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THEMATIC ISSUE

Lithological characteristics and homogeneity of alternative stone for restoration of the Hong Nang Sida temple in Vat Phou, Lao PDR

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Abstract

The Hong Nang Sida temple with significant historical value was designated as a UNESCO world cultural heritage. However, most parts of the main temple were destroyed, and being neglected for a long time. Some remained building structures also have been influenced on asymmetric load, it causes various types of damage including imbalance problem. Accordingly, reasonable conservation treatment and proper restoration processes are required. The stone material of the main temple in Hong Nang Sida is made with sandstone and siltstone, and by assuming that they were extracted from nearby Mt. Phou Kao. Specimens were collected from Mt. Phou Kao, Douangdy and Vat Chompet quarries to review the homogeneity with the stones in Hong Nang Sida temple. Also, by analyzing the sandstone used to restore the Vat Phou temples located around the Hong Nang Sida temple, it was examined whether it could be used for restoration of the Hong Nang Sida temple. The study on the homogeneity of stones revealed that it would be the most desirable to use rocks from Mt. Phou Kao as alternative stones for restoration of the main temple. It has different lithological and geochemical characteristics from the restoration stone of the Vat Phou temple. However, as Mt. Phou Kao was designated as world cultural heritage protection area, it is hard to get sufficient amount of alternative stones for restoration. Thus, it is proper to secure alternative stones from Douangdy and Vat Chompet quarries, considering the geochemical homogeneity, color and sedimentary structure as well as procurement possibility.

Keywords Hong Nang Sida temple site · Sandstone · Lithological characteristics · Provenance interpretation

Introduction

The ancient Khmer empire had influenced most of the Indochina peninsula, and historical monuments of the empire archeological site in Cambodia, Vietnam, Myanmar, Thailand and Lao PDR. There are a number of sites related to Khmer including Angkor sites in Cambodia, My Son sites in Vietnam, Phimai archeological sites in Thailand and Vat Phou sites in Laos. 'Vat Phou temple and ancient dwelling site in Champasak cultural landscape' including Vat Phou and Hong Nang Sida temple in Laos is a popular touristic destination in southern Laos designated as the UNESCO World Cultural Heritage in 2001. Major archeological sites of the Champasak cultural landscape are Phou Kao, Vat Phou Temple Complex, Hong Nang Sida area including Ancient Road, Thao Tao Temple, Temples and Inscriptions, Ancient City, Tomo Temple, Other sites on the Champasak Plain.

The study point, Hong Nang Sida temple, is located on the approximately 1.5 km southside from Vat Phou main

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temple (Fig. 1). Hong means 'room,' Nang 'woman,' Sida 'Queen Sida in Ramayana epic' therefore Hong Nang Sida 'the room of Princess Sida.' The site consists of main temple building, bricks library, main path and ancient road. Unlike Vat Phou Temple, a masculine building at the foot of Phou Kao, Hong Nang Sida is feminine and built on flatland. Hong Nang Sida temple, which is composed of platform–mandapa-antarala-cella; cella and antarala losts its original shape because they were covered by their collapsed upper parts. Moreover, stones of the upper part are being piled up around the temple, making it impossible to enter inside.

Despite the significant historic and academic value of Hong Nang Sida, the main temple has been destroyed and neglected for a long time. It led to imbalance and asymmetric load on the building stones and caused physical damages. Since biological damage is unavoidable each year due to the environment of high temperature and high humidity, Hong Nang Sida needs to get scientific precision diagnosis for conservation and reasonable preservation and restoration.

In 2012, conservation and restoration for Hong Nang Sida temple located in Vat Phou site and scientific study on the ancient Khmer archeological sites were conducted by the Korea Cultural Heritage Foundation. Also, in 2014, digital documentation and long-term conservation management system was developed for Vat Phou main temple and Hong Nang Sida temple by the National Research Foundation of Korea. These research data can be used to establish a long-term plan for the conservation of the Hong Nang Sida temple, and research on temple building materials is required to carry out the conservation project (Korea Cultural Heritage Foundation 2013, 2014).

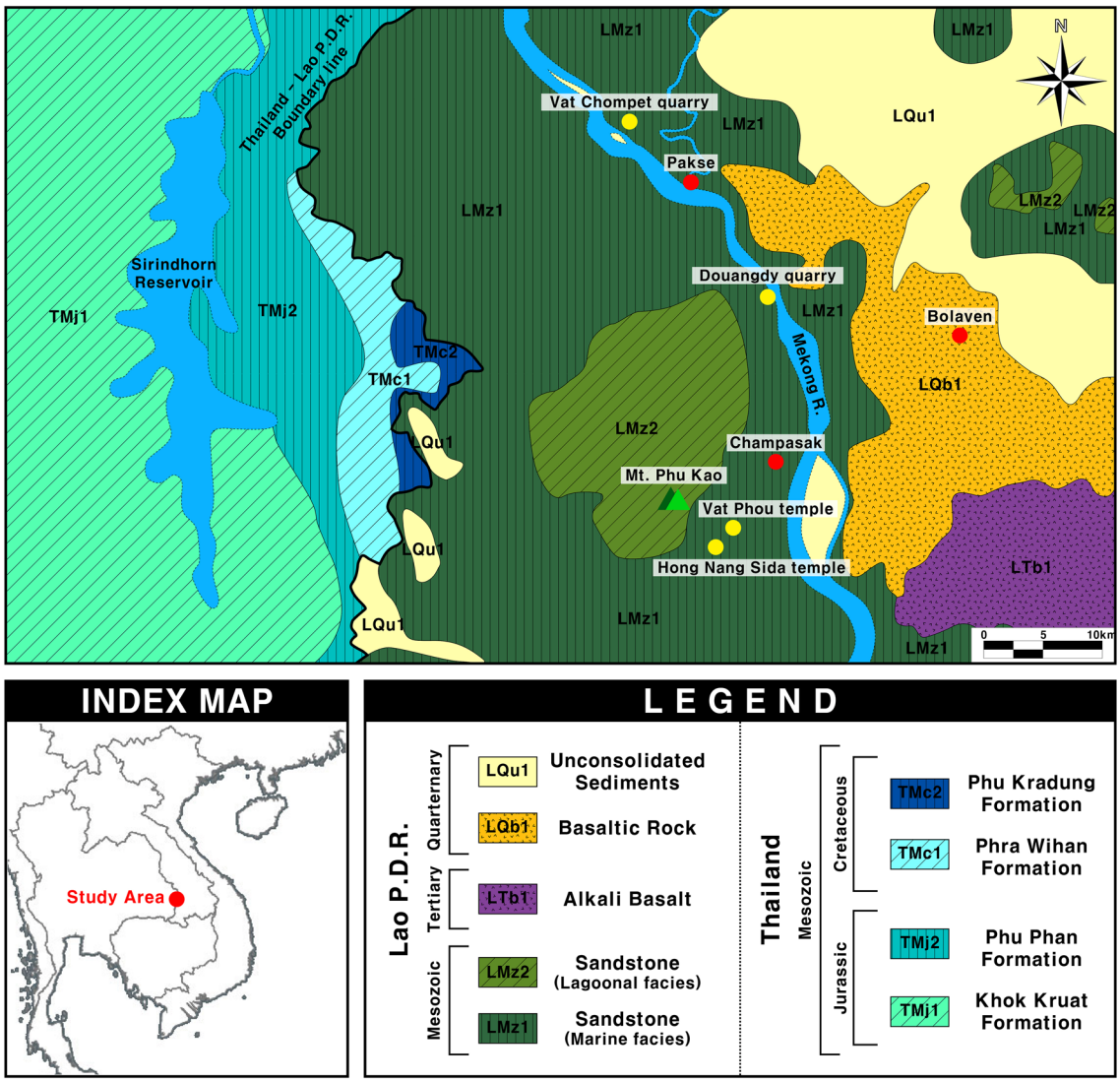

Fig. 1 Geological map and sampling points around the Hong Nang Sida temple site in Lao PDR

In this research, we studied material analysis on rocks consisting of Hong Nang Sida temple, discuss on securing alternative stones and procuring stones through analysis on place of origin of main temple rocks. In addition, the stone used for restoration of the Vat Phou temple were analyzed to confirm the lithological difference from the Hong Nang Sida temple building materials. This is essential for supply and demand of alternative stones for maintenance and restoration of Hong Nang Sida temple in the future and conservation of reused stones.

Methodology

Geography and geological setting

Lao PDR, the only inland nation in Southeast Asia, has mostly steep high mountains in the northside. This country has geography with three distinct characteristics: mountainous area, plateau and plain; mountainous area and plateau account for 1/3 of the total area. Plains in Laos are distributed around the Mekong River that runs north to south, and 'Vat Phou Temple and ancient dwelling site in Champasak cultural landscape' is located on the Champasak plains in southern Laos. Major temples are located in the southeast of Mt. Phou Kao, and the Mekong River runs in the east of the Vat Phou temples.

Hong Nang Sida temple is located on the southeastern flat land of Mt. Phou Kao, and consists of the main temple built as rocks and the library made of bricks (Fig. 2A). The Vat Phou temple is located 1.5 km to the northeast of the Hong Nang Sida temple, and there are two Palace buildings on a flat area at the bottom of the mountain (Fig. 2B). There is a slope on the west side of these buildings and the main temple of the Vat Phou is located on a hillside about 300 m from the Palace (Fig. 2C).

Outcrops of sandstone are exposed in valleys and slopes of Mt. Phou Kao and some traces of quarrying are observed (Fig. 2D, E). Although the color of the sandstones differs depending on their location, the shape and size of the quarried traces has almost similar characteristics. These traces are processed in a step shape on the surface of the rock and some traces have a depth of several tens of centimeters.

The stones used in the buildings of the Khmer Empire are closely related to the geology around the archeological sites, and the stones around the sites were processed and used as building materials (Uchida et al. 2010). Being a world heritage, Hong Nang Sida Temple should be repaired and maintained without damaging the authenticity or integrity. It is desirable to use the same type of rocks to the stones constituting the main temple of Hong Nang Sida for restoration of the original shape. However, the building stones presumed to quarried in the Mt. Phou Kao for finding quarrying trace, but it is difficult to quarry at Mt. Phou Kao as it is designated as a World Heritage Site.

Therefore, it is required to find alternative stones from other areas that can be quarried in large amount for restoration and have the same properties as the stones in the main temple. This research investigated rocks from Douangdy quarry, which is about 20 km north of Hong Nang Sida

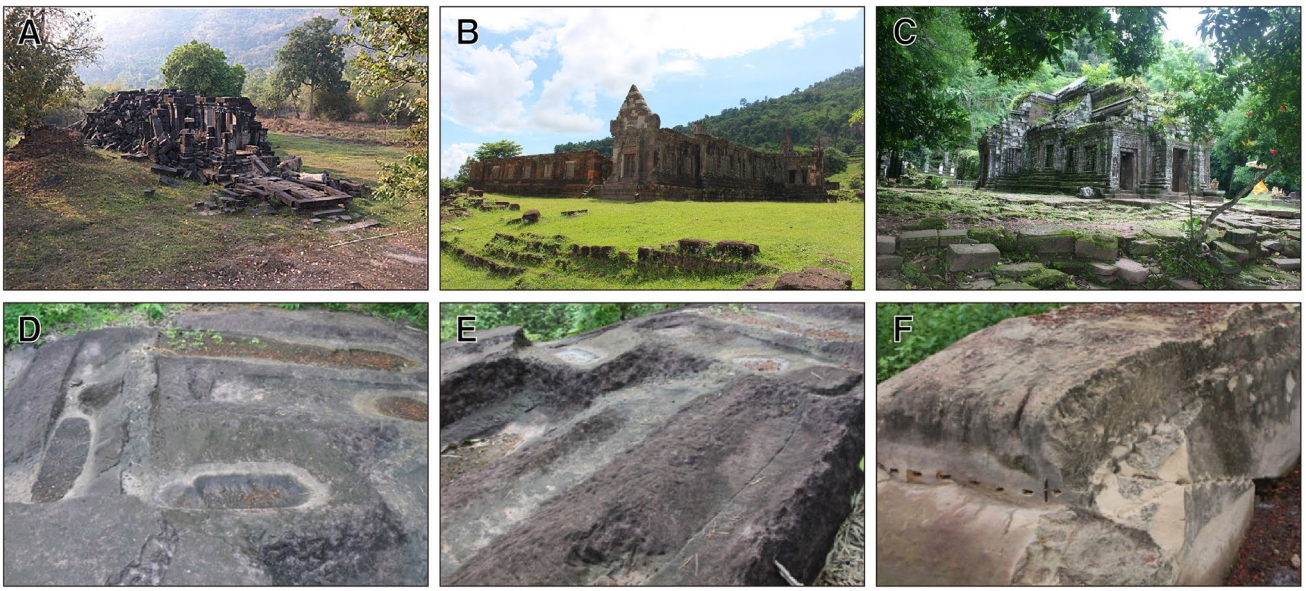

Fig. 2 Status of the archeological site in 'Vat Phou temple and ancient dwelling site in Champasak cultural landscape': **A** the Hong Nang Sida temple. **B** The Palace building of Vat Phou. **C** The main temple of Vat Phou. **D**, **E** Quarry traces observed in Mt. Phou Kao. **F** Ancient quarry traces that exist on the outcrop of Vat Chompet quarry

temples, and quarry near Vat Chompet Temple that is approximately 20 km northwest. These areas are capable of mass quarrying, and quarrying has been conducted until recently. In particular, an outcrop with traces of ancient quarrying was confirmed in the Vat Chompet quarry, and it shows that quarrying has been carried out since ancient time (Fig. 2F).

The distribution of rocks in this area was roughly investigated through regional geological inspection, but inspection has not been performed in detail. There were some partial studies mostly focusing on the northern regions of Laos. As such, materials on wide distributions of geological features and local research in Laos, Thailand and Cambodia were referred to for the distribution of geological features at Hong Nang Sida Temple area.

Geotectonically, Laos belongs to Indochina massif where sedimentary rocks of the Mesozoic era are widely distributed. Clastic sedimentary rocks are distributed within a dozens kilometers radius centering on Hong Nang Sida Temple, and from near the Mekong River in the east is plateau area where mafic rocks, which intruded in the latter period, are distributed (Fig. 1). The bedrock of the area where Hong Nang Sida temple is located is marine facies sandstone, and the both quarries belong to the same sandstone formation. However, the sandstone of Mt. Phou Kao may be different from the sandstone of temples as it is deposited in a lagoon environment.

As for Thailand that is about 30 km west, more detailed geological feature inspection was conducted compared to Laos. The border of Thailand and Laos is sedimentary basin of the Jurassic period and the Cretaceous period in the Mesozoic era, and it was named as khorat group. Various types of fossils including dinosaur bones, eggs and footprints were discovered along with rock floor from the sedimentary layer, and the sedimentary environment was investigated relatively in detail (Buffetaut et al. 2005; Le Loeuff et al. 2005, 2009; Sato and Tumpeesuwan 2005; Matsukawa et al. 2006).

Although the geology of Champasak province in Laos was revealed to be sandstone area through regional geological inspection, it seems that there are differences in rock formation like the detailed investigation in Thailand. Older strata exists on west of Thailand, the research areas are also likely to have the same pattern. Moreover, as sedimentation of the border area was formed in upper Jurassic, the sedimentation period of the research area is considered earlier than Thailand sedimentary rock (Kozu et al. 2017).

Method of analysis

For this study, we performed visual inspection to identify the lithological characteristics of the Hong Nang Sida temple building stones and classified the lithofacies. Specimens were collected for each type of lithofacies for scientific analysis. The mineralogical and structural characteristics of stones that constitute the temple were observed with stereoscopic and polarization microscope based on the collected samples.

In Mt. Phou Kao located on the northwest side on the Hong Nang Sida temple, there are large number of outcrops with traces of quarrying. There is partially a slight difference in stone color, refined structure and grain size, and although most of them have similar petrographic features to stones used in the main temple of Hong Nang Sida Rocks having similar characteristics to the stones constituting the temple were collected and compared with those of the temple.

The restoration of the temple requires a large-scale supply of stones, and samples were collected from quarries where similar rocks are distributed. During the research process, several samples were secured from Douangdy and Vat Chompet quarry, and the restoration stones of Vat Phou temple were analyzed to examine the rock and homogeneity of the Hong Nang Sida temple. In this study, various analyses were conducted to identify the lithological characteristics of samples collected from Hong Nang Sida temples, Mt. Phou Kao, Douangdy quarry, Vat Chompet quarry, and restoration materials of the Vat Phou temple and to verify mutual homogeneity.

In addition, quantitative colors and magnetic susceptibility of rocks were also measured and compared with rocks used as building materials for Hong Nang Sida temples. Magnetic susceptibility is an effective method to identify homogeneity by characterizing materials of rocks. It has also been used for restoration of cultural assets by being applied to interpretation of the place of origin such as behavior of stone cultural assets, stoneware and ancient ceramics (Lee et al. 2004, 2007; Jo and Lee 2015). In particular, the archeological sites of the Khmer empire, which are distributed throughout Southeast Asia, consist mostly of sandstone, and various studies have conducted magnetic susceptibility measurements for the interpretation of provenance (Uchida et al. 2007, 2010; Uchida and Shimoda 2013).

For quantitative analysis of major, rare earth elements, large ion lithophile elements and high field strength elements that constitute the samples, geochemical analysis were performed using Instrumental Neutron Activation Analysis (INAA), Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). The accuracy and precision were verified with standard sample, sample blank and duplicate sample. The homogeneity of rocks was reviewed by compiling all the analysis results, and the procurement of restored stone was proposed to preserve the authenticity of the World Heritage Site.

Results and discussions

Lithological characteristics

Samples for analysis were collected from the main temple of Hong Nang Sida, outcrops in Mt. Phou Kao area, Douangdy quarry, Vat Chompet quarry and restoration stone of Vat Phou temple. The samples were classified according to geological formation and color, and the mutual homogeneity and similarity were explored. Analysis was performed on a total of 22 samples, including a total of five samples taken around Hong Nang Sida temple, and the sample names and types of rocks are shown in Table 1.

Sandstone, consisting of the Hong Nang Sida temple, can be divided into gray sandstone, grayish-green siltstone, grayish-green sandstone and dark gray sandstone in detail (Fig. 3). Depending on the location of the temple, the colors of the rocks are divided, with gray-green sandstone and siltstone used on the north side, and gray sandstone on the east side. However, all stones have similar mineral composition and texture, although there are differences in the color of the rocks.

The grain size of the sandstone is around 0.5 mm, the sorting is good, and the roundness is subround or subangular. Quartz accounts for the most rock-forming minerals, and a small amount of feldspar and mica are observed. The grain size of siltstone is about 0.1 mm, and the mineral composition and texture are similar as that of the sandstone. There are no bedding and sedimentary structures commonly observed in sedimentary rocks, and they appear to be massive sandstone facies.

Located in northwest of the main temple of Hong Nang Sida, Mt. Phou Kao consists of sandstone, and evidence of quarry is observed in outcrop. The grain size of sandstone is approximately 0.5 mm, and they have equi-granular structure, with subrounded roundness and well-sorted. Quartz accounts for the most grains, and some feldspar and mica are observed. Partially, matrices are observed, which consist of quartz. Siltstone has lithological characteristics similar to sandstone, but weak bedding is observed with biotite arranged in a linear.

The sandstone of the Douangdy quarry has a grain size of about 0.5 mm, but slight difference is observed by formation. Sedimentary structure including cross bedding and false bedding is clearly observed, and massive rocks are partially identified. Rocks without a sedimentary structure, such as those used in Hong Nang Sida temple, are distributed in the lower part of the formation. The roundness is subround or subangular, and the sorting is good. Quartz accounts for the most grains, and some feldspar and mica are observed.

Rocks from Vat Chompet Quarry have a smaller grain size than rocks from Douangdy Quarry, and most stones quarried for the production of crafts are siltstone. Rocks extracted from Vat Chompet quarry do not have clear

Table 1 Sample list and their rock type

Location	Sample name	Rock type
Hong Nang Sida temple (HNS Group)	HNS-01	Gray sandstone
	HNS-02	Greenish gray siltstone
	HNS-03	Greenish gray siltstone
	HNS-04	Greenish gray sandstone
	HNS-05	Dark gray sandstone
Mt. Phou Kao (PK Group)	PK-01	Greenish gray siltstone
	PK-02	Dark gray sandstone
	PK-03	Dark gray sandstone
	PK-04	Dark gray sandstone
	PK-05	Dark gray sandstone
Douangdy Quarry (DAQ Group)	DAQ-01	Dark gray sandstone
	DAQ-02	Dark gray sandstone
	DAQ-03	Dark gray sandstone
	DAQ-04	Dark gray sandstone
	DAQ-05	Dark gray sandstone
Vat Chompet Quarry (VCQ Group)	VCQ-01	Gray siltstone
	VCQ-02	Gray siltstone
	VCQ-03	Greenish gray siltstone
Restoration stone of the Vat Phou temple (VPR Group)	VPR-01	Light gray siltstone
	VPR-02	Gray siltstone
	VPR-03	Purple siltstone
	VPR-04	Yellowish white sandstone

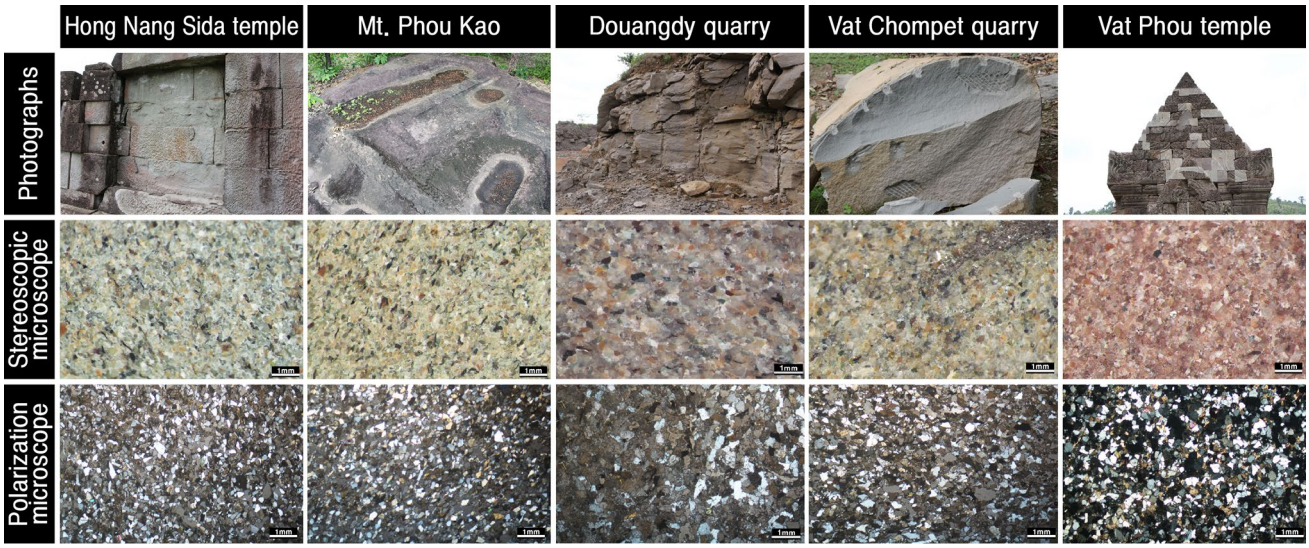

Fig. 3 Lithological and microphotographs images of the analysis samples

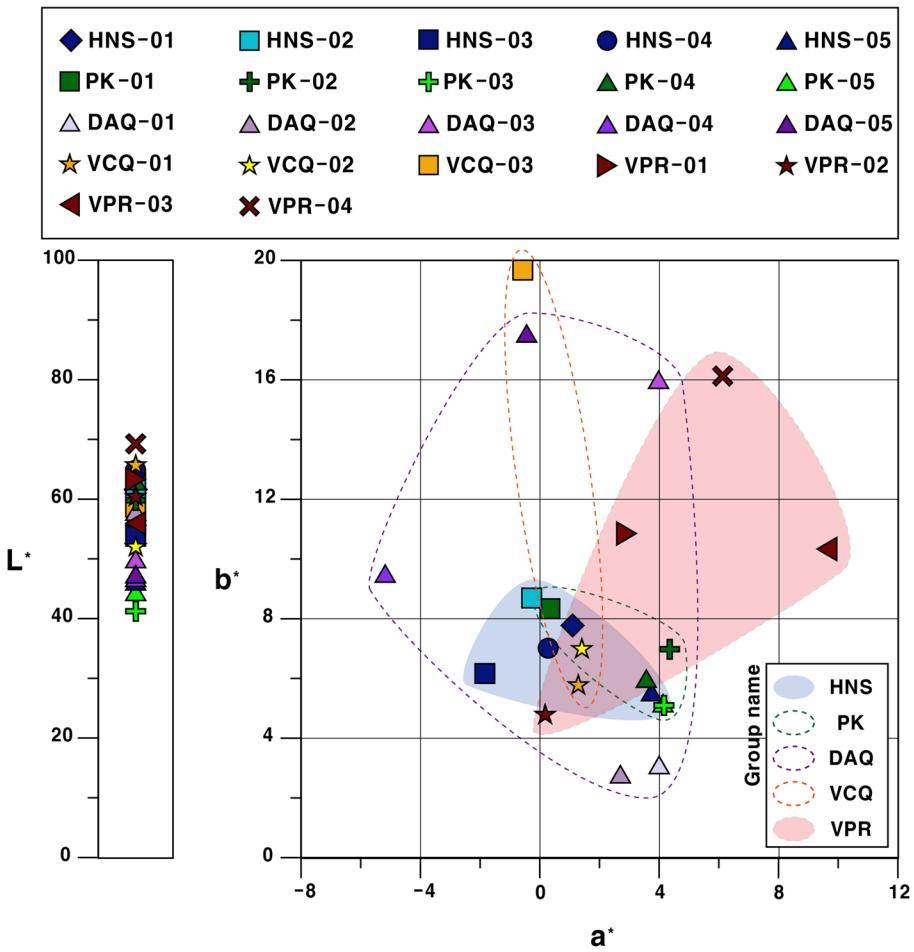

Fig. 4 Diagram showing chromaticity of sandstones

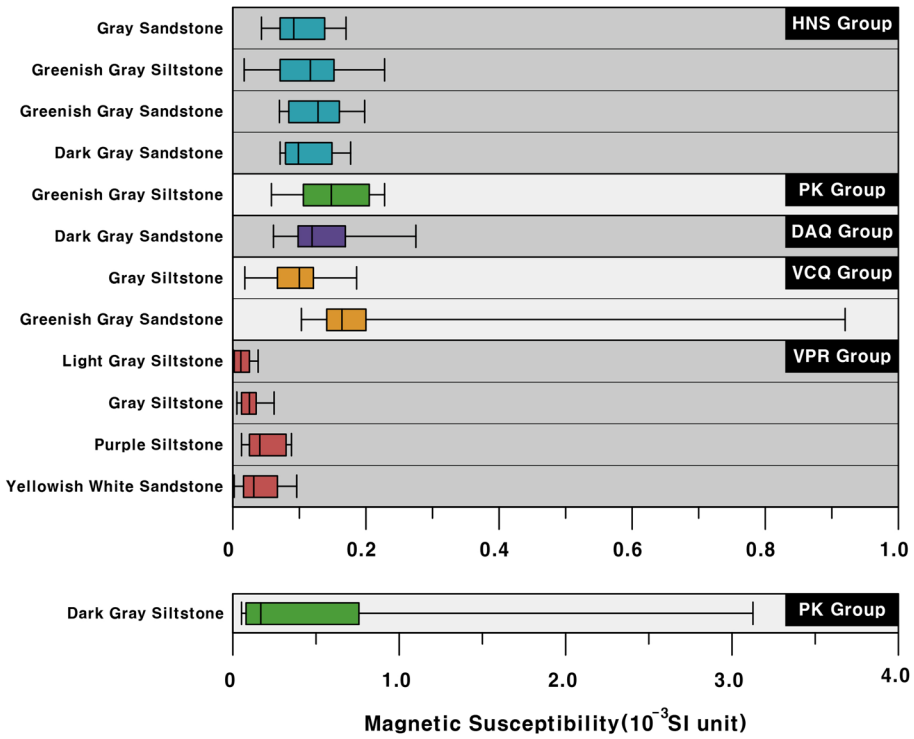

Fig. 5 Diagram showing magnetic susceptibility of sandstones

sedimentary structure, and are produced in the shape of horizontal bedding or massive. The grain size of siltstone is approximately 0.2 mm, and some matrices are contained. The roundness is subangular, and the sorting is poor. The major minerals of the rocks are quartz, feldspar and mica.

Lastly, the stones used to restore the Vat Phou temple come in various colors such as pinkish gray, gray, purple, pale yellow. These rocks have differences in particle size, sorting, and roundness according to their color, and they are all massive clastic sedimentary rocks without sedimentary structure. The stone used in the Vat Phou temple is very different from that of the Hong Nang Sida temple in cementation. The cement of the Hong Nang Sida temple stone is a silicate mineral, whereas the cement of the stone used to restore the Vat Phou temple is calcite, the carbonate mineral.

Chromaticity

Since all types of rocks have their own unique color, color is an important feature to separate from other rocks. Due to soil covering the rocks, however, it is hard to distinguish with naked eyes, and discoloration and contamination may occur due to continuous changes in surrounding environment. This makes it difficult to estimate the color of rocks from a subjective perspective with naked eyes. Therefore, it is necessary to express objective and quantitative chromaticity difference to show clear color.

L^* values of HNS group sandstones collected from Hong Nang Sida temple were 46.26–64.89 (average 57.68), a^* − 1.84 to 3.74 (average 0.60), and b^* 5.55–8.70 (average 7.04). PK group samples collected from Mt. Phou Kao, at the back of Hong Nang Sida temples, show L^* of 41.24–63.27 (average 54.38), a^* of − 0.34 to 4.35 (average 3.31), and b^* of 5.10—8.34 (average 6.32), having the similar chromaticity to HNS group samples (Fig. 4).

DAQ group samples from Douangdy quarry, which is still being quarried, had L^* of 46.86–57.95 (average 51.88), a^* of − 5.18 to 4.00 (average 1.01), and b^* of 2.80–17.56 (average 9.80), showing somewhat different results in chromaticity from the HNS group. However, the chromaticity of DAC-01 and DAC-02 had little difference compared to that of HNS group and PK group.

VCQ group samples collected from Vat Chompet quarry showed L^* of 52.18–65.85 (average 58.91), a^* of − 0.57 to 1.41 (average 0.71), and b^* of 5.81–19.68 (average 10.84), having the most similar chromaticity with HNS. However, VC-03 sample had totally different chromaticity from VC-01 and VC-02.

On the other hand, VPR group stones used to restore the Vat Phou temple showed L^* of 55.99–69.28 (average 62.30), a^* of 0.18–9.62 (average 4.71), and b^* of 4.82–16.13 (average 10.54), a wide range of chromaticity. They had relatively high redness and yellowness compared to other samples, and the deviation among samples also was significant.

Table 2 Major elements (wt%) and trace elements (ppm) contents of samples

	HNS group					PK group					DAQ group					VCQ group			VPR group			
	01	02	03	04	05	01	02	03	04	05	01	02	03	04	05	01	02	03	01	02	03	04
SiO_2	73.25	70.50	69.72	73.34	79.88	71.33	75.02	76.98	78.59	76.75	79.70	77.78	73.28	69.70	78.07	76.24	76.73	73.48	76.03	74.49	75.68	95.59
Al_2O_3	11.90	13.07	13.17	11.23	10.69	13.24	12.84	11.58	12.00	11.42	10.65	11.13	12.76	15.30	11.73	11.61	11.15	12.45	5.26	5.82	5.96	3.04
Fe_2O_3	4.19	4.64	4.04	3.90	2.20	3.82	2.76	2.38	1.89	2.22	1.98	2.47	2.99	3.56	2.03	3.08	2.90	3.63	1.32	1.45	1.90	0.21
MnO	0.27	0.04	0.06	0.07	0.06	0.06	0.06	0.03	0.04	0.03	0.02	0.04	0.04	0.05	0.03	0.08	0.05	0.06	0.16	0.15	0.07	0.01
MgO	1.92	1.82	1.86	1.28	0.47	1.75	0.96	0.60	0.51	0.62	0.48	0.67	1.06	1.34	0.62	1.31	1.04	1.24	0.48	0.72	0.71	0.07
CaO	0.76	0.31	1.03	0.77	0.19	1.01	0.15	0.16	0.16	0.16	0.51	1.03	0.77	1.07	0.83	0.76	0.79	0.71	7.53	7.11	6.89	0.03
Na_2O	3.03	3.46	3.24	3.30	4.34	3.25	4.34	4.25	4.10	4.79	4.03	4.16	3.68	3.17	4.21	4.01	4.17	3.82	0.57	0.75	0.89	0.05
K_2O	1.61	1.12	2.03	1.67	0.73	2.05	0.97	0.63	0.71	0.69	0.96	1.09	1.50	2.64	1.03	0.87	0.83	0.93	0.50	0.55	0.72	0.28
TiO_2	0.58	0.45	0.58	0.48	0.22	0.56	0.47	0.24	0.23	0.21	0.18	0.28	0.29	0.45	0.26	0.47	0.51	0.50	0.32	0.39	0.47	0.17
P_2O_5	0.13	0.17	0.15	0.14	0.06	0.12	0.05	0.06	0.03	0.04	0.06	0.08	0.10	0.11	0.07	0.10	0.12	0.10	0.05	0.07	0.06	0.01
LOI	2.93	3.09	2.61	2.41	1.61	3.38	2.55	2.08	2.07	1.74	1.57	1.88	2.09	2.62	1.45	1.86	1.66	2.26	7.69	7.23	7.11	1.12
Total	100.60	98.66	98.48	98.58	100.40	100.60	100.20	98.97	100.30	98.67	100.10	100.60	98.57	100.00	100.30	100.40	99.94	99.18	99.90	98.74	100.50	100.60
La	42.3	37.5	40.3	34.1	49.5	23.6	28.1	39.1	26.8	24.7	19.3	25.3	44.1	40.9	22.9	26.6	26.3	16.9	22.9	26.6	26.3	16.9
Ce	71	61	76	63	103	48	57	69	50	45	38	46	69	76	43	53	46	35	43	53	46	35
Nd	24	34	43	18	28	16	19	39	18	21	16	15	33	37	20	21	30	15	20	21	30	15
Sm	5.0	3.3	3.7	3.2	4.6	2.5	2.5	4.2	2.8	2.2	2.1	2.6	4.1	4.2	3.0	3.5	3.4	1.8	3.0	3.5	3.4	1.8
Eu	1.1	0.8	0.9	0.6	1.2	0.2	0.4	0.8	0.2	0.1	0.1	0.6	0.8	1.0	0.7	1.1	0.9	0.3	0.7	1.1	0.9	0.3
Tb	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.8	0.5	0.5	0.5	0.5	0.5
Yb	1.9	1.3	1.7	1.8	1.7	1.2	1.0	1.7	1.0	1.0	0.8	1.3	1.9	1.6	1.5	1.9	1.5	0.7	1.5	1.9	1.5	0.7
Lu	0.26	0.13	0.25	0.25	0.26	0.17	0.15	0.29	0.15	0.14	0.12	0.17	0.27	0.23	0.15	0.27	0.15	0.13	0.15	0.27	0.15	0.13
Sr	181	97	183	154	75	171	92	82	87	75	177	167	146	212	162	136	141	137	58	55	61	11
Rb	20	100	110	40	20	80	20	20	20	20	20	40	20	70	20	20	20	20	20	20	40	20
Ba	386	450	672	297	181	311	150	85	122	84	1,660	637	790	3	984	964	1,390	1,360	956	104	254	51
Th	12.0	8.6	10.1	10.0	6.2	10.2	8.9	5.7	5.5	6.2	5.7	6.8	5.8	7.4	4.6	9.7	11.1	9.1	7.2	8.8	6.7	4.6
Ta	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Zr	299	131	229	234	75	249	176	89	97	68	78	109	94	157	97	238	260	266	199	284	248	134
Hf	8.3	3.9	7.0	5.9	1.9	5.8	4.8	2.5	2.2	2.2	2.6	2.9	3.0	4.5	2.7	5.6	7.8	7.1	5.4	8.1	6.8	4.0
Y	73	55	61	46	25	63	44	24	24	26	30	36	17	17	11	52	52	19	31	35	41	12
Sc	8.2	7.4	8.1	6.5	3.8	8.5	8.0	4.0	3.9	4.1	3.5	5.0	4.6	6.7	3.2	7.2	7.7	6.0	3.7	4.3	4.3	1.5
Cr	62	48	56	52	14	65	38	26	19	14	16	30	27	13	20	53	51	47	32	44	46	17

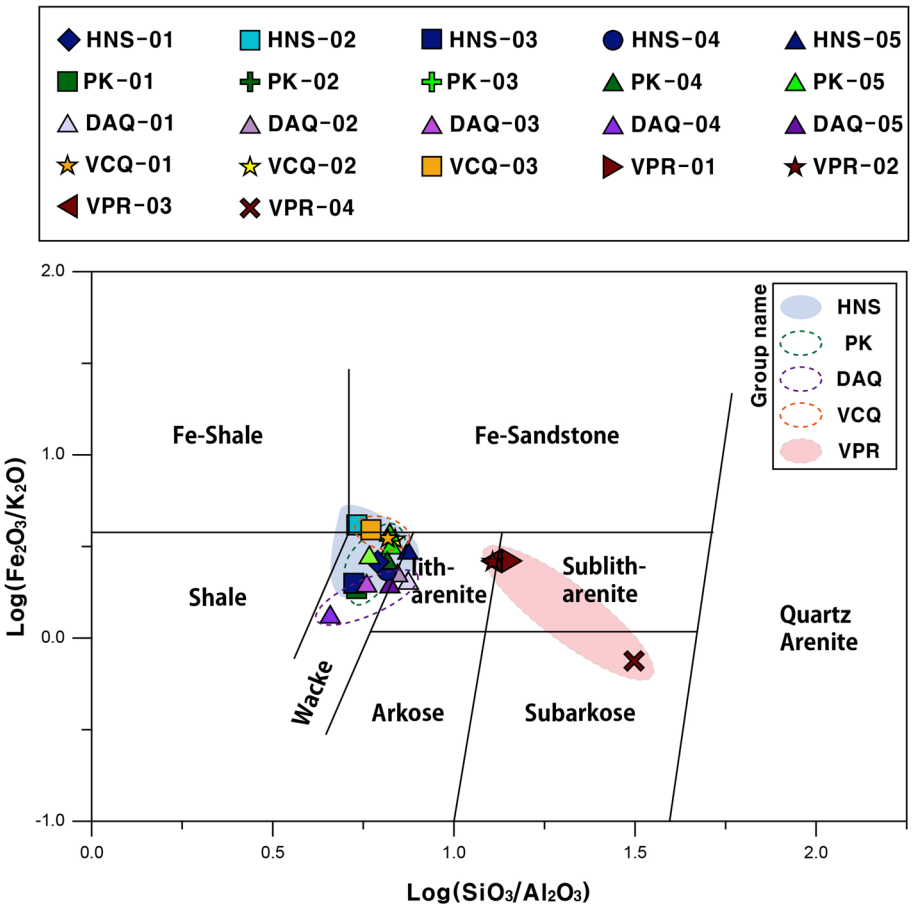

Fig. 6 Classification in geochemical characteristics of sandstones (Herron 1988)

When it comes to chromaticity, it is proper to obtain alternative rocks for repairs and maintenance for Hong Nang Sida temples nearby Mt. Phou Kao. However, Mt. Phou Kao has been designated as World Cultural Heritage along with Hong Nang Sida temples, and it is hard to get enough stones for restoration of the temple. Thus, it is suitable to provide alternative rocks from Vat Chompet quarry or Douangdy quarry, which had the most similar chromaticity.

Magnetic susceptibility

Magnetic susceptibility is constant determining the magnetic characteristics of matters, significantly depends on the content magnetite, one of the ferromagnetic minerals, and is proportional to magnetite content. The classification of the two series through magnetic susceptibility can reflect geological environment, which is not considered in the original rock classification system. The research classified collected samples according to color and particle size, and measured each sample 20 times. Based on the results, the distribution of magnetic susceptibility was identified, and genetic homogeneity was reviewed.

The magnetic susceptibility of gray sandstone constituting the Hong Nang Sida temple showed distribution of 0.043–0.170 ($\times 10^{-3}$ SI unit), and the average was 0.099 ($\times 10^{-3}$ SI unit) (Fig. 5). Grayish-green siltstone had distribution of 0.017–0.228 ($\times 10^{-3}$ SI unit), and the average was 0.119 ($\times 10^{-3}$ SI unit). The magnetic susceptibility of grayish-green sandstone was 0.070–0.198 ($\times 10^{-3}$ SI unit), and the average was revealed to be 0.125 ($\times 10^{-3}$ SI unit). The magnetic susceptibility of dark gray sandstone was 0.071–0.177 ($\times 10^{-3}$ SI unit), and the average was 0.115 ($\times 10^{-3}$ SI unit) distribution.

PK sandstone samples of outcrops collected from Mt. Phou Kao area were divided into grayish-green siltstone and dark gray sandstone. The magnetic susceptibility of grayish-green siltstone was 0.058–0.228 ($\times 10^{-3}$ SI unit), and the average 0.149 ($\times 10^{-3}$ SI unit). The distribution of dark gray sandstone was 0.006–3.080 ($\times 10^{-3}$ SI unit), and the average 0.484 ($\times 10^{-3}$ SI unit), showing the widest range of magnetic susceptibility among the samples.

All the samples of Douangdy quarry were dark gray sandstone, and the magnetic susceptibility was 0.061–0.275 ($\times 10^{-3}$ SI unit), and the average 0.135 ($\times 10^{-3}$ SI unit). The samples of Vat Chompet quarry were classified into gray siltstone and grayish-green siltstone. The magnetic

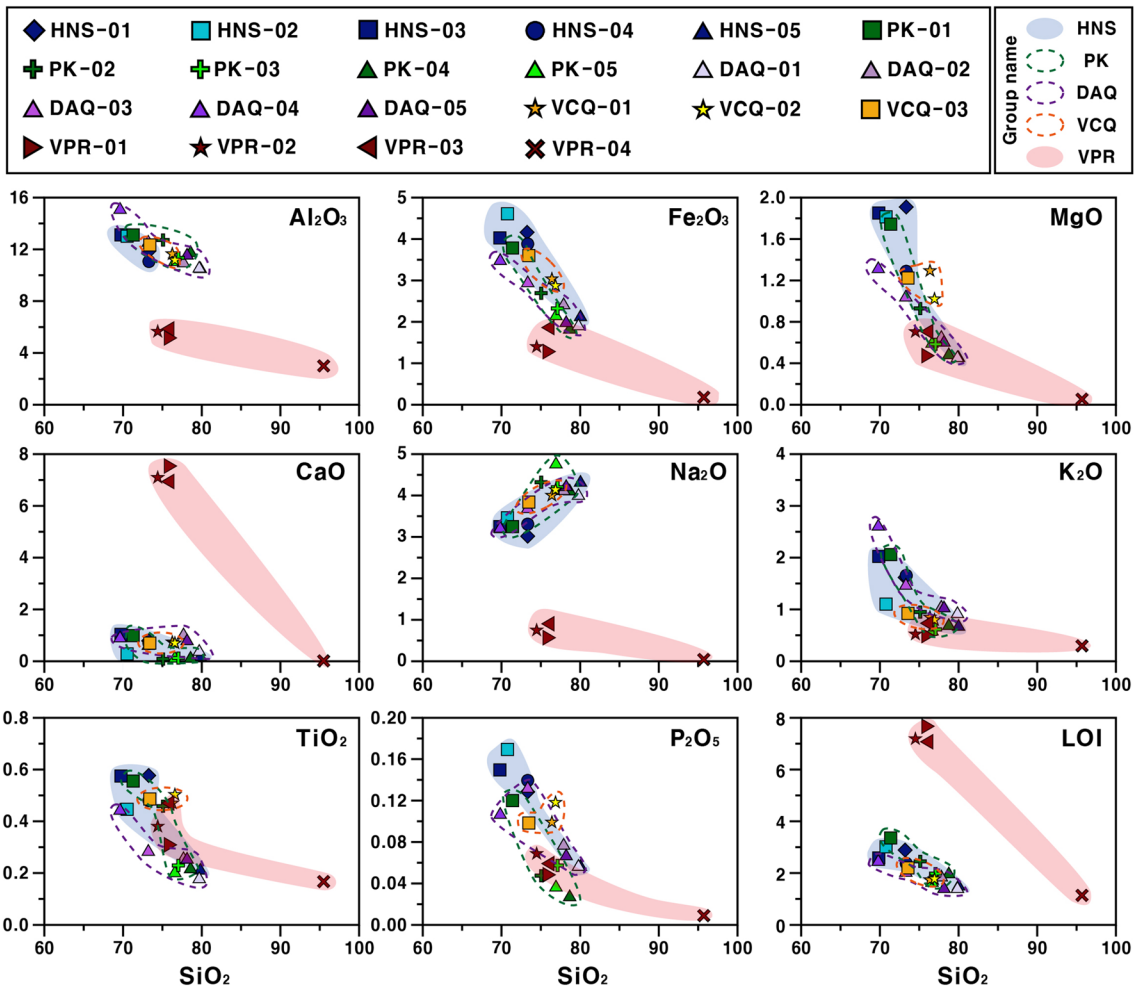

Fig. 7 Diagrams showing relationship between SiO_2 and the other major component elements

susceptibility of gray siltstone was 0.018–0.186 ($\times 10^{-3}$ SI unit), and the average 0.096 ($\times 10^{-3}$ SI unit). Meanwhile, grayish-green sandstone had 0.103–0.920 ($\times 10^{-3}$ SI unit), and the average was 0.202 ($\times 10^{-3}$ SI unit).

VPR sandstone samples used to restore the Vat Phou temple were divided into pinkish gray siltstone, gray siltstone, purple siltstone and pale yellow sandstone. The magnetic susceptibility of pinkish gray siltstone ranged between 0.006 and 0.062 ($\times 10^{-3}$ SI unit), and the average was 0.014 ($\times 10^{-3}$ SI unit). Gray siltstone was 0.006–0.062 ($\times 10^{-3}$ SI unit), and the average 0.026 ($\times 10^{-3}$ SI unit). Purple siltstone was 0.013–0.088 ($\times 10^{-3}$ SI unit) with the average of 0.047 ($\times 10^{-3}$ SI unit). Lastly, pale yellow sandstone was 0.002–0.096 ($\times 10^{-3}$ SI unit), and the average was 0.038 ($\times 10^{-3}$ SI unit).

As a result of the comparison between the analysis samples magnetic susceptibility, it was revealed that the magnetic susceptibility of VP group samples, stones used to restore the Vat Phou temple, did not match with other sample groups. Considering that samples of other groups generally have very similar ranges of magnetic susceptibility with Hong Nang Sida temple, they are genetically very similar rocks.

Geochemical homogeneity

Rocks are created with various chemical composition according to the origin and process of creation. As sedimentary rocks are generally formed through the process of erosion, transport and sedimentation by flow of running water, it reflects the effects of diagenesis more than the characteristics of magmatic differentiation. Therefore, it is difficult to interpret the direct origin, and it is significant to compare homogeneity and similarity among rocks. The results of geochemical analysis are shown in Table 2.

For detailed classification of rocks, chemical analysis data wes drawn according to the sedimentary rock classification

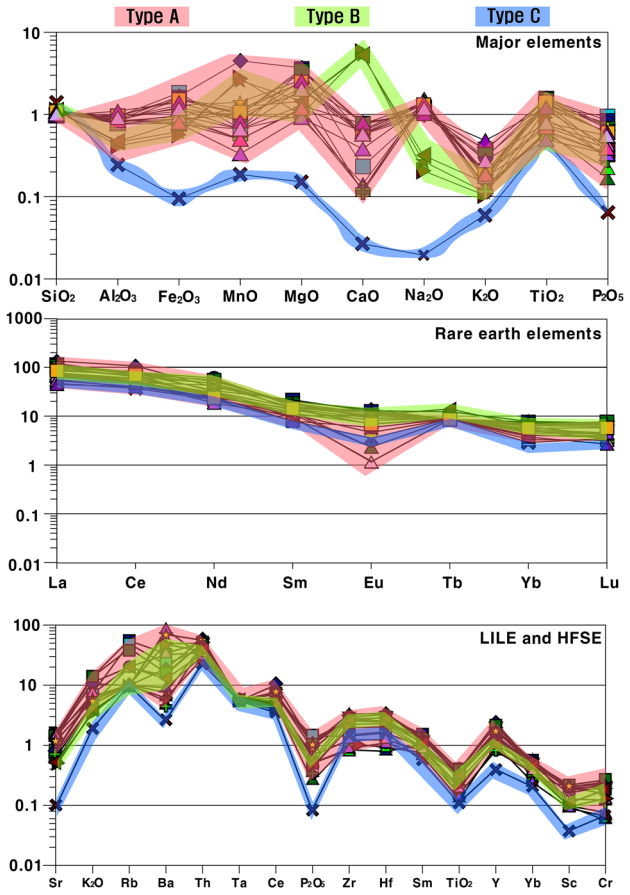

Fig. 8 Classification in geochemical characteristics as three types

method based on the geochemical characteristics suggested by Herron (1988). As a result, most rocks related to Hong Nang Sida in Laos fall under the category of graywacke (Fig. 6). Having relatively fewer contents of matrices and rock fragments, stones used to restore the Vat Phou temple were divided into the border of lithic arenite and sublith arenite. In particular, VPR-04, the restoration stone of the Vat Phou temple, which had the most different lithological characteristics, was drawn into subarkose with the most content of SiO_2.

To identify the trend of changes in major elements for the content of SiO_2, Harker diagram was drawn. As a result, sandstones from the main temple of Hong Nang Sida, Mt. Phou Kao, Douangdy and Vat Chompet quarry were arranged linearly to study the tendency clearly (Fig. 7). While stones used to restore the Vat Phou temple showed difference in rocks and main components from Hong Nang Sida, the slope of change tendency was different.

Major elements, rare earth elements, large ion lithophile elements and high field strength elements were analyzed to determine the homogeneity between rocks. As a result, rocks quarried in Laos, such as Hong Nang Sida temples, Mt. Phou Kao, Douangdy and Vat Chompet quarries, all samples have similar content of major elements, and there is a clear difference between the restored stone materials of the Vat Phou temple (Fig. 8). Differences in geochemical characteristics are also observed in rare earth elements, large ion lithophile elements, and high field strength elements, but it is difficult to distinguish compared to the analysis of major elements, and they were classified into

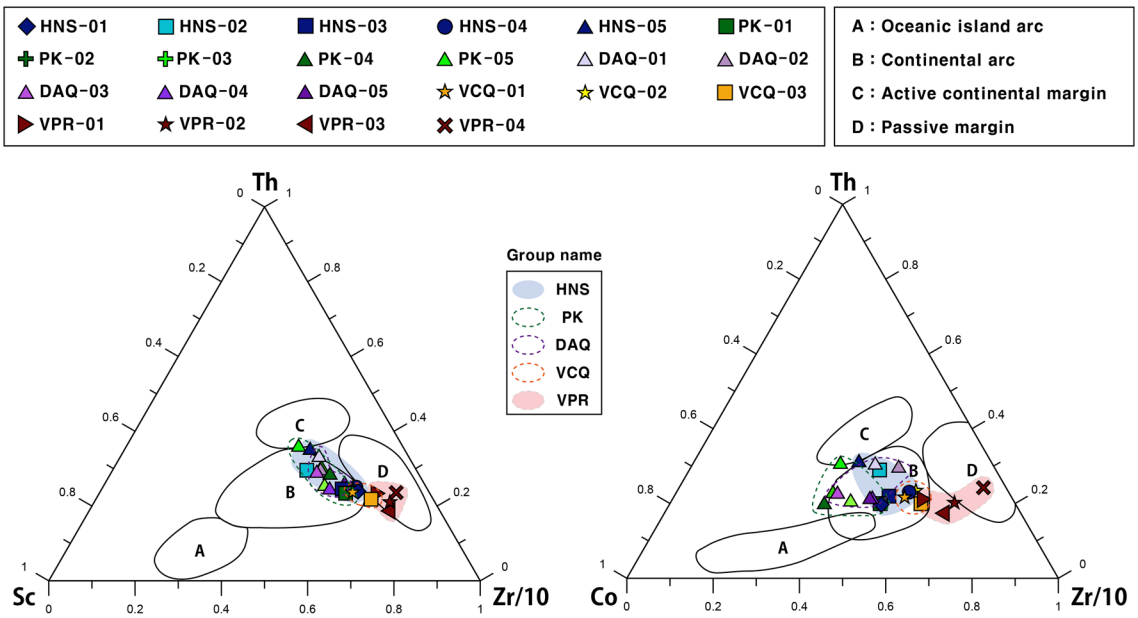

Fig. 9 Ternary diagrams showing the tectonic environment of sedimentary rocks (Ghosh and Sarkar 2010)

Table 3 Summary of analysis results of sandstone in the study area

Location	Sample name	Rock type	Chromaticity	Magnetic Susceptibility	Mineral contents	Geochemical characteristics
Hong Nang Sida temple	HNS-01	Gray sandstone	L^*: 46.26–64.89 a^*: − 1.84 to 3.74 b^*: 5.55–8.70	0.017–0.228	M, Pl, Q	Type A
	HNS-02	Greenish gray siltstone			M, Pl, Q	Type A
	HNS-03	Greenish gray siltstone			Ch, M, Pl, Q, K	Type A
	HNS-04	Greenish gray sandstone			M, Pl, Q	Type A
	HNS-05	Dark gray sandstone			M, Pl, Q	Type A
Mt. Phou Kao	PK-01	Greenish gray siltstone	L^*: 41.24–63.27 a^*: − 0.34 to 4.35 b^*: 5.10–8.34	0.006–3.080	Ch, M, Q, K	Type A
	PK-02	Dark gray sandstone			M, Pl, Q	Type A
	PK-03	Dark gray sandstone			M, Pl, Q	Type A
	PK-04	Dark gray sandstone			Ch, M, Pl, Q	Type A
	PK-05	Dark gray sandstone			M, Pl, Q	Type A
Douangdy quarry	DAQ-01	Dark gray sandstone	L^*: 46.86–57.95 a^*: − 5.18 to 4.00 b^*: 2.80–17.56	0.061–0.275	M, Pl, Q	Type A
	DAQ-02	Dark gray sandstone			M, Pl, Q	Type A
	DAQ-03	Dark gray sandstone			M, Pl, Q	Type A
	DAQ-04	Dark gray sandstone			M, Pl, Q	Type A
	DAQ-05	Dark gray sandstone			M, Pl, Q	Type A
Vat Chompet Quarry	VCQ-01	Gray siltstone	L^*: 52.18–65.85 a^*: − 0.57 to 1.41 b^*: 5.81–19.68	0.018–0.920	M, Pl, Q	Type A
	VCQ-02	Gray siltstone			M, Pl, Q	Type A
	VCQ-03	Greenish gray siltstone			M, Pl, Q	Type A
Restoration stone of the Vat Phou temple	VPR-01	Light gray siltstone	L^*: 55.99–69.28 a^*: 0.18–9.62 b^*: 4.82–16.13	0.001–0.096	Q, Pl, Ca	Type B
	VPR-02	Gray siltstone			Q, Pl, Ca	Type B
	VPR-03	Purple siltstone			Q, Pl, Ca	Type B
	VPR-04	Yellowish white sandstone			Q, Pl	Type C

M mica, *Pl* plagioclase, *Q* quartz, *Ch* chlorite, *K* k-feldspar, *Ca* calcite

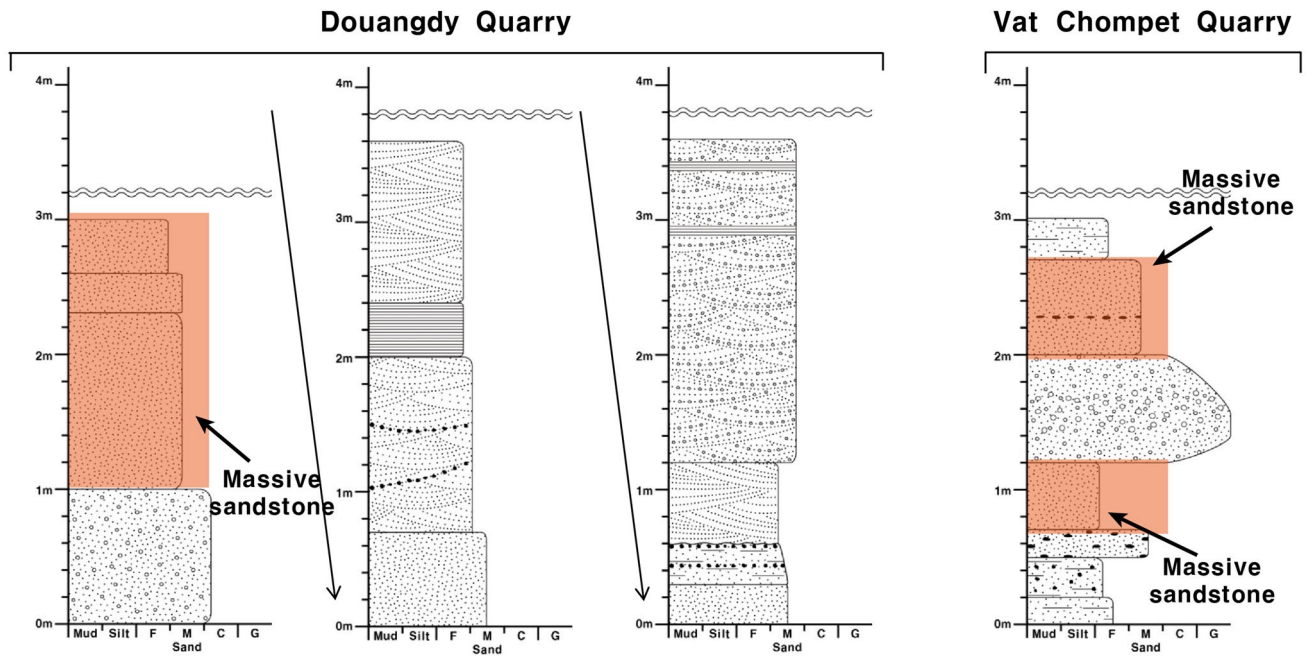

Fig. 10 Columnar section of strata in Douangdy and Vat Chompet quarries, and distribution of massive sandstones without sedimentary structure

three types according to the analysis results of major elements.

Differences in the geochemical properties of the analyzed rock samples are closely related to the origin of the rocks. In general, sandstones deposited in marine environment have low Th/U below 0.1 and wide La/Ce (Vine and Tourtelot 1970; Vassiliou 1980). All the analyzed rock samples had similar Th/U and La/Ce ratios, indicating that they were all deposited in the non marine environment. In addition, sedimentary rocks originated from basic igneous rocks have high content of Co or Sc, while those from acid igneous rocks have low contents, using these characteristics, it is possible to estimate the tectonic environment when deposition occurs (Ghosh and Sarkar 2010).

As a result, the rocks of Hong Nang Sida temples, Mt. Phou Kao, Douangdy and Vat Chompet quarries appeared to be rocks deposited in the continental arc environment, and the restored stone materials of the Vat Phou temple were deposited in the passive margin environment (Fig. 9). Therefore, the sedimentary environment of the two rocks is obviously different. It should be avoided to use of restored stone of the Vat Phou temple as an alternative stone for Hong Nang Sida Temple in the future.

Conclusions

International organizations such as UNESCO, ICOMOS, IIC and UNDP implements projects aiming protection and preservation of cultural properties. The basic principle related to their conservation process emphasizes restoration the original shape, outstanding universal value, authenticity and integrity. It is also emphasized to apply traditional and innovative technology by case and secure reversibility of process methods and materials and compatibility with original materials.

Through the lithological and geochemical characteristics, mineral composition, chromaticity and magnetic suscpetibility distribution, etc. of the research specimens, homogeneity between the Hong Nang Sida temple and surrounding rocks were investigated. As a result, stones from Mt. Phou Kao, Douangdy and Vat Chompet quarry and those in Hong Nang Sida temple had similarity (Table 3). However, as stones used to restore the Vat Phou temple had different petrographic characteristics and little homogeneity with the rocks, they are not suitable for alternative stones. In particular, restoration stones of the Vat Phou temple contain calcite due to cementation, their resistance to chemical weathering may be different.

Therefore, rocks from Mt. Phou Kao, Douangdy and Vat Chompet quarries need to be used as alternatives. Rocks from Mt. Phou Kao show the highest similarity in the lithological characteristics, mineral composition and geochemical characteristics with stones constituting the main temple of Hong Nang Sida. The distribution of magnetic susceptibility is also the same, and several evidences of quarry observed in Mt. Phou Kao directly prove that stones were supplied near this area. It is the most suitable sandstone around Mt. Phou Kao for restoration and maintenance of the temple of Hong Nang Sida.

However, it is difficult to acquire a great volume of stones, as Mt. Phou Kao is designated as a world cultural heritage. Therefore, it is possible to utilize a small amount of boulder stones for restoration, and special discussion is required for massive quarrying. Rocks from Douangdy and Vat Chompet quarries has similar lithological and geochemical characteristics to rocks constituting the main temple of Hong Nang Sida. However, a few sedimentation structures are observed in wide areas, color differences are observed according to heterogeneity of rocks, and fractured zones are found here and there.

Alternative stone for restores must be obtained by selecting some parts of the massive sandstone without sedimentary structure. The outcrops in the quarry have a thickness of dozens meter, and are composed of clastic sedimentary rocks with various grain sizes and sedimentary structures. To produce sandstone of homogeneous quality, it is necessary to record the lithological characteristics according to the location of the sandstone formation.

In this study, a stratigraphic columnar section was created to indicate the location and distribution of sandstone suitable as an alternative stone for restoration (Fig. 10). As for rocks Douangdy and Vat Chompet quarries, massive sandstones produced from 1 to 2 m away from the bottom possessed the highest similarity to the Hong Nang Sida temple. Therefore, these stones need to be supplied selectively through similarity review including chromaticity.

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