



Nature and provenance of the sandstone used for Bayon style sculptures produced during the reign of Jayavarman VII

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ABSTRACT

Under Jayavarman VII (1182/83–ca.1218 CE) the Khmer empire reached its apex, leaving a heritage of major construction works and unique artistic production. The stone materials of several sculptures produced under his reign were characterized and compared to possible geological sources in northern and eastern Cambodia. The data suggest that a specific type of sandstone, rich in volcanic detritus, was deliberately selected and quarried from a Triassic sedimentary sequence exposed far from Angkor, the main political and economic center at that time.

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1. Introduction

Under the reign of Jayavarman VII (1182/83–ca.1218 CE) many significant construction projects were undertaken, such as major roads, stone bridges, hospitals and temples, which testify to a deep interaction with the local environment and knowledge of its natural resources. Simultaneously, a great number of free standing sculptures were mass-produced and installed in sanctuaries throughout the empire which encompassed, besides present-day Cambodia, parts of Thailand, Laos and Vietnam (Cœdès, 1958; Stern, 1965; Woodward, 1994/95). Several likenesses of the king and members of his family rendered in stone are known, together with numerous images of Buddhist and Hindu deities in the so-called Bayon style (Cœdès, 1958; Stern, 1965; Jessup and Zephir, 1997).

Recent studies using petrography suggest the existence of a specific royal workshop active during the reign of Jayavarman VII which has been characterized, besides by distinctive style and iconography, by a specific type of stone material (Douglas and Sorensen, 2007). The identified stone is an immature sandstone containing significant amounts of microlithic volcanic lithic fragments, albitized feldspar grains, and amphibole.

The provenance of this sandstone and the location of the workshop have been the subject of much speculation. Some scholars have placed the source of stone used for both architecture and sculpture of Bayon style in Phnom Kulen (Kulen Mountains), or more generically among the sandstones belonging to the Khorat series (Delvert, 1963; Woodward, 1980; Jessup and Zephir, 1997). If this hypothesis is true for the stone material used for temples construction under Jayavarman VII (Uchida et al., 2007; Kučera et al., 2008), evidence suggests that the sandstone selected for free standing sculptures does not belong to the Jurassic–Cretaceous formations exposed at Phnom Kulen (Terrain Rouge and Gres Supérieurs Formations) or to any of those formations traditionally included in the Khorat Group (Contri, 1972; Fleuriot de Langle, 1973; United Nations, 1993; Racey et al., 1996; Sotham, 1997; Carò and Im, 2012).

The current study is focused on a Triassic sedimentary formation as the potential source of such sandstone. In particular, the study aims at: 1) characterizing the stone belonging to the Triassic formation in a selected area of Cambodia and verifying the existence of remains of quarrying activity; 2) characterizing the stone materials of an enlarged corpus of Bayon style sculptures; 3) determining whether the stone in vogue under Jayavarman VII originated from the Triassic formation.

Given the vast exposure of Triassic sedimentary rocks in Cambodia, pilot sites must be selected among several that could have been potentially a source of stone material. The surveyed areas

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in this study have thus been chosen either because geological evidence points to lithotypes similar to those described in previous studies (Contri, 1972; Douglas and Sorensen, 2007; Carò, 2009; Douglas et al., 2010), or because ancient quarries have been previously documented in these areas.

2. Materials and methods

2.1. The studied sculptures

The corpus of sculptures includes 57 free-standing figures and steles of Bayon style from the Dépôt de la Conservation d'Angkor (DCA), Siem Reap (42 objects), the National Museum of Cambodia (NMC) (12), The Metropolitan Museum of Art (MMA) (2), and the Arthur M. Sackler Gallery of Art at the Smithsonian Institution (AMSG) (1). The studied objects represent a wide variety of Buddhist as well as Viṣṇuite and Śivaite iconographies of Bayon style and include, in order of abundance, images of Avalokiteśvara/Lokeśvara (11), Viṣṇu (8), Buddha (6), portrait of king Jayavarman VII (4), Śiva (3), Prajñāpāramitā (2), Hevajra (1), Lakṣhmī (1), a series of unidentified male (9) and female (8) figures, and pillar steles with inscriptions (4).

Most of the sculptures are well-provenanced and originate from the Angkor region (36), but also from other sites in Siem Reap province, such as Roluos (3) and Kralanh (1), and other provinces, such as Banteay Meanchey (4), and Preah Vihear (3). Ten objects are of uncertain or unknown provenance. The complete list of objects, including their description, accession number, and provenance is presented in Table 1. Because of the great number of the studied sculptures, only few representative examples are presented in Fig. 1.

2.2. The surveyed areas

The surveyed areas are located in the provinces of Preah Vihear and Kratie, and are included in the 1:200,000 sheets Tbeng Meanchey and Mondulokiri published by the Department of Geology, General Department of Mineral Resources of Cambodia and based on the reconnaissance mapping carried out in 1967/78 by the French Bureau de Recherches Géologiques et Minières (Fig. 2) (Contri, 1972; Fleuriot de Langle, 1973). Natural sandstone outcrops, documented quarries and undocumented traces of quarrying activity on sandstone outcrops have been surveyed and sampled.

In Preah Vihear province, the studied sites are located in the districts of Sangkom Thmai and Rovieng. These sites are distributed in the surroundings of the temple of Preah Khan of Kompong Svay (also known as Bakan) and in the area comprised between the villages of Ta Sang and Svay Damnak, a well-known center of iron mining and smelting since ancient times (Jacques, 2007). The landscape is characterized by flat terraces of Lower Quaternary sediments incised by an intricate network of seasonal streams constituting the drainage system of the Stoung River. These sediments are discontinuously but intensively laterized and rich in iron isolites. Given the reduced thickness of the Quaternary deposits, the Triassic substratum is often exposed in riverbeds and more rarely in extended terraces, in form of massive, almost structureless sandstone boulders separated by a system of orthogonal fractures, and fine-grained, laminated and nodular mudstones interbeds.

Five major sites have been surveyed around Preah Khan of Kompong Svay. The first is located southwest of the temple, in the riverbed of the Angkrong Creek (13°21'32.16"N and 104°40'36.00"E), where a vast outcrop of Lower and Middle Triassic sandstone has been mapped (Contri, 1972).

The last four sites are located along or in the riverbed of Stoung River, in the stretch that runs east of the temple's baray, and

situated between 13°26'44.20"N–104°46'13.40"E and 13°24'26.16"N–104°47'41.40"E. The majority of the samples originated from natural outcrops, as only few traces of aligned wedge holes, indicating possible stone quarrying, have been documented in this area (sample 3599).

Numerous sites have been surveyed north of the village of Svay Damnak. In this area, vast outcrops of Triassic rocks are mapped in the 1:200,000 sheet of Tbeng Meanchey and described by J. P. Contri in the relative explanatory notes (Contri, 1972). Interestingly, Contri mentions in his geological report the similarity between these lithotypes and the sculptures located at that time in the temple of Preah Khan of Kompong Svay. Triassic sandstone is exposed in massive boulders north of Svay Damnak, and forms the plateaus of Phnom Krang Aung and Phnom Chang Han southeast of the village. Sandstone outcrops have been sampled along and in riverbeds in an area of about 20 km². Besides isolated, scattered outcrops, three main sites have been studied. The first two are locally known as Andong Young and Trapeang Khong, and are located in and around the riverbed of a tributary of Stoung River. These two sites bear clear traces of quarrying in form of wedge holes and split boulders (Fig. 3). These traces are concentrated in a limited portion of the site, and masked by abundant sediment. The third site is a vast sandstone terrace 1 km south of Trapeang Khong with no evidence of quarrying activity.

In Kratie province, the studied quarries are located in the district of Kratie, and are known under the names of Thmei Sandan and Trapeang Tuol Kruos (Bruguier, 2006). Recent detailed stratigraphic studies in Sre Sbov, a village about 24 km north Thmei Sandan and Trapeang Tuol Kruos, show that Quaternary deposits are 1–2 m thick and unconformably overlie the Triassic Indosinian sandstone (Demeter et al., 2010).

Thmei Sandan is located 2.6 km east of the Mekong River, 0.5 km northeast of the road between Kratie and Stoung Treng. Here, several pits and channels are scattered around the main outcrop body, and massive dressed blocks of sandstone were left abandoned in the field (Fig. 4). Similar dressed blocks of sandstones can be seen half buried in the village of Sandan, about 1 km south of the quarry.

The quarry of Trapeang Tuol Kruos is located 12 km east of the Mekong, 4 km northeast the remains of Prasat Pram. This site is smaller than Thmei Sandan and consists of a few basins where sandstone boulders, sometimes showing chisel marks, are exposed. A massive squared block, partially dressed in form of a pedestal, is abandoned in the field (Fig. 4).

2.3. Analytical method

Polished thin sections were prepared from sandstone fragments embedded in epoxy resin. For each sample, at least 300 detrital grains were counted and each grain classified and measured by means of a micrometric eyepiece using a Nikon Eclipse E600 polarized light microscope. Detrital minerals have been further characterized by scanning electron microscopy and energy dispersive x-ray spectroscopy (Philips XL30 W/TMP Series electron microscope equipped with an EDAX ECON4 Si(Li) EDS detector and LEO 1455VP electron microscope with Link Pentafet Si(Li) SATW EDS detector).

Samples were analyzed by electron probe microanalysis (EMPA) in spot mode on the JEOL JXA-8900R microprobe in the Smithsonian's Department of Mineral Sciences, National Museum of Natural History. Analyses were obtained at a 15 kV acceleration voltage, a sample current of ~0.025 µA, a counting time of 20 s for each element, and corrected for ZAF. Standards were a combination of silicate and oxide standards calibrated by wet chemical analysis (Jarosewich et al., 1980).

Table 1

Compositional parameters of Bayon style sculptures and sandstones from surveyed sites. Primary parameters are Q = quartz, F = feldspar, L = lithic fragments, and secondary parameters are L_v/L = volcanic lithics over total lithics, mean grain size, and sorting.

Sample n°	Inventory n°	Description	Provenance	Q (%)	F (%)	L (%)	L_v/L	Mean grain size (mm)	Sorting (σ)
NMC54	K54	Male, head	Angkor area	17.2	48.4	34.4	0.83	0.17	0.61
NMC139	K139	Avalokiteśvara/Lokeśvara	Ta Phrom	16.2	38.7	45.1	0.95	0.20	0.62
NMC702	K702	Avalokiteśvara/Lokeśvara	Unknown	14.1	36.1	49.8	0.94	0.20	0.66
NMC935	K935	Buddha	Angkor Thom	21.6	39.4	39.0	0.91	0.19	0.71
NMC990	K990	Avalokiteśvara/Lokeśvara	Angkor Thom, Tep Pranam	43.6	51.9	4.5	0.91	0.20	0.99
NMC1695	K1695	Avalokiteśvara/Lokeśvara	Angkor Thom	21.9	34.6	43.5	0.88	0.21	0.76
NMC1703	K1703	Jayavarman VII	Krol Romeas	15.2	40.7	44.0	0.94	0.16	0.63
NMC1725	K1725	Lakṣhmī	Banteay Chhmar	12.9	47.4	39.8	0.92	0.18	0.65
			Banteay Torp						
NMC2770	K2770	Jayavarman VII	Preah Khan of Kompong Svay	13.3	42.8	43.9	0.90	0.18	0.63
NMC2851	K2851	Jayavarman VII	Preah Khan of Kompong Svay	9.0	46.5	44.4	0.94	0.19	0.67
NMC2995	K2995	Viṣṇu	Angkor Wat	25.2	52.8	22.0	0.63	0.18	0.71
NMC3089	K3089	Jayavarman VII	Krol Romeas	22.1	40.7	37.2	0.85	0.20	0.65
MMA36.96.4	36.96.4	Hevajra	Angkor Thom	22.9	48.2	28.9	0.89	0.18	0.71
MMA02.477	2002.477	Avalokiteśvara/Lokeśvara	Unknown	19.5	47.4	33.2	0.94	0.16	0.63
AMSG1987.910	S1987.910	Avalokiteśvara/Lokeśvara	Unknown	11.7	34.8	53.5	0.88	0.21	0.74
DCA1	1195	Avalokiteśvara/Lokeśvara	Unknown	12.0	37.3	50.7	0.86	0.24	0.68
DCA2	5742/1050	Viṣṇu	Phnom Dei	11.8	43.1	45.0	0.95	0.20	0.72
DCA3	5740	Viṣṇu	Phnom Dei	11.4	42.2	46.5	0.91	0.21	0.65
DCA4	5739	Avalokiteśvara/Lokeśvara	Daun Tei	11.1	45.3	43.6	0.98	0.19	0.69
DCA5	5741/1022	Avalokiteśvara/Lokeśvara	Phnom Dei	19.2	41.0	39.7	0.97	0.19	0.60
DCA6	5743	Śiva	Phnom Dei	13.8	37.7	48.5	0.92	0.19	0.60
DCA7	930	Prajñāpāramitā	Unknown	23.4	31.5	45.2	0.83	0.22	0.71
DCA8	—	Male, bust	Ta Prohm	43.6	48.8	7.6	0.77	0.14	0.60
DCA9	486	Buddha	Prasat Ta Nei	14.5	45.1	40.4	0.87	0.19	0.67
DCA10	488	Buddha	Prasat Ta Nei	14.6	46.5	38.9	0.93	0.24	0.67
DCA11	491	Buddha	Prasat Ta Nei	16.2	46.6	37.3	0.92	0.20	0.63
DCA12	4152/42	Buddha	Unknown	35.1	60.3	4.6	0.27	0.19	0.91
DCA13	675	Viṣṇu	Kok Pei, Phnom Krom	19.9	36.0	44.1	0.68	0.27	0.84
DCA14	35	Buddha	Angkor Thom	9.6	41.7	48.7	0.93	0.18	0.65
DCA15	1200	Stele	Banteay Chhmar	12.7	36.3	50.9	0.92	0.18	0.77
DCA16	1131	Stele	Banteay Chhmar	14.9	42.3	42.9	0.89	0.20	0.59
DCA17	570	Stele	Preah Khan, Siem Reap	35.1	36.6	28.2	0.54	0.28	0.80
DCA19	—	Stele	Banteay Chhmar	13.3	38.1	48.6	0.95	0.20	0.59
DCA20	3368/93	Male, standing	Angkor Thom	21.9	42.9	35.2	0.83	0.16	0.57
DCA21	51	Viṣṇu	Trapeang Pong, Roluos	9.6	40.6	49.8	0.87	0.21	0.62
DCA22	5421/126	Female, standing	Takeo	13.1	34.3	52.5	0.88	0.19	0.56
DCA23	4629/306	Viṣṇu	Bakong, Roluos	12.0	39.6	48.4	0.92	0.19	0.66
DCA24	6827/307	Viṣṇu	Prasat Suor Prat	11.6	44.9	43.5	0.96	0.17	0.61
DCA25	541A/248	Male, standing	Prasat Suor Prat	15.9	34.9	49.2	0.92	0.22	0.67
DCA26	2720/186	Avalokiteśvara/Lokeśvara	Prah Ko, Roluos	11.8	46.0	42.2	0.93	0.21	0.62
DCA27	6829/60	Śiva	Prasat Suor Prat	14.0	43.3	42.8	0.95	0.21	0.61
DCA28	1444/109	Male, standing	Prasat Bay Kaek	14.0	42.7	43.4	0.89	0.22	0.62
DCA29	6770/253	Male, standing	Takeo	12.0	49.8	38.2	0.92	0.16	0.62
DCA30	107	Male, standing	Unknown	16.1	40.2	43.8	0.88	0.20	0.63
DCA31	260	Male, bust	Takeo	15.5	41.2	43.4	0.92	0.20	0.72
DCA32	6353/174	Prajñāpāramitā	Unknown	13.7	48.1	38.3	0.96	0.17	0.62
DCA33	1118/185	Avalokiteśvara/Lokeśvara	Angkor, Western Baray	10.5	28.1	61.4	0.94	0.22	0.69
DCA34	4658	Viṣṇu	Banteay Kdei	8.7	35.9	55.4	0.93	0.24	0.65
DCA35	4652/862	Female, standing	Banteay Kdei	13.7	44.3	42.0	0.94	0.15	0.57
DCA36	6750/870	Female, standing	Prasat Ta Nei	15.8	43.3	40.9	0.92	0.24	0.70
DCA37	4228/864	Female, standing	Angkor Thom	15.6	35.3	49.1	0.94	0.19	0.67
DCA38	6749/782	Female, standing	Prasat Ta Nei	23.9	58.7	17.4	0.63	0.22	0.83
DCA39	753/762	Male, standing	Unknown	17.6	44.6	37.8	0.93	0.19	0.74
DCA41	6300/698	Female, standing	Prasat Kuk Snuol	20.9	71.3	7.8	0.89	0.08	0.66
DCA42	1464/793	Female, standing	Ta Prohm	19.2	33.2	47.6	0.88	0.23	0.68
DCA43	1711	Female, standing	Unknown	11.8	45.4	42.8	1.00	0.13	0.66
DCA44	237B/370	Śiva	Ta Prohm	10.5	43.4	46.1	0.90	0.20	0.67
136B	—	Quarry	Thmei Sandan, Kratie	47.0	45.3	7.6	0.28	0.22	0.92
141	—	Quarry	Trapeang Tuol Kruosm, Kratie	50.0	24.5	25.5	0.31	0.13	0.84
125	—	Outcrop	Stoung, East of Preah Khan Kompong Svay	37.4	48.3	14.3	0.17	0.15	0.89
254	—	Outcrop	Stoung, East of Preah Khan Kompong Svay	17.8	56.6	25.6	0.66	0.27	0.84
3599	—	Outcrop with traces of quarrying	Stoung, East of Preah Khan Kompong Svay	38.9	54.4	6.7	0.08	0.11	0.82
264	—	Outcrop	Angkrong, West of Preah Khan Kompong Svay	39.3	40.6	20.1	0.78	0.27	0.78
265	—	Outcrop with traces of quarrying	Angkrong, West of Preah Khan Kompong Svay	34.5	41.0	24.5	0.88	0.25	0.77
179	—	Outcrop	Trapeang Khong, Svay Damnak	11.6	43.1	45.3	0.90	0.19	0.60
184	—	Outcrop with traces of quarrying	Trapeang Khong, Svay Damnak	26.3	50.0	23.7	0.71	0.23	0.83
191	—	Outcrop	Trapeang Khong, Svay Damnak	24.5	49.8	25.7	0.46	0.24	0.77

(continued on next page)

Table 1 (continued)

Sample n°	Inventory n°	Description	Provenance	Q (%)	F (%)	L (%)	L _v /L	Mean grain size (mm)	Sorting (σ)
239	—	Outcrop	South of Trapeang Khong	38.5	56.7	4.8	0.40	0.14	0.88
161	—	Outcrop with traces of quarrying	Andong Young, Svay Damnak	17.0	58.0	25.0	0.64	0.22	0.78
162	—	Outcrop with traces of quarrying	Andong Young, Svay Damnak	27.5	53.4	19.1	0.56	0.20	0.82
202	—	Outcrop with traces of quarrying	Andong Young, Svay Damnak	26.8	55.0	18.2	0.50	0.20	0.75
210	—	Outcrop	Andong Young, Svay Damnak	22.8	51.2	26.0	0.52	0.23	0.80
214	—	Outcrop	Andong Young, Svay Damnak	24.1	45.5	30.4	0.65	0.23	0.80
164	—	Outcrop	North of Svay Damnak	23.5	50.7	25.8	0.50	0.21	0.92

Note: NMC = National Museum of Cambodia, MMA = The Metropolitan Museum of Art, AMSG = Arthur M. Sackler Gallery, DCA = Dépôt de la Conservation d'Angkor.

3. Results

3.1. Geology of the Triassic formation

In this study, the attention is focused on a complex sedimentary sequence of Triassic age, which is exposed in a vast area of present-day Cambodia stretching east from Preah Vihear province to the border with Vietnam, and in scattered outcrops in the provinces of Kompong Speu and Takeo. Fig. 2 schematically presents the distribution of the outcrop of Triassic age, as well as Jurassic–Cretaceous sedimentary units in the considered area.

North of the plateau of Kompong Cham, in between the provinces of Preah Vihear and Kompong Thom, a vast Triassic peneplain develops with variable altitude and heterogeneous character towards the east and the regions of Kratie and Monduliri (Carling, 2009). This formation is known in Thailand as Huai Hin Lat Formation (Racey et al., 1996), while in Cambodia does not have a conventionally recognized name. Here it is referred to simply as the “Triassic formation”.

Throughout the considered area, the outcrops are discontinuous and highly leveled through weathering. Generally, Quaternary loosely consolidated sand deposits of variable thickness unconformably overlie the Triassic substratum (Alabouvette, 1973). The Triassic formation is best exposed in minor and major riverbeds, such as the secondary branches of the Mekong River in Kratie province, where it forms numerous braided rapids. Some Triassic outcrops in the Mekong River bear traces of inscriptions or chisel marks, such as in Thmâ Krae, or Koh Sam Thom.

Because of its scattered dispersion and variable attitude, it is almost impossible to describe and detail the Triassic sedimentary sequence. The available data, consisting in reconnaissance mapping and sample petrography carried out by J. P. Contri and P. Fleuriot de Langle of the Bureau de Recherches Géologiques et Minières during the years 1966–1970, do not delineate the relationships among the various facies to allow the reconstruction of the stratigraphic column and structural asset of such heterogeneous detrital sequence. However, the French geologists provide indispensable description to construct a basic overview of the most common sedimentary facies and that, in some occasions, are quite detailed even at the outcrop scale.

Field observations clearly indicate that the Triassic formation has been folded and tilted, possibly during the final stages of the Indosinian Orogeny (Metcalfe, 1994; Carter et al., 2001), resulting in variable strike direction and dip of the outcrops throughout the country (Fleuriot de Langle, 1973). In the considered area there is a general tendency for the sequence to crop out striking in the NNE–SSW direction and with an E–SE dip ranging from 30 to 90°.

In central eastern Cambodia, the undifferentiated Triassic sequence is considered to be mostly of marine origin, and correlated by French geologists to the well documented marine succession of Rovieng (early–middle Triassic, Alabouvette, 1973).

Geologists seem to agree that two main facies constitute this Triassic sedimentary sequence: 1. a lower level characterized by mudstone, mostly shales and marls, with subordinate arkosic sandstone interbeds; 2. an upper level characterized by massive sandstone, microbreccias and breccias of variable texture and composition, with occasional marl interbeds.

Several mudstone facies belonging to the lower level are described in the geological explanatory notes by Contri (1972) and Fleuriot de Langle (1973), but no clear understanding of their mutual relationship at the large scale is given. Herein are reported the most common characteristics of this series, as a more detail analysis is beyond the scope of this paper. These fine-grained sediments are usually compact, laminated and with high degree of fissility. Often, they contain irregularly shaped nodules, which are more evident in the weathered rock. The color varies according to the mineralogy and the organic matter from pale gray–yellow to brown, to dark gray and black. Their composition is variable from markedly siliceous shale to calcareous mudstone where the clay fraction is <20%. Content of organic matter and fossils widely varies as well, and includes sterile and fossiliferous horizons, typical of Triassic marine environments (Contri, 1972; Fleuriot de Langle, 1973).

Immature sandstone of average arkosic composition is intercalated to thinly bedded mudstones. These sandstones are generally massive and compacted, with angular to sub-rounded grains of predominant quartz, feldspars and subordinate lithic fragments, in siliceous and calcareous cement. Fieldwork suggests that texture and composition are quite variable, ranging from feldspathic to litho-feldspathic arenite, depending on the abundance of lithic fragments, and either fine- or coarse-grained. Given the scattered information of such a widely exposed heterogeneous formation, any attempt to describe its general characters should be carefully pondered. However, by merging recent direct field observations and the existing geological bibliography, it is possible to recognize some distinguishing features that characterize these sandstones, namely: the massive structure with little or no apparent bedding, the immature character expressed by poor sorting and angularity of the framework grains, and the ubiquitous, though variable, presence of lithic fragments derived from low-grade metamorphic rocks (phyllite), and microlithic to aphanitic intermediate volcanic rocks.

Sandstones, microbreccia and breccias of heterogeneous composition become dominant towards the upper level of the Triassic sequence. These sediments rework Devonian–Carboniferous shale and schist, Permian limestone and andesite, and are generally immature and rich in lithic fragments. These terms crop out with common characteristics in an ample area between the provinces of Kompong Thom and Preah Vihear and extend at shallow depth towards the Mekong River, where emerge in scattered outcrops in the provinces of Stung Treng, Kratie and Kompong Cham, and more extensively, in vast areas of Monduliri



Fig. 1. A selection of Bayon style sculptures included in this study. a) Viṣṇu from Phnom Dei (inventory number 5742/1050, sample DCA2), Dépôt de la Conservation d'Angkor; b) Unfinished Śiva from Phnom Dei (inventory number 5743, sample DCA6), Dépôt de la Conservation d'Angkor; c) Unfinished Viṣṇu from Phnom Dei (inventory number 5740, sample DCA3), Dépôt de la Conservation d'Angkor; d) Seated Jayavarman VII (inventory number K1703, sample NMC1703), National Museum of Cambodia; e) Standing female from Angkor Thom (inventory number 864/4228, sample DCA37), Dépôt de la Conservation d'Angkor; f) Stele from Banteay Chhmar (inventory number 1131, sample DCA16), Dépôt de la Conservation d'Angkor; g) Buddha with Naga from Prasat Ta Nei, Angkor (inventory number 486, sample DCA9), Dépôt de la Conservation d'Angkor. The scale is approximate.

province, where is however included in the undifferentiated Triassic sequence.

Macroscopically, these terrigenous sandstones are greenish- to bluish-gray in color, speckled with coarse white feldspar and dark lithic grains, and show little evidence of internal structures. Oversized angular to sub-rounded clasts (black laminated shale or other lithic fragments of both volcanic and metamorphic nature) are suspended in the sandy matrix, suggesting a possible turbidity current deposit.

Compositionally, they are characterized by abundant feldspars, occasionally albitized and/or replaced by authigenic calcite, and by a lithic fraction dominated by a mixture of volcanic and low-grade metamorphic parent rocks. The abundance and relative proportion

of these lithic fragments vary widely, with volcanic lithic fragments being more common in the finer lithotypes of the northwestern sector. In some cases, such as the outcrops located between Kompong Thom and Preah Vihear provinces or in northeast and southwest Kratie province, intermediate microlithic and vitreous volcanic lithic fragments with amphibole with green pleochroism dominate the framework grains and constitute the fine matrix of this immature sandstone, indicating a nearby, relatively young, and unaltered andesitic source (Contri, 1972; Douglas and Sorensen, 2007).

During their fieldwork in the late 1960s, French geologists noticed for the first time the macroscopic similarity of the outcropping sandstone to the stone of Bayon style sculptures found in the temple of Preah Khan of Kompong Svay (Contri, 1972).

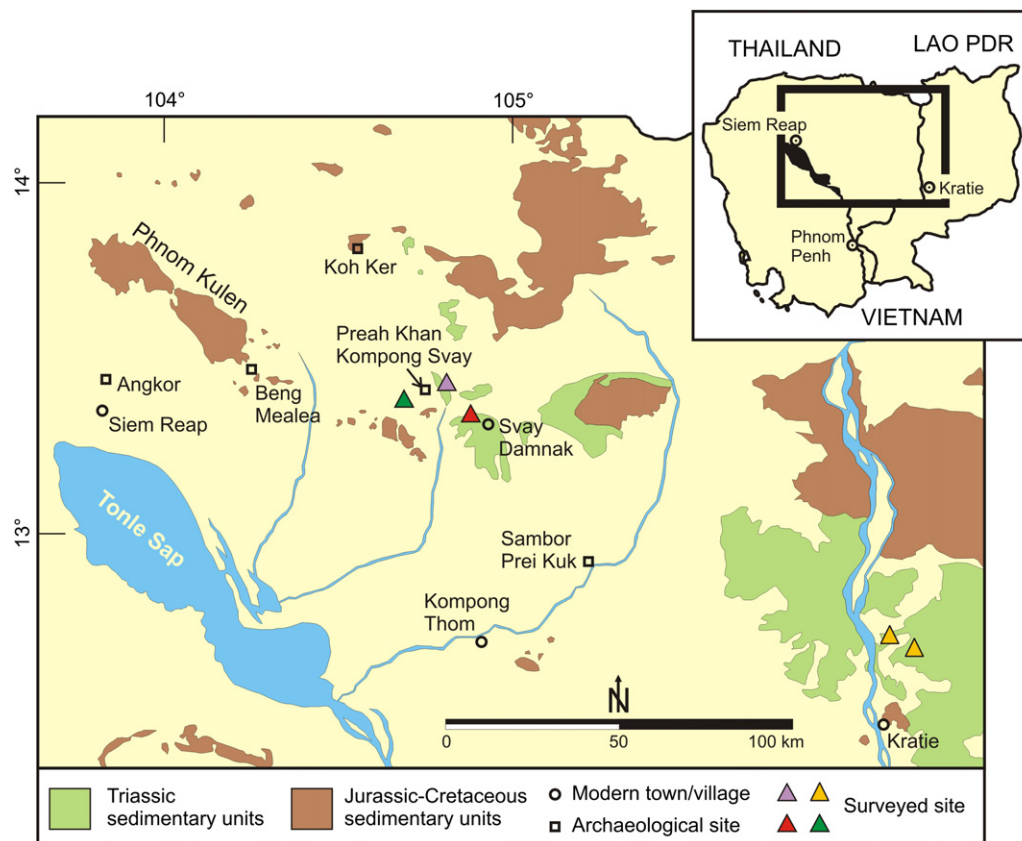


Fig. 2. Schematic geological map of the studied area showing the distribution of Mesozoic sedimentary formations and surveyed sites. Geological data modified after Contri (1972) and Fleuriot de Langle (1973).

Examples of the interaction between andesitic flows, which are abundantly documented in this area, and Triassic sedimentary rocks can be seen around Phnom Klek Klak, a diorite massif located about 40 km northeast of the town of Kratie (Fleuriot de Langle, 1973). Immature sandstones and microbreccias rich in andesite, shale and phyllite fragments and abundant authigenic calcite are exposed also northeast of Memot, along the National Highway 7.

Less detailed is the available information about the Triassic sequence between the Mekong River and the Vietnam border. Despite that the formation covers vast areas of Mondolkiri province, or probably because of this, most of the outcrops are grouped together as “undifferentiated Triassic”, and little is known about the characteristics of the series. The lithotypes show similarities with the Triassic sequence previously described, and include breccia,

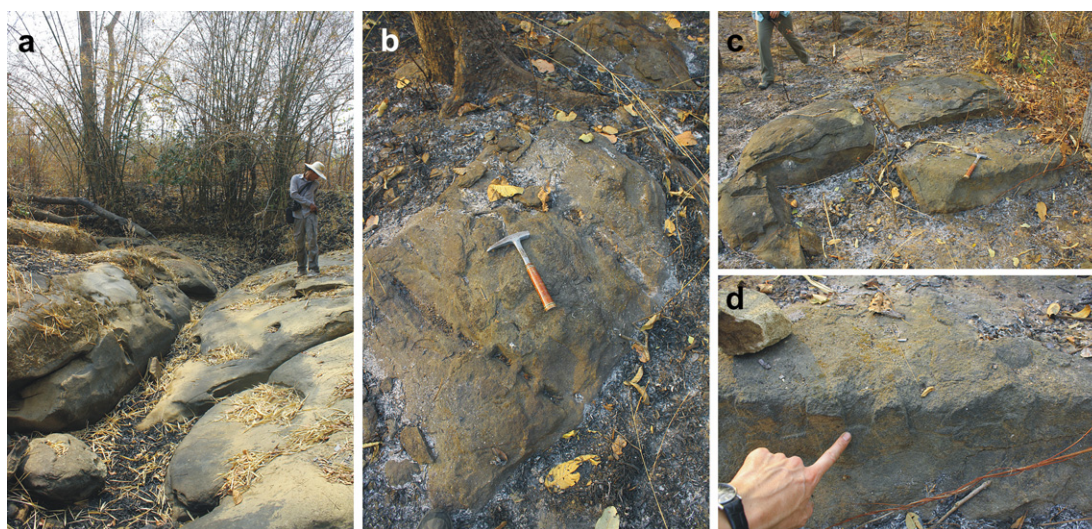


Fig. 3. a) Massive sandstone outcrops in the riverbed of a tributary of Stoung River; b–c) traces of block splitting at the site known as Andong Young; d) trapezoidal wedge holes left on a split boulder at the site of Trapeang Khong. All these sites are located northwest of Sway Damnak.

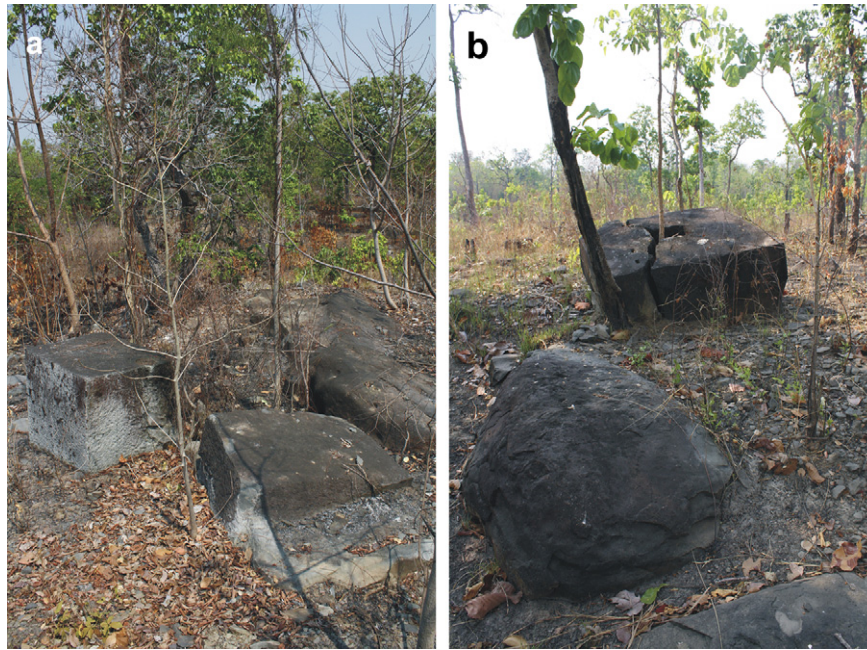


Fig. 4. a) Squared blocks in the quarry of Thmei Sandan, 25 km north of Kratie; b) an unfinished pedestal in the quarry site of Trapeang Tuol Kruos, 22 km northeast of Kratie.

microbreccia and sandstone similar to those described above, occasionally with mudstones interbeds (Fleuriot de Langle, 1973).

3.2. Petrography of the studied samples

The majority of studied field and sculpture samples (95%) are immature sandstone, characterized by well-compacted, moderately sorted, fine- to medium-grained, sub-angular to very angular grains (Figs. 5 and 6; Table 1). Composition and texture of these sandstones (Table 1) are mostly similar to those sediments belonging to plagioclase-rich feldspatholithic suites formed in depositional basins associated with volcanic arc orogens (Valloni and Mezzadri, 1984) (Fig. 5). For this reason, they are herein presented as belonging to a single group, which thus includes samples from both sculptures and outcrops. Samples that cannot be clearly assigned to this feldspatholithic suite are presented separately.

3.2.1. Sandstones belonging to the feldspatholithic suite

These sandstones are characterized by considerable but distinctive compositional variation. Overall, feldspars and lithic fragments typically predominate over quartz, while lithic fragments are typically volcanic in origin.

Within the studied samples group the total quartz content (Q) varies from 8.7 to 50% of the framework grains, and averages 19.6%. Samples from Kratie and Preah Khan of Kompong Svay are among the most quartz-rich. The majority of quartz is present as coarse, angular monocrystalline grains with nonundulatory extinction (51% of the total quartz fraction). Less abundant are undulatory monocrystalline quartz (29%) and polycrystalline quartz (19%).

Feldspar grains averages 43.6% of the total framework and are present as untwinned varieties (80%) and polysynthetic twinned feldspar (20%). Sodium-plagioclase prevails over calcium-plagioclase and alkali feldspar. Characteristic of the suite are albitized and altered plagioclase grains (Fig. 6).

Lithic fragment contents vary widely within the suite, from lithic-poor (4.5%) to lithic-rich (61.4%), with an average of 36.7%. The latter represent the majority of the studied samples, and the specific lithic assemblage includes prevalent igneous and subordinate metamorphic and sedimentary rocks (Fig. 5).

Igneous lithic fragments are dominated by plagioclase- and hornblende-phyric, microlithic volcanic lithic fragments (Fig. 6). Volcanic lithic fragments (L_v) average 79.6%, but in most samples exceed 80% of the total lithic fraction (Fig. 5). Often, volcanic lithic fragments are weathered and replaced by authigenic minerals, such as chlorite and calcite. Rare fragments of plutonic rock, consisting of aggregates of quartz and feldspar, are also present.

Metamorphic lithic fragments (L_m) are generally subordinate to volcanic and average 13.8%. Their relative abundance increases up to 79.5% only in the volcanic lithic-poor sandstones of the suite, in particular in the areas of Kratie and Preah Khan of Kompong Svay. These grains include fragments of low-grade metamorphic rocks, mainly phyllite and dark chlorite schist, rare quartz–mica schist and fine-grained, strained quartzite.

The content of sedimentary lithic fragments (L_s) averages 6.6%. These grains consist of laminated shale, mudstone and rare siltstone. Carbonate lithic fragments, including ooids and coarse intraclasts, are very rare, but abundant in one sample only (DCA13). Fossiliferous skeletal grains are absent except in sample DCA13.

Relatively large (centimetric to decimetric) fragments of dark, angular sedimentary lithic fragments are occasionally present, and clearly visible at the macroscopic scale suspended in the fine- to medium-grained sandstone. Such occurrences, combined with the absence of clear sedimentary structures and the poor sorting, suggest that the sandstone originated from a high-density turbidity current deposit.

The heavy-mineral (Ht) content averages 5.8%. The most abundant and characteristic accessory mineral is calcic amphibole with strong green and brown pleochroism, often present in euhedral grains (Fig. 6).

Other accessory minerals include epidote, apatite, titanite, garnet, augite and rare zircon in variable relative amounts. Micas are also present (1%), with biotite prevailing over muscovite.

Authigenic chlorite and, to a lesser extent calcite, typically replace grains and fine-grained matrix, and constitute the main cement. Heterogeneous chloritization is responsible for the characteristic mottled appearance of the sandstone surface (Fig. 7). In few cases, syntaxial feldspar overgrowth partially cements the

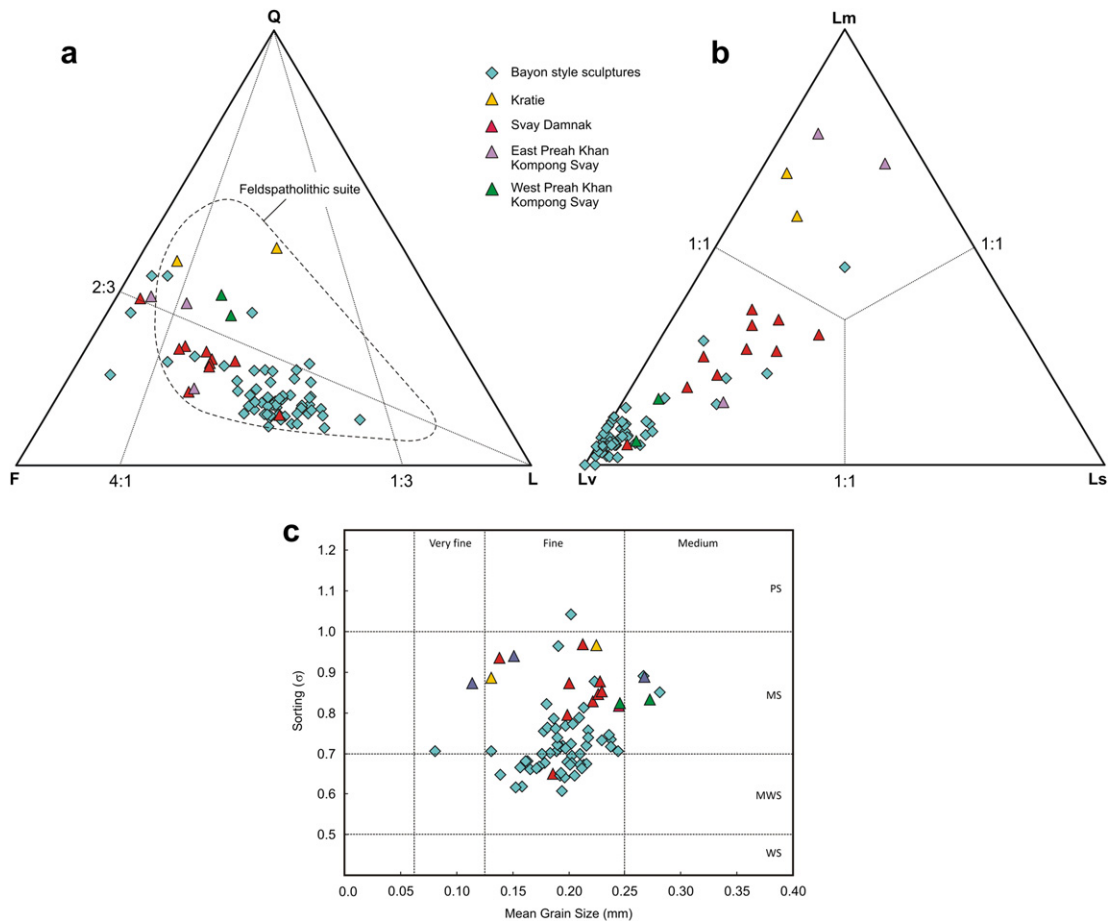


Fig. 5. Ternary plots of a) primary and b) secondary detrital composition of sculpture and outcrops samples. Q: quartz; F: feldspar; L: lithic fragments; L_m: metamorphic; L_v: volcanic; L_s: sedimentary grains. The dashed line shows the compositional field of feldspatholithic suites of arc orogens according to Valloni and Mezzadri (1984). c) Textural classification of the studied samples. WS: well sorted; MWS: moderately well sorted; MS: moderately sorted; PS: poorly sorted.

framework grains. Secondary epidote is often present at grain boundaries and replaces feldspar grains, likely as a product of diagenesis and and/or hydrothermal alteration (Franz and Liebscher, 2004).

The fine-grained matrix consists of chlorite, sericite, quartz and plagioclase laths and averages 9.6% of the total sandstone volume. In some cases, nodules of clay-rich matrix are present among the framework grains.

The texture, as seen in thin section, is quite homogeneous; particularly in L_v-rich sandstones (Fig. 5; Table 1). The mean grain-size ranges from 0.13 to 0.28 mm (fine-grained), while sorting is generally moderate ($\sigma = 0.7$), if we exclude the rare large clasts.

3.2.2. Compositional analysis of amphibole grains

Amphibole group minerals can occur in a fairly complex range in compositions, and are sensitive to the overall chemical environment that prevailed during their formation in an igneous melt, such as pressure, temperature, and the bulk composition of the overall system. For this reason, when a source rock that contains amphibole is disaggregated and its minerals separated from one another, amphibole compositions can help establish whether the population of individual grains originated from a similar geological source.

Earlier research utilizing electron microprobe analysis (EMPA) on amphibole grains present in thin sections of sandstone from Bayon sculptures established this trend (Douglas and Sorensen, 2007). For this reason, a pilot group of a minimum of ten amphibole grains in each of eight thin sections, four field samples from

the area of Svay Damnak and four sculpture samples, was analyzed with EMPA for quantitative elemental composition to determine whether this trend holds. Similarly to the earlier studies, all of these amphibole grains can be further divided into two main compositional groups of calcic amphiboles; one within the edenite–magnesiohastingsite (or pargasite) solid solution series, and the other within magnesiohornblende–tschermakite solid solution series (Fig. 8) (for terminology see: Leake et al., 1997). The compositional similarities in the amphibole data in the quarry and sculpture samples support the hypothesis of the same broad igneous source provided the amphibole detritus for these sandstones.

3.2.3. Sandstones inconsistent with the feldspatholithic suite

Besides the sandstones that can be ascribed to the plagioclase-rich feldspatholithic suite, two other lithotypes, characterized by a more developed textural and mineralogical maturity, have been recognized among the studied samples.

One lithotype is a feldspathic arenite of composition $Q_{44}F_{49}L_7$ used for the male bust DCA8. This sandstone is composed of moderately well sorted ($\sigma = 0.6$), sub-angular to rounded, fine-grained framework grains (mean grain size = 0.14 mm) cemented by authigenic chlorite. Quartz and feldspar constitute the majority of the framework grains. Monocrystalline nonundulatory quartz grains (26.2%) prevail over undulatory (12.2%) and polycrystalline quartz (5.2%). Feldspars include prevalent plagioclase and minor alkali feldspar. Lithic fragments are subordinate (7.7%), and consist,

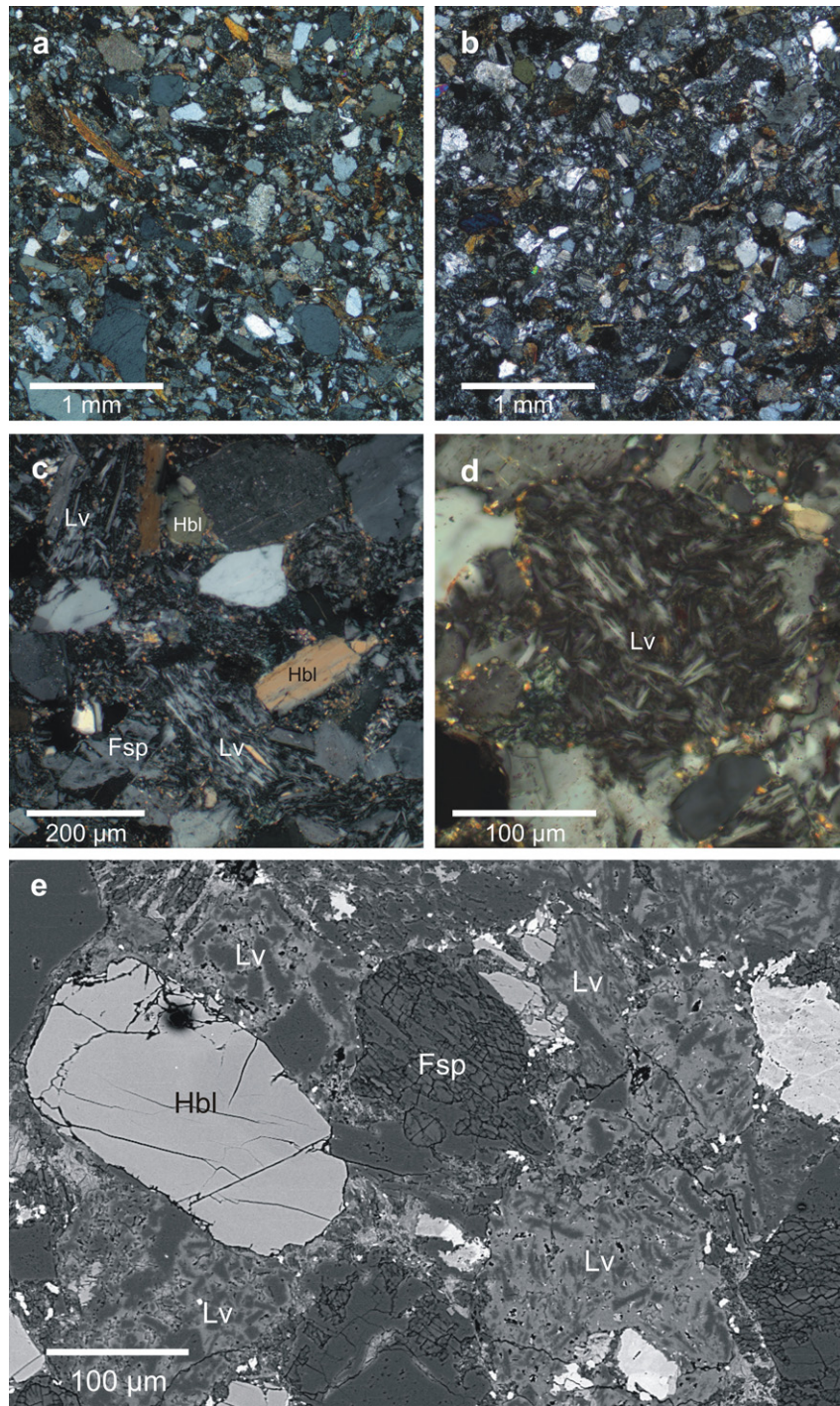


Fig. 6. Micrographs under crossed polarized light showing: a) volcanic lithic-poor (sample 239) and b) volcanic lithic-rich (sample 179) end-member sandstones of the suite; c) volcanic lithic fragments (*Lv*), albitized feldspar (*Fsp*) and Ca-amphiboles (*Hbl*) (sample DCA4); d) a detail of a microlithic volcanic lithic fragment (sample DCA4); e) backscattered electron (BSE) image of the characteristic grains found in the volcanic lithic-rich sandstone of the suite (Sample DCA26) and abundantly used for Bayon style sculptures.

in order of abundance, of small, intensely-altered andesite grains, low-grade metamorphic phyllite, and fragments of argillite and shale. Accessory minerals include micas (1.1%) and heavy minerals such as garnet, epidote, ilmenite, titanite, zircon and apatite (5.9%). Occasional fine grains of hematite and rutile are also present.

A second lithotype has been identified in the standing female DCA41. This sandstone is a feldspathic arenite characterized by a very fine-grained (mean grain size = 0.08 mm; $\sigma = 0.7$), feldspar-rich framework assemblage of composition $Q_{21}F_{71}L_8$. Framework

grains are well laminated and cemented by authigenic chlorite. Monocrystalline (16.5%) and polycrystalline (4.3%) quartz are subordinate to angular to sub-rounded grains of turbid feldspar (64.3%). Rare plagioclase grains with polysynthetic twinning are also present as well as larger zoned feldspar grains. The lithic fraction is poorly represented by small volcanic microlithic and low-grade metamorphic lithic fragments. Heavy minerals are scarce (2.5%) and include predominantly fine-grained iron and titanium oxides, as well as small grains of zircon and epidote. Small

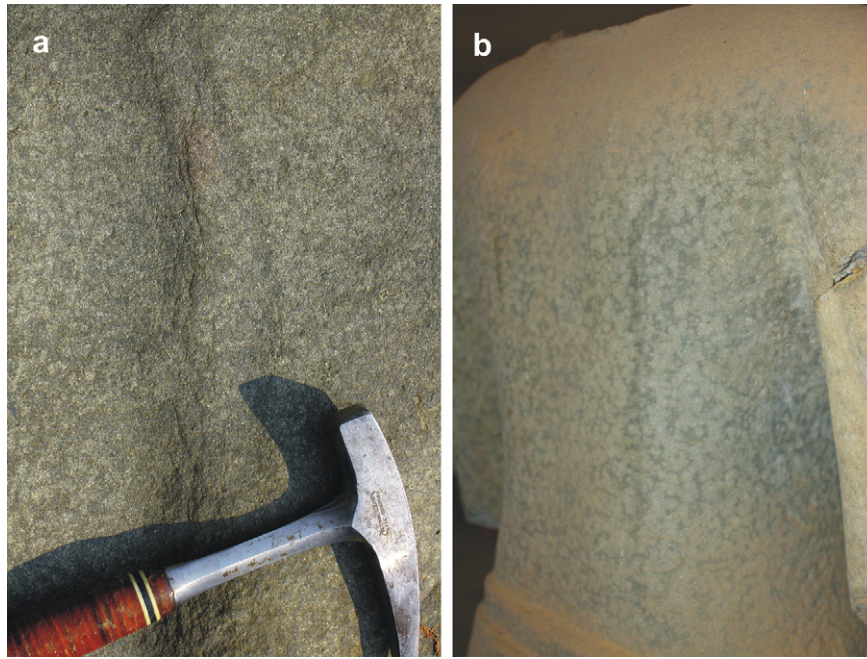


Fig. 7. Details of the mottled appearance of the Triassic sandstone caused by diffused chloritization from a) outcrop in the riverbed of a tributary of Stoung River, and b) as seen on the standing male 6770/253 (sample DCA29), Dépôt de la Conservation d'Angkor.

mica flakes, usually bent between the framework grains, average 0.8%.

4. Discussion

4.1. Sculpture samples

Petrographic analysis of the Bayon style sculptures studied here suggests that the majority (95%) are carved from sandstone belonging to the same feldspatholithic suite which comprises the Triassic formation. The sandstone of the sculptures varies from lithic-poor ($L = 4.6\%$; $L_v = 27.3\%$) to lithic-rich ($L = 61.4\%$; $L_v = 94.3\%$).

Most, however, are markedly lithovolcanic (86%), i.e. are quartz-poor ($Q < 25\%$) and extremely rich in microlithic andesite fragments ($L_v > 83\%$), albitized feldspar, and hornblende grains. The average composition of this latter distinct sandstone type is $Q_{17}F_{42}L_{41}$.

If compared to the overall suite's broad compositional variation ($L_v = 7\text{--}100\%$), the narrow composition variation ($L_v = 83\text{--}100\%$) of most of the sculptural stone is indicative of a localized source, possibly a single quarry district within the Triassic formation.

Few of the studied sculptures are realized from lithic-poor sandstone belonging to the same Triassic feldspatholithic suite. Among them, the Buddha sheltered by Naga of unknown provenance, DCA12, the Lokeśvara head found at Tep Pranam in Angkor Thom NMC990, the stele from Prasat Preah Khan DCA17, the standing female from Ta Nei DCA38 and the Vishnu head from Angkor Wat NMC2995. These sandstones contain more quartz ($Q = 24\text{--}44\%$) and fewer lithic fragments ($4.5 < L < 28.2\%$), and have a higher content of lithic fragments of metamorphic origin ($L_m = 24\%$) than the sandstone commonly used for Bayon style sculptures.

The standing Vishnu from Kok Prei, DCA13, is carved from a distinctive carbonate-rich, immature sandstone characterized by abundant limestone mudrock fragments, calcareous fossil fragments, ooids, abundant calcite matrix and cement. This sandstone

contains also andesite lithic fragments, albitized feldspars, and hornblende grains typical of sandstones of the majority of Bayon style sculptures in this study. This finding suggests this rock type may be a calcareous member of the feldspatholithic suite of the Triassic formation.

Finally, two sculptures are made with sandstones that do not belong to the Triassic formation. The male bust from Ta Prohm, DCA8, is carved from a fine grained (mean grain size = 0.14 mm) feldspathic arenite of composition $Q_{44}F_{49}L_7$ that, for compositional and textural characteristics, can be attributed to the Lower–Middle Jurassic Terrain Rouge Formation (Carò and Im, 2012). Another sculpture, a small standing female DCA41 from Prasat Kuk Snoul, is carved from a very fine-grained feldspathic arenite which is extremely rich in feldspar grains ($Q_{21}F_{71}L_8$). Interestingly, this stone has strong similarities to sculptures carved in Angkor Wat and Baphuon style (unpublished data by the authors) dating from the 2nd half of the 11th century to the 1st half of the 12th century. Currently the provenance of this stone is unknown.

4.2. Field samples

In the surveyed areas, sandstone outcrops show petrographic and textural characteristics compatible with the Triassic formation described in literature (Contri, 1972). The distinctive characteristics of this feldspatholithic sandstone are 1) immature texture of sub-angular to angular, moderately sorted, and fine grain-size; 2) the variable but ubiquitous presence of plagioclase and hornblende-phyric, microlithic volcanic lithic fragments (L_v); 3) hornblende grains and albitized plagioclase grains; and 4) diffuse authigenic chlorite.

Near the village of Svay Damnak, where our sampling campaign was denser, the compositional variation characterizing this suite is demonstrated. Here, the sandstone changes from lithic-poor ($L = 4.8\%$; $L_v = 40\%$) to lithic-rich ($L = 45.3\%$; $L_v = 89.5\%$) within an area of about 1 km². Lithic-rich sandstones are also particularly rich in volcanic lithic fragments.

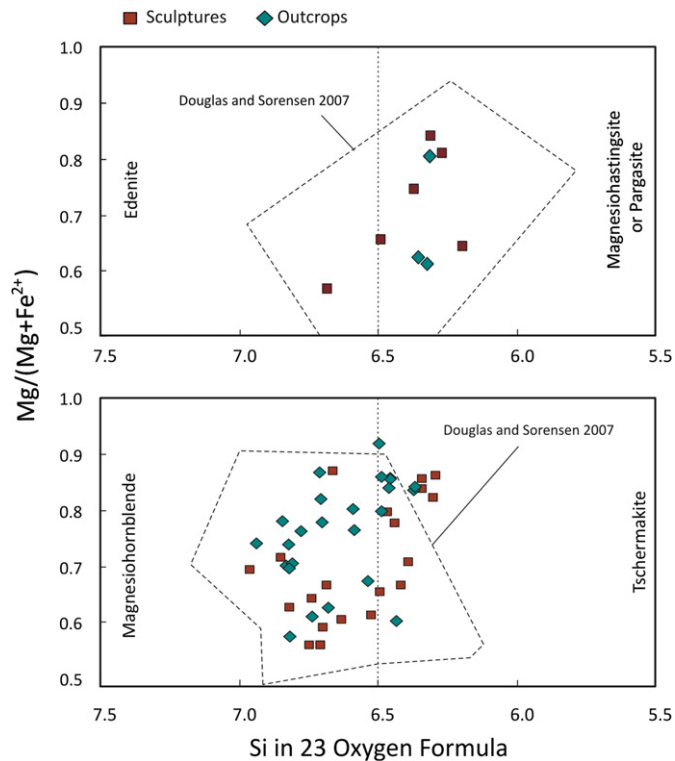


Fig. 8. Amphibole microprobe data of sculpture and field samples compared to Douglas and Sorensen (2007).

Evidence of quarrying activity exists in Kratie province (Bruguier, 2006), while traces have been discovered in the area of Svay Damnak, where further work is needed to determine the extent of their occurrence.

Remains of wedge holes and splitting channels indicate that the sandstone was quarried and sized locally, although currently their date is unknown. Also, these remains alone cannot account for the vast Bayon style sculptural production (Cœdès, 1958; Stern, 1965; Jessup and Zephir, 1997), and further archaeological studies are needed in the area to assess the real extension of the site.

The sandstone from Kratie province and from the surroundings of Preah Khan of Kompong Svay is characterized by higher quartz content ($Q = 33.6\%$) and lower lithic fragments ($L = 18.2\%$), and can be ascribed to the lithic-poor end member of the series. In Kratie, lithic fragments of metamorphic origin predominate over volcanic and sedimentary ones, while around Preah Khan of Kompong Svay the lithic assemblage varies from volcanic-poor ($L_v = 7.7\%$) to volcanic-rich ($L_v = 87.5\%$).

The traces of exploitation found in Svay Damnak, as well as others that have been discovered to date, are not sufficient to confirm the presence of a developed and organized site of stone extraction, nor the presence of stone workshops in this area. No dressed blocks or unfinished sculptures have been found around Svay Damnak and Preah Khan Kompong Svay. Conversely, dressed blocks and unfinished pedestals are still lying in the sites along the Mekong River north of Kratie.

Field observations revealed that Triassic sandstones are exposed in scattered outcrops of small surface extension and height. Outcrops along and in riverbeds are usually the most extensive (Fig. 4b). The traces of stone exploitation were found in the vicinity of riverbeds, and suggest that boulders were split close to their original location. The practice of splitting and dressing existing boulders can be justified by the presence of a diffuse system of almost orthogonal joints that separates the massive sandstone into

defined blocks. This characteristic is particularly intense towards Preah Khan of Kompong Svay, but has been observed in all the surveyed sites included in several outcrops in Kratie province. Severe stone weathering and abundant loose sediment cover may be contributing to conceal further quarry remains. For these reasons, clear and organized traces of sandstone quarries, such as the stepped surfaces found at the foothill of Kulen Mountain in the Terrain Rouge formation (Carò and Im, 2012), may be difficult to find.

5. Conclusion

Based on current geological knowledge of Cambodia, the Triassic formation was chosen for survey as the potential source of sandstone for the production of Bayon style sculpture during the reign of Jayavarman VII. Results from petrographic analysis of field samples show that the Triassic formation is characterized by sandstone of considerable compositional and textural variations.

The study of the large corpus of Bayon style sculptures reveals that the stone used for the majority of the objects belongs to the same Triassic formation that is exposed in the surveyed area. Moreover, the narrow compositional variation of the sculptural sandstone found here and in previous study (Douglas and Sorensen, 2007) strengthens the hypothesis that a localized source of stone was exploited for the production of royal sculptures under Jayavarman VII's reign.

Sandstone of similar texture and composition is exposed in the vicinity of Svay Damnak, a village located about 16 km southeast of Preah Khan Kompong Svay. Remains of quarrying activity in the form of wedging and splitting channels further support the idea that sandstone may have been quarried from this area during Jayavarman VII's reign. The recovery of unfinished sculptures or dressed blocks and other archaeological remains will be essential in the final identification of the royal quarries that provided the majority of the stone used during Jayavarman VII's reign for sculptures of Bayon style. Hopefully the current work can induce further archaeological studies in the area where the Triassic formation occurs.

Although the vast majority of sculptures have been identified as composed of sandstone from the Triassic formation, two sculptures are carved from stone unlike the sandstone of the Triassic formation. This finding suggests that other, albeit minor, geological sources and sculpture workshops existed during the reign of Jayavarman VII. As more sculptures are studied and archaeological research progresses, we can develop a more thorough understanding of Khmer sculpture production from quarrying at the geological source, to carving at the stone workshop, to final installation within a temple.

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