EVIDENCE OF SANDSTONE USAGE FOR SCULPTURE DURING THE KHMER EMPIRE IN CAMBODIA THROUGH PETROGRAPHIC ANALYSIS

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Introduction

Beside stylistic and iconographic studies, petrographic analysis is a fruitful approach to studying Khmer stone sculpture and the sandstone materials of which they are composed. A comprehensive petrographic classification 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, geologic source, and provenance. This paper presents a summary of some of the recent research towards that goal, placed into context of current knowledge about regional geology and ancient quarrying in Cambodia.

Published research on Khmer stone materials utilizing petrographic methods are few, and begin with the studies of stone building materials of Angkor Wat and the surrounding Angkor area (Delvert 1963, Saurin 1954, Uchida et al. 1998). Study of sculpture include a survey of about fifty sculptures from the Musée Guimet's collection (Baptiste et al. 2001); and twenty-nine sculptures from the National Museum of Cambodia (Douglas 2004). Petrographic analyses of Cambodian stone sculptures have also been published sporadically as appendices in several broader art historical studies relating to Khmer art (Newman 1997, Woodward 1994/95).

Geology of Cambodia and quarrying evidence

Cambodia occupies an area of about 177,000 square kilometers in the south-central Indochina Peninsula. A schematic geological map of the area is given in Figure 1. The country is dominated by the

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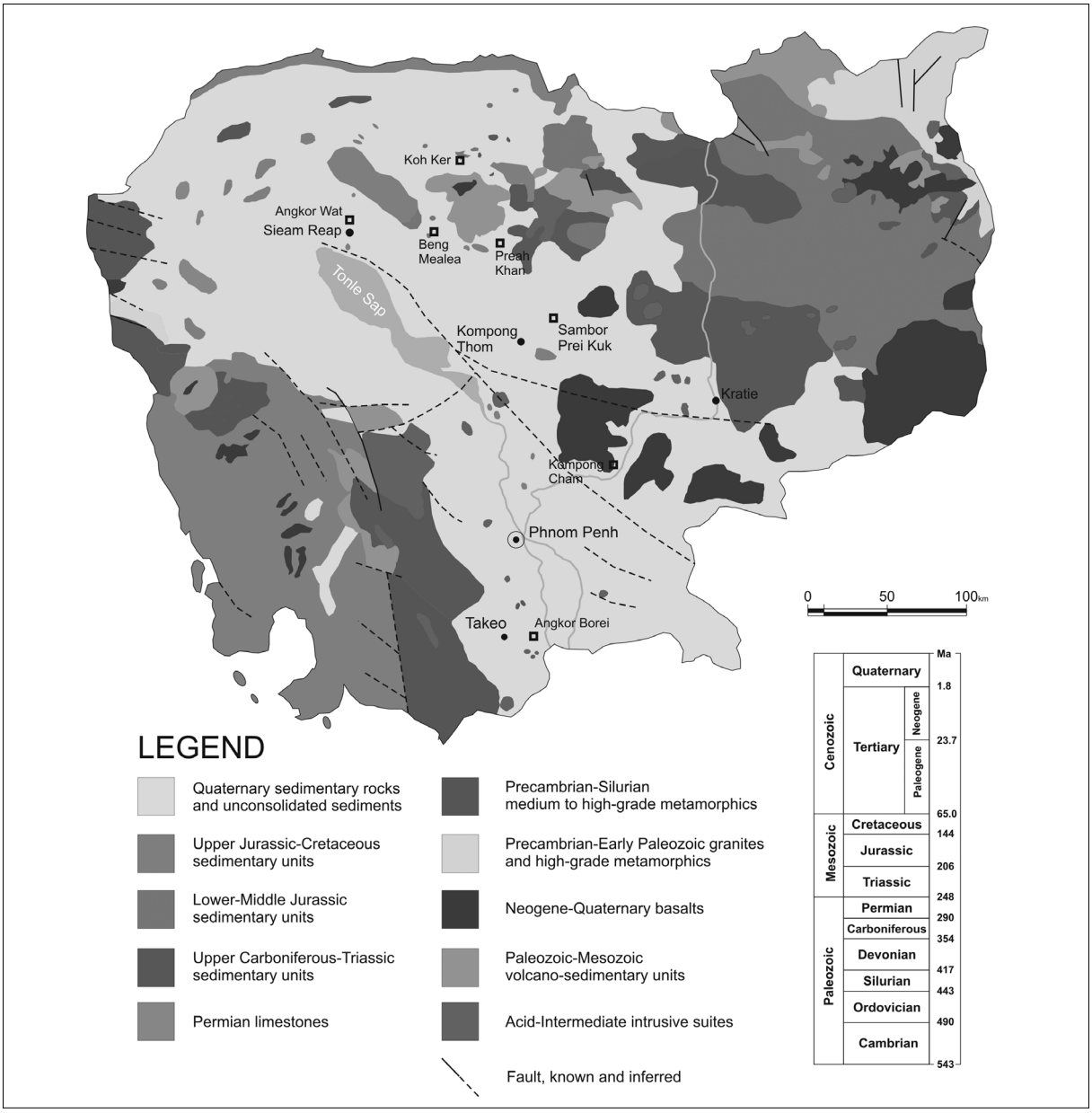

Figure 1: Simplified geological map of Cambodia with location of the main Khmer archaeological sites and relative geological time scale.(after United Nations 1993).

drainage systems of the Mekong and the Tonle Sap Rivers, which join near Phnom Penh before entering the broad Vietnamese delta system. The Great Lake occupies an extensive central plain characterized by alluvial deposits that spread to the foothills of the Dangrek Range, which marks a natural boundary between Cambodia and Thailand. Isolated residual buttes of variable extension and altitude rise from this plain as the result of erosion of the Mesozoic sedimentary units and igneous intrusions.

Cambodia is part of the large crustal block known as Indosinia. Prevailing marine conditions persisted until the Carboniferous period, which resulted in Devono-Carboniferous cherts, shales, sandstones and conglomerates; predominantly Permian limestones; and sparsely fossiliferous clastic sequences during the Triassic period. Once consolidated, this large and mostly submerged tectonic unit remained essentially stable until strong folding related to the regional Indosinian Orogeny culminated during the Middle-Upper Triassic. Emergence of the underwater marine terrain occurred during this time. Triassic sedimentary units are widespread in northern and southern Cambodia with both marine and continental sequences, the latter being particularly characteristic of the Upper Triassic. Undifferentiated marine sequences consist of basal conglomerates and breccias, compact sandstones with intercalated shales, marls, mudstones, and marly limestones. Starting from the Upper Triassic onwards, the area was characterized by erosion of the land surface and deposition of thick successions of Jurassic and Cretaceous continental conglomerates, sandstones and siltstones.

In Cambodia, the main episode of the Indosinian Orogeny is marked by the important unconformity at the base of the Lower-Middle Jurassic sub-horizontal sedimentary unit known as *Terrain Rouge*. This sequence is widely distributed in Mondolkiri and Ratanakiri provinces and in northern Cambodia, while absent in the south-central areas of the country. This sequence mostly occurs in isolated outcrops and comprises conglomerates, sandstones and siltstones of sub-continental origin. In northern Cambodia, this Jurassic unit is covered by thin, unconsolidated Quaternary deposits. As a consequence, this Jurassic sandstone is typically exposed in numerous riverbeds in Siem Reap and Preah Vihear provinces (Delvert 1963, Moriai 2001, Jacques and Lafond 2004).

Overlying the *Terrain Rouge*, a thick continental sequence, called *Grès supérieur,* was deposited during Upper Jurassic and Lower Cretaceous periods. The Upper Jurassic-Cretaceous conglomerates and sandstones are widespread in northern and western Cambodia, and constitute the south margin of the Khorat Plateau, Phnom Kulen, Tbêng Mountain, and other isolated outcrops in Siem Reap and Preah Vihear provinces. This sequence is also broadly exposed in western Cambodia in the Cardamom Mountains. Medium to fine-grained, quartz-rich sandstones with some conglomerates are most common, while abundant fine volcanic rock fragments and pyroclasts are also found in stone outcrops exposed in Siem reap province and in the central plain of the Tonle Sap River.

Upper Cretaceous and Tertiary rocks are not known in Cambodia. Pliocene sediments and plateau basalts are generally covered by loosely-consolidated Quaternary deposits and, when exposed, are strongly laterized.

Widespread Mid- to-Upper Triassic intermediate to acid volcanism and numerous syn-tectonic

intrusions, mainly of granitic composition, are associated with the different thrusts of the Indonisian Orogeny. As a result, Triassic and older sedimentary units are folded and have undergone metamorphism of variable grade and type.

The building and sculptural material during the whole Khmer Empire are thought to have been provided mostly from the Jurassic to Cretaceous sedimentary units, although Triassic formations could have been also exploited for early statuary and building materials (Delvert 1963, Uchida et al. 1995, Baptiste et al. 2001, Douglas 2004).

Although Triassic sandstones are nowadays exploited as construction material, less is known about quarries active during the Khmer Empire for building and sculptural purposes. Stone blocks of Triassic sandstone showing chisel marks have been found along the Chikreng River, about 15 km north of Kompong Kdei, but no actual quarries are documented in Preah Vihear province (Delvert 1963). In southern Cambodia, for example at Phnom Borei or Phnom Chisor, Triassic sandstones are intercalated with meter-thick layers of shale, locally metamorphosed (Sotham 1997) and, although no petrographic analysis exists, strong visual evidence suggests that similar lithotypes were used for many stelae, and architectural elements.

The most obvious evidence of multiple episodes of quarrying is present near Beng Mealea at the foot of Phnom Kulen and in the riverbed of the Mealea River, where Lower-Middle Jurassic sandstones, primarily used for the building of the temples in the Angkor area, are exposed in horizontal layers (Delvert 1963). No other quarry remains have yet been documented in Siem Reap province, but previous studies of Khmer stone material suggest that other sources have been exploited through time, from both the Lower and Upper Jurassic units (Delvert 1963, Uchida et al. 1995, 1996, Uchida and Maeda 1998, Uchida and Ando 2001, Douglas 2004). In Koh Ker, Preah Vihear province, rock-carvings on a sandstone outcrop known as Ang Khna are thought to be realized on the vertical surfaces of an abandoned quarry (Jacques and Lafond 2004). Moriai (2002) reports an important pit quarry in a riverbed about 8 km north of Koh Ker, where massive sandstone monoliths 5 m long are still present on the ground, while in a recent field-trip we identified at least two other quarries and multiple sandstone outcrops having similar attitude scattered in the surrounding of Prasat Thom. Pit quarries in the *Grès supérieur* have been located about 3 km east of Banteay Srei on Phnom Dey (Delvert 1963).

Pre-Angkor sculpture: Calcareous sandstones

Most stone sculptures dated to the pre-Angkorian period (c. AD 550 to 800) were found in the province of Kompong Thom where the seventh century major cultural and socio-political center of Sambor Prei Kuk is located, and along the lower Mekong, in the southern (Kandal, Kompong Speu, Prei Veng, Svay Rieng and Takeo) and eastern (Kompong Cham, Kratie) provinces and in the Mekong delta (Parmentier 1927, Dupont 1955, Malleret 1959). Despite extensive art historical studies, little is known about the nature and provenance of materials they are made of; and in some early studies, scholars mention

that statues from this period seem to be carved out of a kind of 'gray-blue volcanic rock' (Marchal 1951, Delvert 1963). Some pre-Angkorian steleae have been reported to be composed of a type of 'schist' (Groslier 1925, Parmentier 1927), although no petrographic data have verified the usage of this type of stone.

It has long been recognized that during the Angkorian period different sandstones were used for the statuary and the construction of the temples. In his seminal research work on sandstone erosion of the Angkor monuments, Delvert noticed that most of the statues from the Roluos and Angkor groups were carved in green-bluish sandstone, very different from the gray sandstone of Lower-Middle Jurassic age generally found on the monuments, but comparable to a green sandstone almost exclusively used for the upper platform sanctuaries of the Ta Keo temple (Delvert 1963). From a petrographic point of view, this rock was described as a compact dark gray-green sandstone with a conglomeratic micro-texture belonging probably to Triassic formations (Saurin 1935). Composition wise, the main differences with the gray sandstones are a coarser fabric and higher amounts of calcite and the presence of corroded quartz grains and volcanic rock fragments of intermediate to acidic composition (andesite, dacite) showing a microlithic or vitreous texture. These characteristics, confirmed by our analysis of samples from Ta Keo temple, are of particular interest in the present study as they show some similarities with pre-Angkorian sculptural materials. Conversely, there are also major differences that justify the consideration of the latter as a separate group with specific lithology.

Visual observations of a large number of pre-Angkorian sculptures have confirmed that the stone of most stelae and a few sculptures, such as the Nandin on a pillar at the Musée Guimet (MG14930), is indeed a type of schist. More importantly, petrographic analysis of samples from pre-Angkorian statues have shown that the stone used to carve them is not volcanic in origin, but a particular type of gray-greenish, sometimes dark, compact sandstone which was categorized as lithic arenite containing significant amounts of detrital grains from a calcareous source rock (Douglas 2004), but also under the field term 'graywacke' (Baptiste et al. 2001). Beyond matters of classification, the integration of these data with recent analysis of other sculptures from both the Musée Guimet and the National Museum of Cambodia indicates that the sandstones used during the pre-Angkorian period display a fairly homogeneous typology and allows us to give a detailed description of their petrographic features.

These sandstones can be generally described as poorly-sorted, immature, fine to medium-grained with a dark greenish-gray color. They are characterized by a heterogeneous fabric supported by the quartz - feldspar - rock fragment framework in association with cementing material composed of clay minerals, mainly chlorite, squashed argillaceous rock fragments forming a 'pseudomatrix' and the systematic occurrence of secondary calcite. The natural bedding, not always visible, is highlighted by the alignment of elongated detrital particles and, when present, mica flakes. The 'soft' material is often deformed at the contact with harder particles such as quartz, reflecting intense compaction and probably low-grade metamorphism. As a consequence, these sandstones are extremely hard and dense, and have a very low porosity (< 2%). Rock fragments are largely dominant and form 40 to 60% of the framework grains, while quartz and feldspars

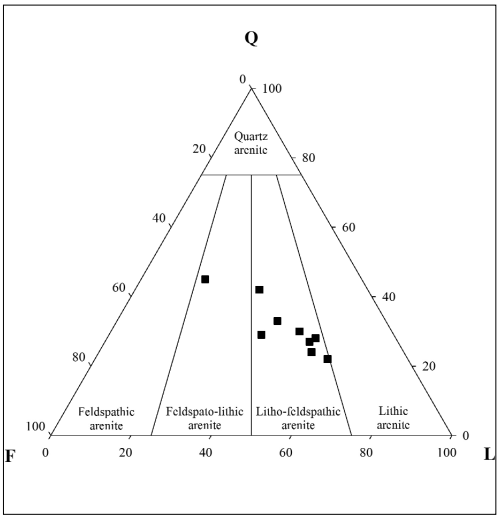

Figure 2: Ternary diagram of framework grain composition of Pre-Angkorian sculptures from the National Museum of Cambodia and the Musée Guimet.

are present in lower amounts with average values between 20 and 30%. Based on the Gazzi-Dickinson classification system (Gazzi 1966, Dickinson 1970), in a QFL ternary diagram[1] most of these sandstones plot into the litho-feldspathic arenite field (Figure 2).

Quartz appears as angular to sub-rounded mono- (Q_m) and polycrystalline (Q_p) particles. The values of the Q_p/Q_m ratio range from 0.2 to 0.5 and are much higher than those of the gray sandstone found on the monuments ($Q_p/Q_m < 0.1$). Feldspar minerals are characterized by the abundance of sodium-rich plagioclases, mainly albite, over alkali feldspars. Rock fragments are in majority of volcanic origin with an intermediate to acidic composition and an aphanitic to microlithic texture. Remaining rock fragments of metamorphic origin are composed of mica schist and slate, while those from a sedimentary source are mainly limestone, shale and chert.

Mica is a minor component (≤4%) and when present, is almost always biotite which occurs in often bent and kinked flakes oriented parallel to the bedding. Most of the biotite is partially or completely transformed into chlorite that suggests an aggradation process frequently encountered in hydrothermal and low-grade metamorphism tectonic settings. Accessory minerals are dominantly epidote, titanite and apatite, with lesser amounts of zircon, tourmaline, rutile and pyrite; garnet is rare if not absent.

Finally, an important characteristic of these sandstones is the systematic occurrence of calcite. Beside the individual rock fragments originating from a calcareous source rock, most calcite is present in the form of a secondary cement filling the inter-granular porosity and replacing partially weathered feldspar minerals and altogether, calcite amounts can vary from 10 to 20%.

[1] The quantitative petrographic analysis of sandstone is accomplished through the point counting of standard thin sections with a sample thickness of 30μm. For each sample, the maximum number of detrital grains is counted and each grain classified and measured by means of a micrometric eyepiece using a polarized light microscope and a mechanical stage. Counts could vary according to the dimension of samples and on the grain size and sorting of the sandstone, but usually at least 300 points are counted.

Key petrographic parameters as well as the grain size distribution and textural features are used to classify each sample of rock. The most common classification scheme is based on the relative abundance of three major typologies of grain, notably quartz (Q), feldspars (F) and rock fragments (L). Their abundance is usually projected on ternary diagrams where each apex represents one of the mentioned grain type. The sandstone composition is also expressed with the notation $Q_xF_yL_z$, where x, y, and z are the relative abundances of each constituent in percentage.

While the sandstones of most pre-Angkorian sculptures analyzed so far show a petrography consistent with the above description despite some variability in the mineralogical assemblage, there are also a few exceptions. For example, the sandstone of the Vishnu from the Phnom Da triad (National Museum of Cambodia, K1639) (Dupont 1955, Cooler 1978), though it has a similar texture and still classifies as litho-feldspathic arenite, is slightly different and contains more quartz and less volcanic rock fragments ($Q_{42}F_{27}L_{31}$).

Figure 3: Left: Harihara from the Asram Maha Rosei sanctuary (Musée Guimet, MG14910). Right: Micrographs showing (a) the general texture of the sandstone (porosity in blue, polarized light), and (b) details of the mineralogy (crossed polars, Qtz: quartz, Bt: biotite, Kfs: K-feldspar, Cal: calcite, Lv: volcanic rock fragment).

More interestingly, the sandstone from the Harihara (Musée Gumiet MG14910; see Baptiste and Zéphir 2008, p. 52-57) found at the Asram Maha Rosei sanctuary located a few miles south of Angkor Borei (Mauger 1936, Jessup and Zéphir 1997)) is composed of quartz, mostly mono-crystalline ($Q_p/Q_m<0.1$), feldspars and rock fragments in a mean ratio of $Q_{45}F_{39}L_{16}$, some chlorite and rare calcite, and shows an intermediate degree of textural maturity (Figure 3). Though located near the feldspathic arenite field on the QFL diagram (Figure 2), it classifies as feldspato-lithic arenite and is the only known example of a pre-Angkorian free-standing sculpture carved out of a gray sandstone with a petrography similar to the ones found on most Angkorian monuments. Natural outcrops of this type of sandstone are virtually absent in the southern provinces of Cambodia which implies that the material is not from a local source and was brought in from somewhere else, or more likely, that this Harihara was carved in another place and subsequently transported to the site. This interpretation, if correct, would also be consistent with Mauger's hypothesis about the non-local origin of the stone used atof the Asram Maha Rosei. He found that this sanctuary was built with basalt, and given its similarity to basalts from the Kompong Cham area, postulated that the stone was transported from there to the temple site (Mauger 1936).

Regarding the provenance of the typical sandstones used during the pre-Angkorian period, available data about the geology and stratigraphy of Cambodia (Saurin 1935, Fromaget 1941, Workman 1977, Tien et al. 1991, Sotham 1997) and the analysis of some observations made by Delvert regarding source rocks would suggest that these sandstones are most likely of Triassic age, an assumption supported by the presence of strongly folded Triassic sandstone formations north of Kompong Thom and southwest of Kompong Speu as well as in the numerous isolated hills scattered in the wetlands of southern Cambodia such as Phnom Chisor and Phnom Borei. However, petrographic analysis of samples collected in the aforementioned

areas during a field campaign in 2008 has shown that these Triassic sandstones, despite some textural and mineralogical similarities and their 'graywacke' lithofacies, are much coarser and contain often amphibole minerals absent in pre-Angkorian sandstones (Figure 4); in fact, their petrographic characteristics are closer to those of the green-bluish sandstones from the Ta Keo sanctuaries. Although the presence of fine-grained layers within these Triassic sandstones can not be ruled out and needs to be further investigated, based on the data collected so far, it is improbable that these specific formations provided the materials for the pre-Angkorian sculptures.

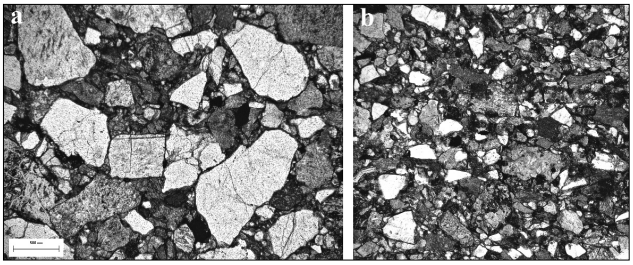

Figure 4: Micrographs showing textural differences between sandstones from (a) Triassic formations southwest of Kompong Speu, and (b) typical pre-Angkorian sculptures (polarized light).

Koh Ker sculpture: Feldspar-rich, fine-grained sandstone

Koh Ker was the primary political center of the Khmer empire at the beginning of the 10th century. Strictly confined in time and space, this site flourished with distinctive architecture and sculpture which make it a unique example in Khmer history (Jessup and Zéphir 1997, Jacques and Lafond 2004). In less than one generation, a specific Koh Ker style developed, characterized by the monumental use of stone material. Koh Ker itself lies on a vast and massive sandstone terrace of Lower-Middle Jurassic age which still retains the traces of systematic exploitation, so that it is tempting to question to what extent this peculiar production has been influenced by nature and abundance of local stone material.

Recent petrographic study of several free-standing sculptures and architectural elements in the Koh Ker style from the collections of the National Museum of Cambodia and The Metropolitan Museum of Art adds new information about the composition of stone used in the first half of the tenth century in northern Cambodia (Figures 5 and 6). Micrographs of the two major sandstone types and some of their characteristic grains are shown in Figure 7.

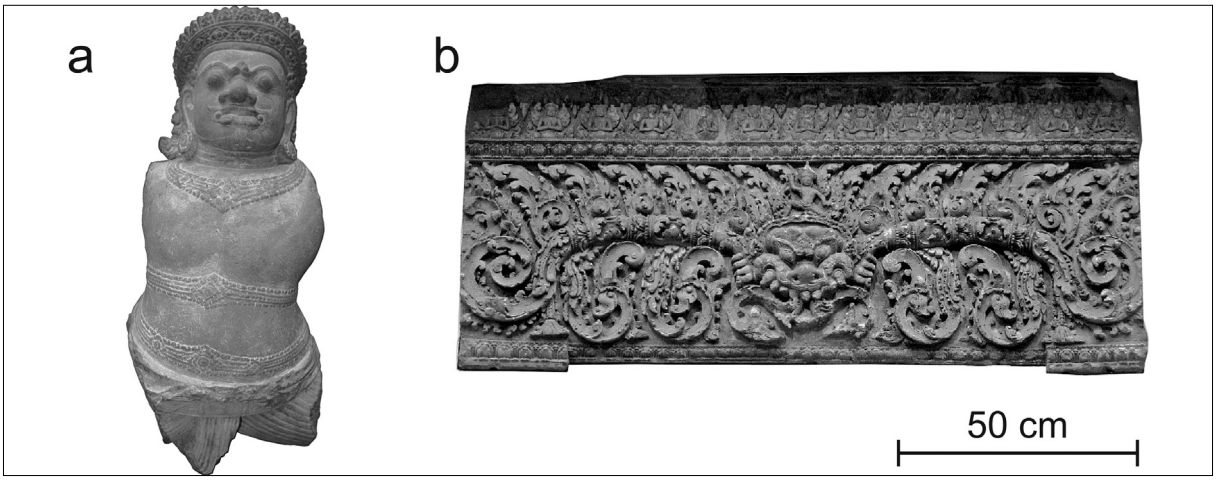

Figure 5: (a) Guardian deity (MET 1987.308), and (b) lintel with Kala head (MET 1994.111) from the Koh Ker style sculptures at The Metropolitan Museum of Art.

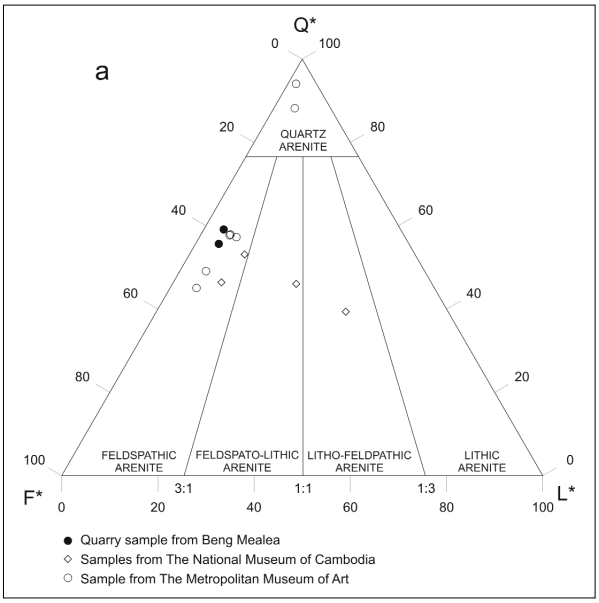

Figure 6: Ternary diagram showing framework grain composition of ancient quarry samples from near Beng Mealea and samples from Koh Ker style sculptures from the National Museum of Cambodia and The Metropolitan Museum of Art.

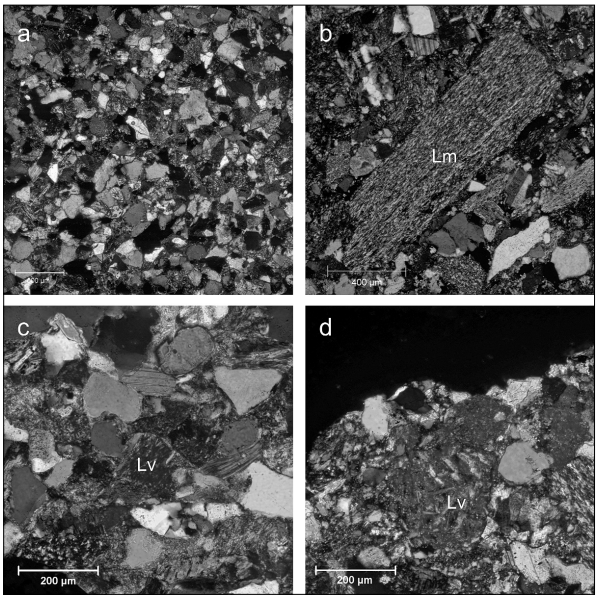

Figure 7: Micrographs of sandstones used in Koh Ker sculptures: (a) feldspathic arenite, and (b) feldspato-lithic arenite, (c and d) examples of their characteristic lithic grains (crossed polars).

The majority of the Koh Ker sculptures have been carved from a feldspathic (or arkosic) arenite of noticeable compositional and textural homogeneity. Macroscopically, this sandstone is characterized by a yellowish-gray color and a granular texture. Usually, it is easy to distinguish the natural bedding at the scale of the sculpture, especially when the surface has suffered fairly intense weathering. This feldspathic arenite is composed of very fine to fine, moderately well sorted, sub-angular to rounded grains cemented by predominant chlorite. Detrital grains are mostly composed of quartz, feldspar and rock fragments in a mean ratio of $Q_{52}F_{40}L_{8}$. The lithic fraction reflects mostly a metamorphic source, and comprises, in order of abundance, microcrystalline quartz, mica schist phyllite, elongated quartzite, siltstone, shale and intermediate to acidic volcanic rock fragments. Micas and detrital chlorite are minor constituents and usually bent between the framework grains. The heavy mineral fraction comprises mostly epidote, allanite, rutile, titanite, zircon, apatite, hematite, magnetite, ilmenite, and rare amphiboles.

Among the stone material used by the Khmer, similar compositional and textural characteristics are found in the sandstone quarried in ancient times near the site of Beng Mealea at the foothill of Phnom Kulen, although these are characterized by a variable content of secondary calcite filling interstices and replacing weathered minerals.

Despite the homogeneity of the Koh Ker sandstone, the analysis of two sculpture fragments from Prasat Chrap (National Museum of Cambodia, K1667, K1817), a shrine which lies along the direction of the Rahal, the local *baray*, on its northeast corner, indicates that other types of sandstones could have been

available in the surroundings of Koh Ker. This sandstone plots on the ternary diagram in the field of feldspato-lithic and litho-feldspathic arenite. It is characterized by less sorted grains and is richer in rock fragments, in comparison to the before-mentioned feldspathic arenite. The average proportion of quartz, feldspar and rock fragments is $Q_{43}F_{25}L_{32}$. The rock fragments are similar in nature to the feldspathic arenite. They are dominated by fragments of muscovite schist of variable dimension, microcrystalline and poly-crystalline elongated quartz, smaller siltstone and shale fragments, and basaltic to rhyolitic rock fragments. Micas are accessory while the heavy mineral fraction is represented by epidote, zircon, garnet, and 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.

The correlation of the studied samples to specific rock formations exposed in the areas near Koh Ker still represents 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 these Koh Ker style sculptures.

The existing field data (e.g. Contri 1971, Dottin 1972, Delvert 1963, Tien et al 1991, United Nations 1993, Uchida et al. 1995, 1996, Uchida and Maeda 1998, Uchida and Ando 2001) and comparison with samples from the Thmâ Anlong quarry, where Mesozoic sandstones were extensively exploited during the Khmer Empire, suggest that the stones used were quarried from these Lower-Middle Jurassic (*Terrain rouge*) sandstone outcrops, or their equivalents elsewhere within the same formation.

As shown in the geological map of Cambodia (Sotham 1997, Tien 1991, United Nations 1993), these Jurassic sequences are exposed in various areas surrounding Koh Ker in a radius of 50 km. This sedimentary unit forms the shallow bedrock of the Koh Ker site and is also scattered in Siem Reap and Preah Vihear provinces. Unfortunately, less is known about the various sandstone outcrops documented in the riverbeds of seasonal streams which flow through and around the archaeological site, as these outcrops are not mapped and no publications exist about their distribution, geology, or petrography. Indeed, evidence of stone exploitation is still detectable in Koh Ker, even in the immediate surroundings of the monuments and often of monolithic dimensions. The abundance of massive sandstone at the site might have facilitated the use of local monumental stone blocks used for building and sculptural purposes. However, 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.

Bayon sculpture: Volcano-sedimentary sandstones

A general petrographic survey of sculpture from the National Museum of Cambodia showed that five sculptures of Bayon style are composed of a specific type of sandstone consisting of grains derived from a mixture of volcanic and shallow intermediate igneous lithology (Douglas 2004). These and additional sculptures were subsequently studied for elemental composition using scanning electron microscopy

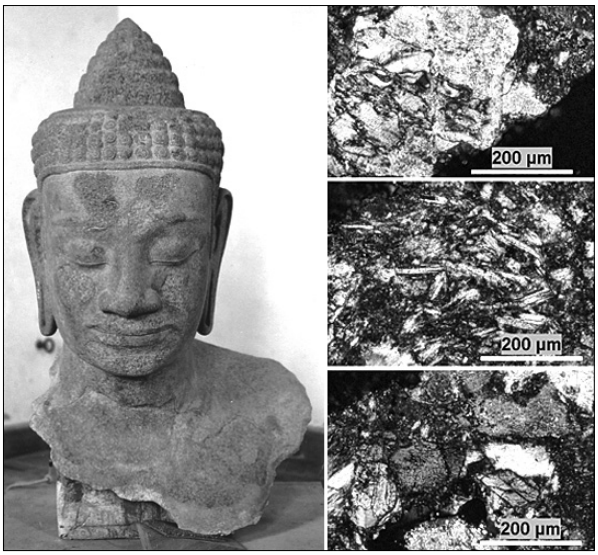

Figure 8: Buddha head (National Museum of Cambodia, Ga 935), and characteristic grain types from the head which were identified in several other Bayon sculptures: left: feldspar laths, center: albitized feldspar, right: amphibole (crossed polars).

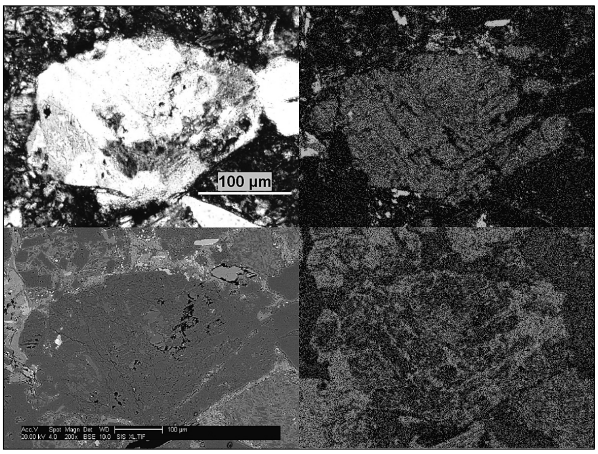

Figure 9: Albitized feldspar grain from the Ta Reac head (National Museum of Cambodia, Ga 3089): (a) petrographic micrograph (crossed polars) showing mottled grain extinction. (b) backscattered electron image. (c) Ca x-ray map. (d) Na x-ray map. The grain is a Ca-Na plagioclase feldspar that has been "albitized" or enriched in Na feldspar (albite) along cracks and other grain imperfections.

and microprobe analysis (Douglas 2007). The study showed that a group of Bayon-style sculptures can be further characterized based on the presence of three types of grains: 1) feldspar laths, 2) albitized feldspar, and 3) amphibole grains (Figure 8).

Feldspar laths are finely-divided acicular grains typically about 20 µm in length but ranging up to 200 µm. The laths are present as single and twinned crystals within the matrix, and occasionally occur as part of aggregate rock fragments. The presence of these feldspar laths indicates that their host sandstone formed in part from a parent source rock of nearby, relatively young, and unaltered volcanic rocks.

Many larger albitized feldspar grains display a mottled texture, where a single grain shows two or more zones of extinction under crossed polars in the petrographic microscope, and study by scanning electron microscopy show some chemical variations within these mottled zones (Figure 9). This texture is the result of a geochemical process known as "albitization", which transforms a calcium, sodium, and potassium-bearing feldspar in the anorthite-orthoclase-albite (An-Or-Ab) solid solution into the Na-end member feldspar albite. Some of the physical and chemical factors that influence the albitization process have been addressed by a kinetic model for recrystallization (Perez and Boles 2005).

In the case of the feldspars in the Bayon samples, cracks and other imperfections are albitized, suggesting that fluid access is critical for the reaction to occur. The textural similarities of albitization among the samples, and the evidence for progress of a distinctive low-grade metamorphic reaction together strongly indicate that the sandstones which contain partially albitized feldspar had a common fluid and thermal history. The simplest

way to account for this feature is to conclude that all of the samples that contain partially albitized feldspar grains are from a similar or the same geological source.

Amphibole compositions are sensitive to the overall chemical environment that was predominant during their formation, that is, pressure, temperature, the bulk composition of the overall system, and the compositions and assemblage of minerals that crystallized in equilibrium with amphibole. For this reason, even if a source rock that contains amphibole is disaggregated and its minerals separated from one another, amphibole compositions have the potential to establish whether the population of individual grains originated from a similar source.

Amphibole grains in the sandstones of the Bayon sculptures which contain feldspar laths and albitized feldspars were analyzed by electron microprobe (EMPA), and found to have similar calcic compositions. The compositional data suggest that the same igneous source provided the amphibole detritus for these sandstones. The geological criteria of the sandstone of nine of the sculptures in this study, including the presence of feldspar laths, albitized feldspar, and Ca-rich amphiboles, were found to be distinctive enough to suggest that their sandstone may have come from the same sandstone formation, and possibly the same quarry.

Although further work is desirable, the analysis of even a limited number of stone samples from Bayon sculpture in this study supports a hypothesis that a particular type of sandstone was predominately used by the royal workshops to carve sculpture during the reign of Jayavarman VII.

Decorative lintels: Quartz-rich, very fine- to fine-grained sandstones

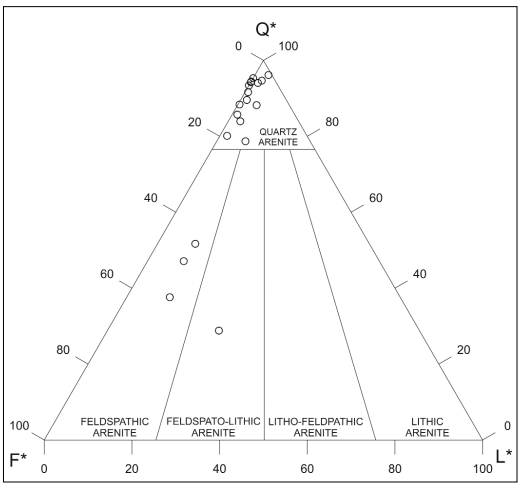

Figure 10: Ternary diagram showing framework grain composition of architectural elements from the National Museum of Cambodia and The Metropolitan Museum of Art.

Decorative lintels constitute a special variety of sculptural arts produced by the Khmer, which differ in several ways from free-standing sculpture. Unlike sculpture, lintels are architectural in nature, and tend to occupy pre-eminent positions in entryways of Khmer temples. Due to the intricately carved designs of many lintels, such artworks would have been particularly time-consuming and expensive to create. They are thought to have been normally carved in-situ by specialized craftsmen using a prescribed and standardized set of motifs (Polkinghorne 2007a, 2007b, and 2008).

Petrographic study of a selection of lintels from the National Museum of Cambodia and The Metropolitan Museum of Art show that these finely carved lintels are mostly worked from a quartz arenite, which is significantly richer in quartz grains and usually finer in grain size (Figure 10). In contrast to other sandstone types discussed

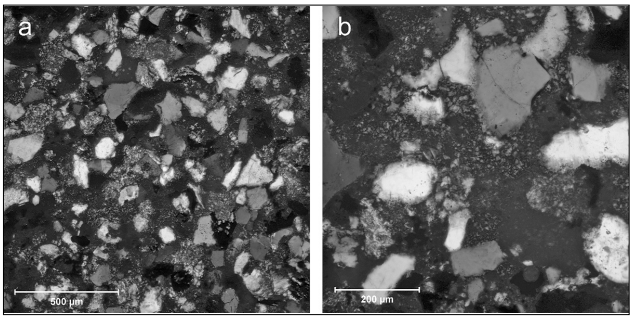

Figure 11: Micrograph showing (a) an overall view of the very fine-grained quartz arenite used for Khmer architectural elements, and (b) a detail of the characteristic kaolinite cement (crossed polars). The red material is fine-grained hematite.

previously in this paper, quartz arenite contains very fine to fine grains that are moderately well-sorted, and is composed primarily of mono- and microcrystalline quartz grains cemented by kaolinite (Figure 11). Accessory minerals are altered alkali feldspar, muscovite, and opaque iron-rich minerals, mostly represented by ilmenite and fine-grained hematite. The average framework composition is $Q_{91}F_8L_1$. If microcrystalline quartz grains are excluded, the rock fragments are poorly represented only by small, elongated grains of mica schist. The heavy mineral fraction is almost absent. Characteristic of the finer types is a diffuse film of hematite which coats the grains and the interstices, accounting for the pink to reddish coloration of the stone.

A similar lithotype is traditionally associated with the exuberant architectural and sculptural carvings of Banteay Srei style (Saurin 1954, Delvert 1963). The sandstone is visually identified by its characteristic reddish color and fine grain-size, although lighter and coarser types have been documented both in north and south Cambodia.

More recently, petrographic analyses of sculptures from the Guimet collection classified as quartz arenite most of the pediments, lintels and columns of Angkor period (Baptiste et al. 2001). The evidence to date clearly lead us to the idea that the quartz arenite was purposefully chosen for the production of architectural elements characterized by deeply carved, intricate details.

Although quartz arenite can be correlated to the younger Upper Jurassic-Cretaceous *Grès supérieur* (Saurin 1954, Delvert 1963, United Nations 1993), more research needs to address whether various geological sources of this lithotype had been used. The continental Upper Jurassic-Cretaceous sandstones are widely distributed in northern Cambodia in the upper layers of numerous mesas and buttes, with major outcrops westward on Phnom Kulen, eastward on Phnom Tbêng and north in the Dangrek range. However, there has been no visible trace of exploitation of these sandstones found to date, except for the small pit quarries found by Delvert few kilometers east of the temple of Banteay Srei and on top of Phnom Kulen (Delvert 1963) and which have not yet been studied.

Conclusions

This review of existing data about Khmer stone materials, besides providing a description of their petrographic characteristics and their distribution across Cambodia, also underscores that further research needs to be undertaken to clarify the position of the identified lithotypes in the stratigraphic column, and

the geographic location of the outcrops which could have been exploited for sculptural purposes. The challenging provenance of the dark gray-green sandstone in use during the Pre-Angkor period is a clear example of how the characterization of the artistic medium and location of its source can have important implication in the reconstruction of social, cultural and economic evolution of the Khmer Empire. On the other hand, the results obtained for the Bayon sculptures support the soundness of the approach as they undoubtedly show how it is possible to infer sculpture material provenance from petrographic analysis.

In view of the numerous questions still to be resolved, various studies are currently being carried out to address matters of geological source, based on comparative petrographic and geochemical analysis of samples from pre-Angkorian, Koh Ker, and other period sculptures, as well as from ancient quarries and natural outcrops. Analysis of unprovenanced sculptures in museum collections is also an ongoing line of research and is expected, once compared with well-provenanced material, to provide clues on to their origin.

An important goal of this research is to progressively build up a multidimensional database that links scientific data about materials and provenance with archaeological and art historical records and to make it accessible to students, scholars and other professionals interested in this field. Furthermore, the collection of such a large data set on stone materials from well-provenanced objects can offer invaluable support to current archaeological excavations in Southeast Asia. Ultimately, this research will also significantly contribute to our understanding of ancient Khmer material culture and artistic traditions.

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សង្ខេប

Evidence of sandstone usage for sculpture during the Khmer Empire in Cambodia through petrographic analysis

ដោយ Janet G. Douglas, Federico Carò and Christian Fischer

ក្រៅអំពីការសិក្សាលើសិល្ប:និងរចនាបទ ការវិភាគក៏មានសារ:សំខាន់ដែរ ក្នុងការសិក្សាចម្លាក់បុរាណខ្មែរនិងថ្មកក់ដែលយកមកប្រើ។ ការសិក្សាហ្មត់ចត់ទៅលើការប្រើ, ប្រភេទនិងប្រភពថ្ម ច្បាស់ជាអាចជួយសម្រួលដល់បុរាណវិទូ, អ្នកអភិរក្សព្រមទាំងអ្នកស្រាវជ្រាវផ្សេងៗទៀត។ អត្ថបទនេះសង្ខេបលទ្ធផលនៃការស្រាវជ្រាវថ្មីៗនេះខ្លះដែលធ្វើឡើងក្នុងក្របខណ្ឌនៃពត៌មានដែលស្គាល់សព្វថ្ងៃស្តីពីភូគពសាស្ត្រនិងការដ្ឋានបុរាណយកថ្មនៅកម្ពុជា។

អ្នកនិពន្ធបង្ហាញទិន្នន័យផ្សេងៗស្តីពីថ្មដែលប្រើក្នុងចម្លាក់ប្រតិមានៅសម័យមុនអង្គរ, ក្នុងរចនាបទកោះកេ្ដ៏និងបាយ័ន្ត ព្រមទាំងថ្មដែលយកមកធ្លាក់ផ្ដែមួយចំនួនទៀត។ គោលបំណងសំខាន់មួយ គឺវៀបចំជាបន្តបន្ទាប់នូវមូលដ្ឋានទិន្នន័យធំទូលាយមួយ ដែលភ្ជាប់ពត៌មានស្តីពីថ្មប្រើប្រាស់ព្រមទាំងប្រភពដែលបានមក ទៅនឹងពត៌មានស្តីពីប្រវត្តិសាស្ត្រនិងបុរាណវិទ្យា ហើយធ្វើយ៉ាងណាឲ្យមូលដ្ឋាននេះអាចជ្រួតជ្រាបដល់និស្សិត, អ្នកស្រាវជ្រាវ។ល។ ពុំតែប៉ុណ្ណោះ មូលដ្ឋានទិន្នន័យដែលមានលក្ខណ:ទូលំទូលាយនេះនឹងផ្ដល់ប្រយោជន៏ដល់ការស្រាវជ្រាវផ្នែកបុរាណវិទ្យា ដែលកំពុងធ្វើនៅទីនានាក្នុងអាស៊ីអាគ្នេយ៏នេះ។

Abstract

Evidence of sandstone usage for sculpture during the Khmer Empire in Cambodia through petrographic analysis

Janet G. Douglas, Federico Carò and Christian Fischer

Beside stylistic and iconographic studies, petrographic analysis is a fruitful approach to studying Khmer stone sculpture and the sandstone materials of which they are composed. A comprehensive petrographic classification 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, geologic source, and provenance. This paper presents a summary of some of the recent research towards that goal, placed into context of current knowledge about regional geology and ancient quarrying in Cambodia.

Data are presented here on the petrographic study of stone materials used for free-standing sculpture of pre-Angkor, Koh Ker, Bayon styles, as well as the special variety of sculptural arts represented in architectural decorative lintels. An important goal of this research is to progressively build up a multidimensional database that links scientific data about materials and provenance with archaeological and art historical records and to make it accessible to students, scholars and other professionals interested in this field. Furthermore, the collection of such a large data set on stone materials from well-provenanced objects can offer invaluable support to current archaeological excavations in Southeast Asia.

Résumé

Evidence of sandstone usage for sculpture during the Khmer Empire in Cambodia through petrographic analysis

Janet G. Douglas, Federico Carò and Christian Fischer

A coté des examens stylistique et iconographique, l'analyse pétrographique constitue une approche digne d'intérêt pour étudier la sculpture lapidaire khmère et les différents grès utilisés. Archéologues, conservateurs et autres chercheurs intéressés par l'usage de la pierre, la source et la provenance géologiques bénéficieraient d'une classification pétrographique exhaustive des grès utilisés. Cet article résume les résultats de quelques-unes des recherches récentes conduites selon l'état des connaissances actuelles de la géologie régionale et des anciennes carrières de pierre au Cambodge.

Ici sont présentées les données sur les matériaux utilisés pour la ronde-bosse préangkorienne, des styles de Koh Ker et du Bayon, de même que ceux d'une série de linteaux. L'un des buts essentiels de la présente recherche est de bâtir petit à petit une base de données qui mettrait en relation les données sur les matériaux et leurs provenances avec les données historiques et archéologiques, et de la rendre accessible aux étudiants, chercheurs et autres. En outre une telle base exhaustive de données sur les types de pierre avec indication précise de la provenance de l'objet constituerait une aide précieuse aux présentes recherches archéologiques conduites en Asie du Sud-Est.