblende) with fluid inclusions. In each case, incipient crystallization around the borders of larger grains indicates that these sandstones have undergone some metamorphism. A good example of this type of stone is the seated Jayavarman VII K1703 as shown in Figure 6 along with petrographic features that characterize this sandstone.

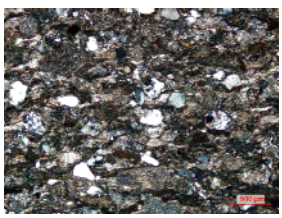

Figure 5: micrograph

Figure 5: The Visnu body K1805 composed of a sandstone with grains from a calcareous rock source, such as a limestone.

[5] A "diamictite" is a fine matrix-supported sandstone, typically a conglomerate, formed in a depositional environment where the ratio of water to sediment is low. Diamiticites can form through turbidity currents when unconsolidated sediment becomes resuspended in water, forming a fluid of high density where sediment is suspended and prevented from settling out. When deposition occurs fine and coarse-grained materials are mixed with little or no layering.

Two additional sculptures outside of the collections of the National Museum of Cambodia have also been identified as this type of sandstone. These include the Arthur M. Sackler Gallery's Bodhisattva Avalokiteśvara S1987.910 (see Woodward, 1994/95), and a Kneeling Prajnaparamita (private collection) - both identified as lithic arkose. Further petrographic analysis on Bayon-style sculpture and architectural objects dating to the late 12th- early 13th century will help determine the geographical and chronological extent of the use of this stone, which has been shown through this study to be used during the reign of King Jayavarman VII.

Figure 6: Jayavarman VII (K1703) composed of a sandstone composed of grains largely from an igneous rock source. Here, Jayavarman VII is shown after completion of its restoration with the Director of the National Museum of Cambodia, Khun Samen, and the conservation team in 1999. Micrographs show some of the characteristic features of this sandstone type: 1. the overall texture of this sandstone, 2. an exsolved feldspar grain, 3. matrix composed of fine feldspar microliths, and 4. an amphibole grain.

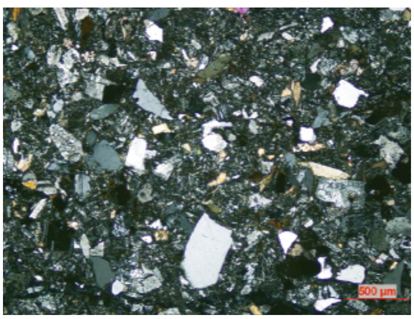

Figure 6: micrograph 1 overall

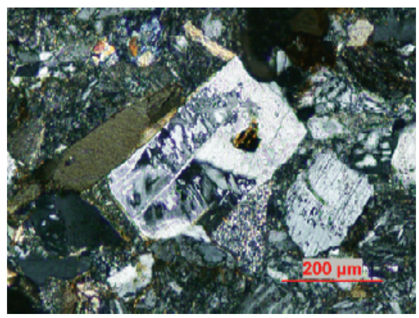

Figure 6: micrograph 2 exsolved feldspar

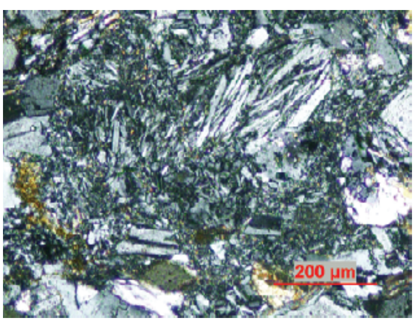

Figure 6: micrograph 3 feldspar microliths

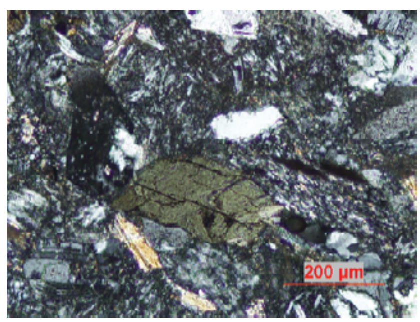

Figure 6: micrograph 4 amphibole

Conclusions

Petrographic study of this small group of well-provenanced and important Khmer sculptures shows that all are composed of sandstone with relatively equal proportions of quartz, feldspar and rock fragments, some with a higher proportion of rock fragments. Rock types include lithic arkose, feldspathic litharenite and litheranite, although further distinctions in sandstone types have been identified. The first group consisting of the majority of sculptures was found to be composed of sandstones with detrital grains from mixed sedimentary parent rock sources. A second group of six sculptures are composed of sandstones originating from a calcareous parent rock source, and tend to contain a relatively higher proportion of rock fragments, particularly calcareous ones. Four of the sculptures date to the Pre-Angkor period, and two others date to the early Angkor period, suggesting this type of stone was used in these early periods of Khmer history. A third group of five sculptures are composed of a distinctive type of sandstone derived from an igneous parent rock source. In each case, these sculptures are of the Bayon style dating to the 12th and 13th centuries. This work strongly suggests a common source for these sandstones, although this remains to be more fully explored. It should be mentioned that all of the Bayon style sculptures studied are of this third sandstone type, except the two samples from the bas-reliefs K2859-1 and K2859-2 from Banteay Chmar, which is located approximately 100 km to the northwest of the Angkor area. A plausible explanation is that a sandstone source in closer proximity to Banteay Chmar was used. Petrographic analysis of more samples will provide more data on sculptural stone usage during the early Khmer periods, and more research needs to address stone usage at each archaeological site as well as potential ancient sources of stone.

Appendix 1: Petrographic methods of analysis

Sample preparation and detrital grain identification

Stone fragments were embedded in Hytal NYL-1 Epoxy Resin, and polished thin sections were prepared by Tim Gooding at the Smithsonian Institution Museum of Natural History, Department of Mineral Sciences. Petrographic analysis was carried out at the Freer Gallery of Art / Arthur M. Sackler Gallery, Department of Conservation and Scientific Research using a Nikon Eclipse E600 polarized light microscope equipped with an Olympus DP70 digital camera.

The identification of individual grains was accomplished through standard petrographic procedures using the optical properties (Phillips 1971, Phillips and Griffen 1981, Deer, et. al.1992, Tucker 1991, Adams et. al. 1984), and in some cases, further characterized using textural features (see Folk 1974).

Grain size parameters

Grain size was estimated by determining the lengths of the largest grains in each of three categories: quartz, feldspar and rock fragments. A more accurate method of grain-size distribution would require a larger sample to obtain statistically meaningful results. Following are the sand-size classes of the Udden-Wentworth grain-size scale for sediments and sedimentary rocks (Tucker 1991):

0.062 to 0.125 mm	very fine
0.125 to 0.25 mm	fine
0.25 to 0.5 mm	medium
0.5 to 1 mm	coarse
1 to 2 mm	very coarse

Textural maturity

As sediments undergo increasing mechanical energy through the abrasive and sorting action of waves or currents, they pass sequentially through the following 4 stages of textural maturity:

1. Immature stage. Sediment contains over 5% clay matrix, sand grains usually poorly sorted and angular.
2. Submature stage. Sediment contains under 5% clay, but sand grains usually poorly sorted and not well rounded.
3. Mature stage. Sediment contains little or no clay, and sand grains well sorted, and not rounded.
4. Supermature stage. Sediment contains no clay, sand grains well sorted and well rounded.

Many of the Khmer sculptural samples were found to be immature, with a lesser number being submature. Immature and submature sandstones are typically formed in low energy depositional environments such as floodplains, alluvial fans, lagoon and swamp and neritic environments, as opposed to high energy environments such as beaches, Aeolian and dune environments. Similarly, immature and submature sandstones are formed through deposition via high energy turbidity current. In this case, once the sediment is deposited it is simply buried by more sediment and does not undergo further sorting or winnowing.

Immature sandstones contain more unstable feldspars, rock fragments and accessory minerals than more mature sandstones. Maturity reflects the weathering processes in the source area and degree and extent of reworking and transportation. Immature sediments tend to be located close to their source area, or they have been rapidly transported and deposited with little reworking from the source area (Tucker 1991).

Porosity

Porosity is based on simple estimation through study of the stone sample using the stereomicroscope, and the thin section using the petrographic microscope. Categories used are: low (<5%), medium (approximately 5-10%), and high (approximately 10-20%).

Matrix

Matrix materials consist of a complex mixture of fine-grained clays, iron oxides and hydroxides and vitreous material that are difficult to positively identify using petrographic methods. The predominant clay minerals are most likely illite and montmorillonite based on SEM microanalysis of some of the thin sections. Some of this fine grained material has formed through post-depositional weathering and therefore occurs more diffuse and as coatings on larger grains. Chlorite is common as a secondary mineral in the matrix, and glauconite was observed in some cases. These matrix materials also act as a natural cement. In certain cases, some calcite was observed in the interstices of the grains.

Table 1: Description of Khmer sculpture and location of samples studied
Numbering systems: National Museum of Cambodia inventory numbers (Kxxx); Numbers assigned by George Groslier: (Bxxx)

Sculpture description (Inventory Numbers)	**Date**	**Style**	**Provenance**	**Sample location and remarks**
Pre-Angkor Period				
Male torso (K1762, B707)	6th to 7th c.	Phnom Da	Vat Kompong Luong, Takeo	fragment
Male Divinity (K1633, B291)	6th to 7th c.	Phnom Da	Vat Sampau, Takeo	fragment
Balarama (K1640, B367)	6th to 7th c.	Phnom Da	Prasat Phnom Da	right leg
Parasurama (K1608 B729)	6th to 7th c.	Phnom Da	Phnom Da, Takeo	left arm; surface
Rama (K1638)	7th c.	Phnom Da	Prasat Phnom Da	fragment
Harihara (K1607, B272)	early 7th c.	Sambor Prei Kuk	Sambor Prei Kuk	gouged stone
Lintel (K1748, B470)	7th c.	Sambor Prei Kuk	Sambor Prei Kuk	fragment
Standing Buddha (K1582, B697)	7th c.	Pre-Angkor	Angkor Borei, Takeo	small fragment from ankle
Durga Mahisasuramardini (K 2927)	late 7th c.	Pre-Angkor	Phnom Tumlapp, Kompong Speu	left elbow
Harihara (K1616, B865)	late 7th to early 8th c	Prasat Andet	unknown temple, Takeo	right leg
Angkor Period				
Dvarapala (K1758, B115)	early 12th c.	Angkor Vat	Thbong Khmum, Kompong Cham	from surface
Female divinity (K881)	early 12th c.	Angkor Vat	?	fragment
Visnu (K1634)	9th c.	Kulen	Prasat Thma Dap, Phnom Kulen	gouged stone
Lintel (K1795, C309)	9th c.	Kulen	Prasat O Paong, Phnom Kulen	from surface
Visnu (?) body (K1805)	1st quarter of 10th c.	Bakheng	Prasat Neang Khmau	neck
Lintel (K1802, C340)	2nd half of 9th c.	Preah Ko	Prasat Preah Ko, Roluos	fragment
Lion (K1807)	2nd quarter of 10th c.	Koh Ker	Prasat Thom, Koh Ker	from head

Hand and shield (K1871, B212)	2nd quarter of 10 th c.	Koh Ker	Prasat Kraham, Koh Ker	belongs with K890
Large head of Siva (K890 B863)	2nd quarter of 10 th c.	Koh Ker	Prasat Kraham, Koh Ker	degraded stone fragments
Siva (K1817, B823)	2nd quarter of 10 th c	Koh Ker	Prasat Chrap, Koh Ker	neck
Siva (?) - A (K1667, B805)	2nd quarter of 10 th c.	Koh Ker	Prasat Chrap, Koh Ker	back
Buddha head (K935, B836)	late 12th to early 13 th c.	Bayon	Angkor Thom, Siem Reap	degraded stone fragments
Lokesvara (K1695, B322)	late 12th to early 13 th c.	Bayon	Angkor Thom, Porte des morts, Siem Reap	fragment
Bas-relief - 1 (K2859)	late 12th to early 13 th c.	Bayon	Banteay Chmar	fragment
Bas-relief - 2 (K2859-2)	late 12th to early 13 th c.	Bayon	Banteay Chmar	from surface
Jayavarman VII (K1703, B347)	late 12th to early 13 th c.	Bayon	Preah Khan, Angkor	gouged stone
Jayavarman VII (K2851)	late 12th to early 13 th c.	Bayon	Preah Khan, Kompong Svay	gouged stone
Ta Reac head (K3089)	late 12th to early 13 th c	Bayon	Angkor Vat	neck
Post-Angkor Period				
Buddha (K316)	probably 15 th - 16th c.	Post-Angkor period	Prasat Preah Theat, Kompong Thom	fragment of left foot

Table 2: Summary of petrographic analysis of Khmer sandstone sculptures

	Quartz			Feldspar		Rock fragments	Q / F / RF ratio	Maturity	*Porosity*	*Grain size*	Rock name (after Folk, 1974)
	C	V	M	Plag	Al						
Pre-Angkor Period											
Male torso (K1762, B707)	20	80	0	50	50	(sh, mq, carb) *	20 / 5 / 75	immature	low	medium to coarse	litharenite
Male Divinity (K1633, B291)	50	20	30	25	75	(mq, phy, sh) volc, gn	30 / 25 / 45	immature	medium	coarse - very coarse	feldspathic litharenite
Balarama (K1640, B367)	35	50	15	30	70	(mq, sh, phy), volc	30 / 10 / 60	immature	medium	coarse to very coarse	litharenite
Parasurama (K1608, B729)	25	55	25	25	50	(sh, phy, mq), carb *	25 / 15 / 60	immature	medium	coarse	litharenite
Rama (K1638)	10	70	10	25	75	(mq, carb, volc) phy	25 / 20 / 55	immature	low	medium	feldspathic litharenite
Harihara (K1607, B272)	20	60	20	50	50	(sh, phy, carb, mq, volc), gn	25 / 10 / 65	immature	medium	coarse	litharenite
Lintel (K1748, B470)	45	45	10	25	75	(sh, volc) carb, mq	35 / 30 / 35	submature	low	medium	feldspathic litharenite
Standing Buddha (K1582, B697)	20	65	15	25	75	(volc, mq, sh)	40 / 30 / 30	submature	low	medium	feldspathic litharentie
Durga Mahisasuramardini (K2927)	10	85	5	25	75	(carb, mq, sh, phy)	25 / 10 / 65	immature	low	medium to coarse	litharenite
Harihara (K1616, B865)	10	65	25	25	75	(sh, phy, mq)	30 / 5 / 65	immature	medium	coarse	litharenite

Key

Quartz - C = common quartz; Quartz - V = vein quartz; Quartz - M = metamorphic quartz (including schistose metamorphic, stretched metamorphic and recrystallized metamorphic)

Feldspar - Plag = plagioclase; Feldspar - Al = alkali feldspars

Rock fragments include: sh = shale; mq = microcrystalline quartz; volc = volcanic; gn = gneiss/granitic; carb = carbonate (typically limestone); phy = phyllite

Angkor Period											
Dvarapala (K1758, B115)	45	50	10	80	20	(sh, phy, volc) carb, mq	35 / 30 / 35	sub to immature	low	medium	feldspathic litharenite
Female divinity (K881)	15	80	5	20	80	unidentified *	20 / 55 / 25	submature	low	medium	lithic arkose
Visnu (K1634)	60	15	25	50	50	(mq, carb, sh)	30 / 20 / 50	immature	low	very coarse	feldspathic litharenite
Lintel (K1795 C309)	60	35	5	50	50	(sh, mq, phy, gn) carb	50 / 20 / 30	submature	low	medium	feldspathic litharenite
Visnu(?) body (K1805)	20	75	5	100	0	(carb, mq, volc)	30 / 5/ 65	immature	low	medium	litharenite
Lintel (K1802, C340)	60	40	0	50	50	(sh, phy, carb) volc, mq	35 / 30/ 35	submature	high	medium	feldspathic litharenite
Lion (K1807)	45	50	5	75	25	(sh, mq) carb, volc	35 / 25 / 40	submature	low	medium to coarse	feldspathic litharenite
Hand and shield (K1871, B212)	40	40	20	60	40	(sh, volc, gn, mq) phy,carb	35 / 30 / 35	immature	low	medium	feldspathic litharenite
Large head of Siva (K890, B863)	60	35	5	50	50	(sh, mq, volc)	40 / 30 / 30	submature	low	coarse	lithic arkose or feldspathic litharenite
Siva (K1817, B823)	15	60	20	75	25	(mq, phy, volc)	35 / 25 / 40	immature	low	very coarse	feldspathic litharenite
Siva (?) (K1667)	25	65	20	25	75	(mq, sh, phy) carb	30 / 20 / 50	immature	low	coarse	feldspathic litharentie
Buddha head (K935, B836)	20	60	20	25	75	mq, others *	30 / 30 / 40	immature	low	coarse	feldspathic litharenite
Lokesvara (K1695, B322)	75	10	15	40	60	(sh, volc, gn) *	30 / 40 / 30	immature	low	coarse	lithic arkose
Bas-relief - 1 (K2859)	40	50	10	25	75	(mq, sh, phy) volc, gn, carb	40 / 25 / 35	submature	low	medium	felspathic litharenite
Bas-relief - 2 (K2859-2)	80	15	5	40	60	sh, volc, gneiss	40 / 30 / 30	submature	low	medium	lithic arkose or feldspathic litharenite
Jayavarman VII (K1703, B347)	70	10	20	25	75	(gn, phy, mq) volc	30 / 40 / 30	immature	medium	coarse	lithic arkose
Jayavarman VII (K2851)	60	20	20	50	50	(gn, ph, volc, mq) carb	25 / 35 / 40	immature	medium	coarse to very coarse	feldspathic litharenite
Ta Reac head (K3089)	30	65	0	25	75	(gn, ph, volc, mq) carb	25 / 40 / 35	immature	low	coarse	lithic arkose
Post-Angkor Period											
Buddha (K316)	55	40	5	75	25	(sh, mq, volc) carb *	35 / 30 / 35	submature	low	medium	feldspathic litharentite

* = Samples are heavily weathered and hence, some rock fragments are difficult to identify; the stone sample from the Female Divinity (K881) is almost completely weathered.

Table 3: Petrographic features of five similar Bayon style sculptures.

Sculpture description (Inventory Numbers)	Buddha head (K935 B836)	Lokesvara (K1695 B322)	Jayavarman VII (K1703 B347)	Jayavarman VII (K2851)	Ta Reac head (K3089)
Quartz					
Common or vein	X	X	X	X	X
Polycrystalline / microcrystalline	X	X	X	X	X
Metamorphic varieties	X	X	X	X	X
Feldspar					
Plagioclase microliths in matrix	X	X	X	X	X
Alkali feldspar with fluid inclusions	X	X	X	X	X
Exsolved plagioclase	X	X	X	X	X
Volcanic rock fragments					
Vitreous grains with opaque mineral inclusions	X	X	X	X	X
Vitreous grains with a cicular inclusions	X	X	X	X	X
Amphibole					
Hornblende (pleochroic – green to brown)	X	-	X	X	X
Fluid inclusions in hornblende	X	-	X	X	X
Evidence of metamorphism based on presence of incipient crystallization along grain boundaries	X	X	X	X	X

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