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Siliceous Sandstones Used in Local Khmer Temples in Battambang, Ta Keo, and Kampong Cham Provinces, Cambodia

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Abstract: Siliceous sandstones used in Khmer temples such as the Prasat Basset, Wat Ek Phnom, and Phnom Banan temples in Battambang Province, Phnom Chisor and Ta Prohm temples in Ta Keo Province, and Wat Nokor Bachey temple in Kampong Cham Province in Cambodia were investigated in this study to determine the supply source of the siliceous sandstones used in these temples. Chemical composition analyses and magnetic susceptibility measurements were conducted for the sandstone blocks used in these temples. Siliceous sandstone is the primary construction material in the investigated temples, except for the Phnon Chisor (bricks). Two types of siliceous sandstone, pale brown and red, were found. Pale brown siliceous sandstone was used for the construction of all the investigated temples. In contrast, red siliceous sandstone was found only in the Wat Ek Phnom, Prasat Basset, and Phnom Banan temples. It is suggested that the pale brown siliceous sandstone originated from the Phra Wihan Formation within the Khorat Group. Based on the chemical composition analysis, the pale brown siliceous sandstone in the Ta Prohm temple at Tonle Bati and the Wat Nokor Bachey temple may have been sourced from the lower level of the Phra Wihan Formation. In contrast, the pale brown siliceous sandstone used in the Prasat Basset, Wat Ek Phnom, Phnom Banan, and Phnom Chisor temples was likely sourced from the upper level. The origin of the red siliceous sandstone is proposed to be from the Sao Khua Formation, which is situated above the Phra Wihan Formation.

Keywords: Khmer temple; siliceous sandstone; gray sandstone; magnetic susceptibility; chemical composition; Phra Wihan Formation; Sao Khua Formation; Cambodia

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1. Introduction

The Khmer monuments are a group of temples constructed by the Khmer people between the 9th and 15th centuries and are located mainly in Cambodia, but also in Thailand and Laos. Representative Khmer monuments include the Angkor monument, Koh Ker monument, Preah Khan monument at Kampong Svay (Great Preah Khan monument), Preah Vihear temple and Banteay Chhmar temple in Cambodia; the Phimai temple and Phanom Rung temple in Thailand; and the Wat Phu temple in Laos. Of these, the Angkor monument, Wat Phu temple, Preah Vihear temple, Koh Ker monument were registered on the World Heritage List of UNESCO in 1992, 2001, 2008, and 2023, respectively. In the Angkor monument, sandstone, laterite, and bricks were used as the primary construction materials. Three types of sandstone, such as gray to yellowish-brown sandstone, greenish graywacke, and red siliceous sandstone, were used [1]. These correspond to gray sandstone, green sandstone, and red sandstone, respectively, on the basis of the classification by Delvert [2]. Among these, the most used sandstone was the gray to yellowish-brown sandstone, whereas the other types of sandstone were rarely used [1,3]. The gray to yellowish-brown sandstone was a primary construction material in the Angkor monument, Koh Ker monument, Preah Khan monument at Kampong Svay, Banteay Chhmar temple, and Wat Phu temple. Greenish graywacke was used for the sanctuaries in the Ta Keo

temple, as well as statues and linga/yoni [4,5]. In contrast, across the Khmer temples throughout Cambodia, siliceous sandstone is frequently observed. Typical examples are the Banteay Srei and Preah Vihear temples [5,6]. Red siliceous sandstone was a primary construction material in the Banteay Srei temple, and pale brown siliceous sandstone was a primary construction material in the Preah Vihear temple. In addition, in local Khmer temples in Battambang, Ta Keo, and Kampong Cham provinces in Cambodia, such as the Prasat Basset, Wat Ek Phnom, Phnom Banan, Phnom Chisor, Ta Prohm at Tonle Bati, and Wat Nokor Bachey temples, pale brown siliceous sandstone and also a small amount of red siliceous sandstone were used. Siliceous sandstones are found in the Cretaceous Phra Wihan, Sao Khua, and Phu Phan formations of the Khorat Group from bottom to top [7–11]. Thus, the purpose of this investigation is to determine whether the siliceous sandstones used in the aforementioned local small- to medium-sized Khmer temples were supplied from the Phra Wihan, Sao Khua, or Phu Phan formations.

2. Siliceous Sandstones of the Khorat Group

The Khorat Group consists of the following nine formations ranging from Triassic to Cretaceous: the Huai Hin Lat, Nam Phon, Phu Kradung, Phra Wihan, Sao Khua, Phu Phan, Khok Kruat, Maha Sarakham, and Phu Thok formations. Siliceous sandstone is generated from the Cretaceous Phra Wihan, Sao Khua, and Phu Phan formations, arranged in ascending order from lower to higher levels (Figure 1) [7–11].

Figure 1. Map showing the distribution of the Khorat Group (the Phu Kradung, Phra Wihan, Sao Khua, and Phu Phan formations) and locations of major Khmer monuments and temples, including the temples investigated in this study. Blue stars show monuments and temples built primarily of gray (gray to yellowish brown) sandstone, and green stars show monuments and temples built primarily of siliceous sandstone [7,8].

The Phra Wihan Formation consists mainly of pale yellowish brown to gray, fine- to coarse-grained quarzitic sandstone, 50–350 m in thickness. It is in conformable contact with the underlying Phu Kradung Formation and the overlying Sao Khua Formation [9–11]. The sandstone of the Phra Wihan Formation consists mainly of quartz and fragments of siliceous rock, with minor amounts of muscovite and plagioclase. The sandstone exhibits a magnetic susceptibility lower than 0.068×10^{-3} SI units. [12].

The Sao Khua Formation consists of reddish-brown, fine- to medium-grained sandstone, siltstone, and mudstone [9–11]. The thickness ranges from 100 to 760 m [10]. The primary constituents of the sandstone include quartz and siliceous rock fragments, along with minor proportions of feldspar, muscovite, and calcite. The magnetic susceptibility of the sandstone varies within the range of 0.016 to 0.086×10^{-3} SI units [12].

The Phu Phan Formation generally consists of grayish-white, medium- to coarse-grained sandstone [9–11]. This formation is 75–150 m thick. The sandstone consists mainly of quartz and siliceous rock fragments. The particles are well-sorted and well-rounded. The sandstone exhibits a magnetic susceptibility below 0.030×10^{-3} SI units [12].

3. Investigated Temples

3.1. Prasat Basset Temple

The Prasat Basset temple is located approximately 11 km northeast of Battambang city (Figures 1 and 2a). This is a temple of the Baphuon style, built in the 11th century by Suryavarman I [13,14]. It consists of a central sanctuary, a mandapa, and a northern tower. The northern tower is unfinished and is estimated to have been constructed in a later period. The central sanctuary, mandapa, and northern tower are made entirely of siliceous sandstone. The central sanctuary and mandapa are primarily made of pale brown siliceous sandstone, but small amounts of red siliceous sandstone blocks are observed in some parts. The northern tower was built using pale brown siliceous sandstone, with no presence of red siliceous sandstone.

The pale brown siliceous sandstone blocks used in this temple are regularly stacked and have square cross-sections. The orientations of the bedding planes of the stone blocks are random. These observations are consistent with the construction of this temple in the 11th century [15].

3.2. Wat Ek Phnom Temple

The Wat Ek Phnom temple is located approximately 9 km north of Battambang city (Figures 1 and 2b). It is a temple of the Baphuon style, constructed in the 11th century by Suryavarman I [13,14]. The structure comprises a platform with five lower layers of laterite blocks and two upper layers of sandstone blocks, a gallery built of laterite and sandstone blocks, a sandstone mandapa, a sandstone central sanctuary, and a southern library built of sandstone and laterite blocks. The primary construction material was pale brown siliceous sandstone. However, red siliceous sandstone was used in the central sanctuary, mandapa, and lattices of windows of the gallery, except for lattices of windows of the eastern gopura, where gray sandstone was used instead (Figure 3a).

The pale brown siliceous sandstone and laterite blocks have square cross-sections and randomly oriented bedding planes. In addition, the stone blocks were stacked such that they were of uniform height with successive bed joints. These observations are consistent with construction in the 11th century [15].

3.3. Phnom Banan Temple

This temple may have been built in the Bayon style period (from the end of the 12th to early 13th centuries) (Figures 1 and 2c) [13]. However, the lintel of the central sanctuary has a style from the 10th to the 11th centuries. The central sandstone sanctuary is surrounded by laterite walls with four laterite gopuras in the east, west, south, and north. The sandstone of the central sanctuary is pale brown siliceous sandstone with some red siliceous sandstone blocks.

The pale brown siliceous sandstone, red siliceous sandstone, and laterite blocks have rectangular cross-sections and are thin. In addition, the stone blocks are irregularly stacked. These observations suggest that this temple was built in the Bayon style period [15].

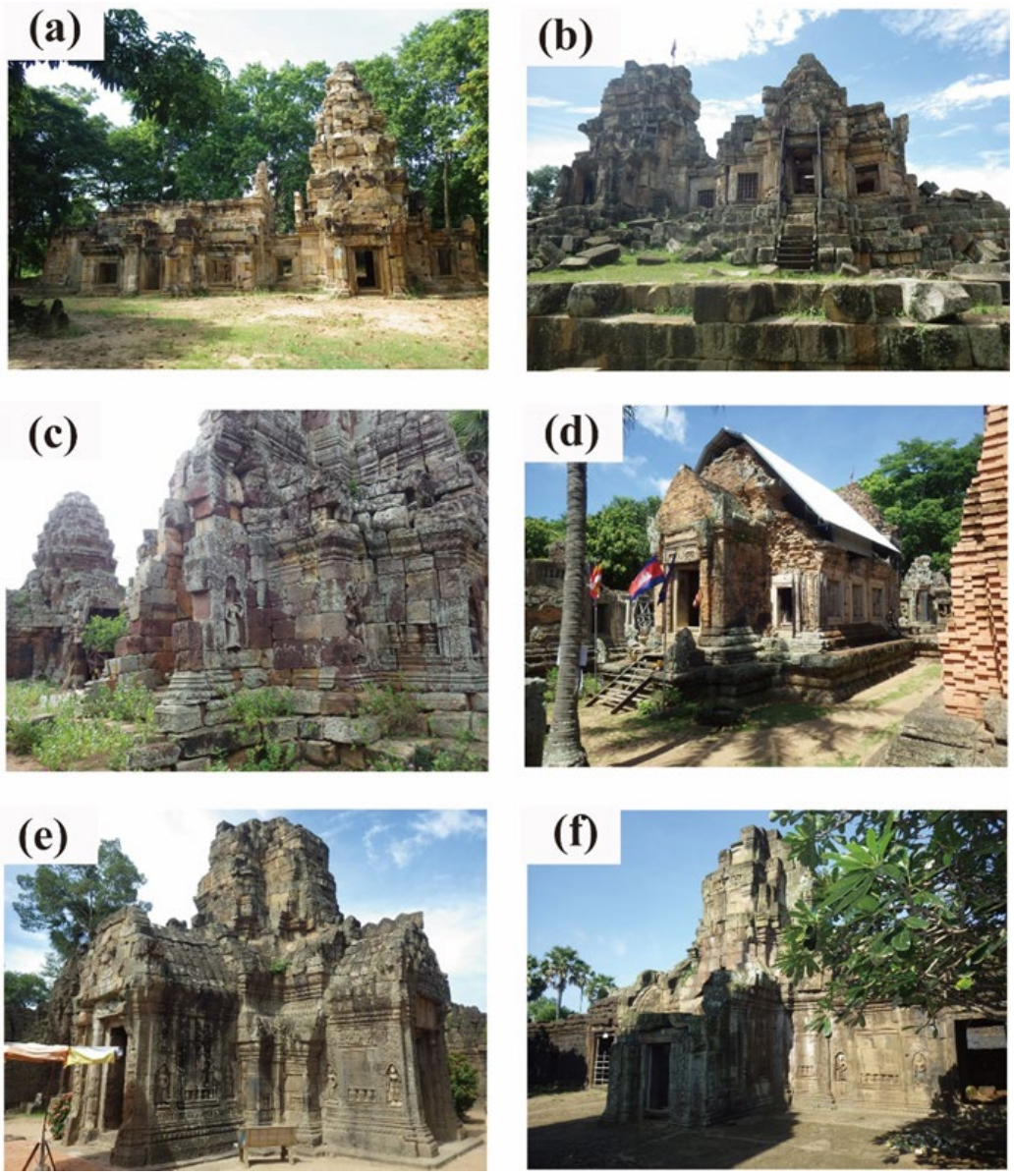

Figure 2. Photographs of the investigated temples. (**a**) The sanctuary (**right**) and mandapa (**left**) in the Prasat Basset temple built of pale brown siliceous sandstone; (**b**) the sanctuary (**left**) and mandapa (**right**) on the platform in the Wat Ek Phnom temple; (**c**) the central sanctuary built of pale brown siliceous sandstone blocks and red siliceous sandstone blocks in the Phnom Banan temple; (**d**) the mandapa built of bricks in the Phnom Chisor temple; (**e**) the central sanctuary built of pale brown siliceous sandstone blocks in the Ta Prohm temple at Tonle Bati; and (**f**) the central sanctuary built of pale brown siliceous sandstone blocks in the Wat Nokor Bachey temple.

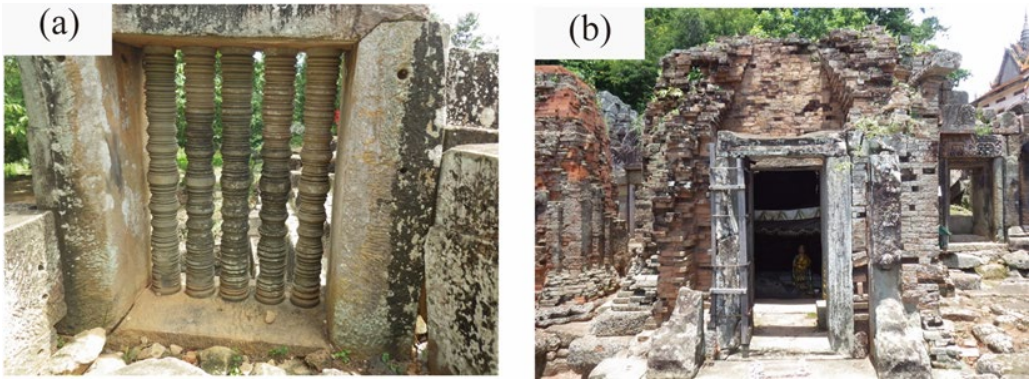

Figure 3. Gray sandstone used in (**a**) a lattice window in the Wat Ek Phnom temple and (**b**) a door frame of the Phnom Chisor temple.

3.4. Phnom Chisor Temple

The Phnom Chisor temple is located about 42 km south of Phnom Penh (Figures 1 and 2d). This temple was constructed by Suryavarman I in the 11th century [13,14]. The entire complex was constructed on top of a hill of graywacke, approximately 133 m in height. It consists of a central sanctuary, a mandapa, five shrines, and two libraries inside a gallery (Figure 4). The platforms were built of laterite blocks, whereas the upper structures were built of bricks. Sandstone blocks were used for the door and window frames, as well as lintels. The sandstone is pale brown siliceous sandstone; gray sandstone was used only in the shrine located between the central sanctuary and the southwestern shrine (Figures 3b and 4). The platform and wall of the gallery were built of laterite blocks, but the lowermost and uppermost parts of the wall, as well as the window and door frames and entrance lintels, were built of pale brown siliceous sandstone blocks.

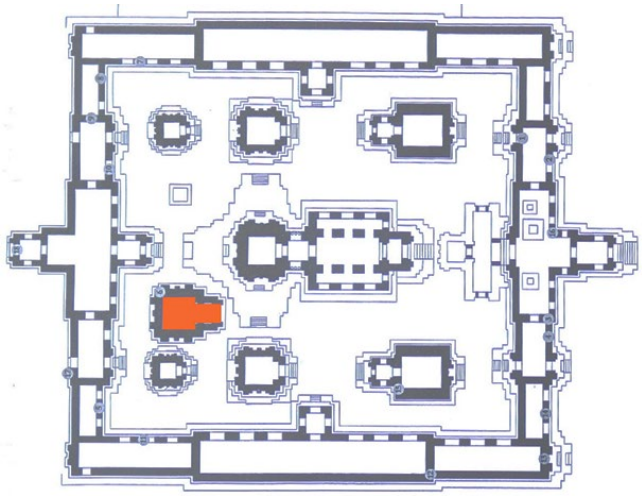

Figure 4. Plan of the Phnom Chisor temple. The shrine with gray sandstone blocks is colored red [14].

In the Phnom Chisor temple, many bricks were used in the construction of the central sanctuary, shrines, and libraries. Based on speculation regarding the Angkor monument, where bricks were used in and before the 10th century, it has been estimated that the temple was built in the 10th century or earlier [16]. Pale brown siliceous sandstone and laterite blocks were also used, but their cross-sections are square and the orientations of their bedding planes are random. Additionally, the stone blocks were systematically stacked. Although it is believed that this temple was built in the first half of the 11th century, these findings indicate the possibility that this temple was constructed in the 10th century or earlier [15].

3.5. Ta Prohm Temple at Tonle Bati

The Ta Prohm temple at Tonle Bati is located 30 km to the south of Phnom Penh (Figures 1 and 2e). This is a temple of the Bayon style built by Jayavarman VII in the end of the 12th to early 13th centuries [13]. This temple is surrounded by a laterite outer wall with gopuras to the east and west and an inner gallery with gopuras to the east, west, south, and north. Sandstone blocks were used for the door, window frames, and stairs. Inside the inner gallery, there is a central sanctuary built of pale brown siliceous sandstone blocks and northern and southern libraries built of laterite blocks.

The pale brown siliceous sandstone and laterite blocks exhibit rectangular cross-sections and are thin. The stone blocks were randomly stacked. These characteristics suggest that this temple was built in the Bayon style period [15].

3.6. Wat Nokor Bachey Temple

The Wat Nokor Bachey temple is located 2.2 km from Kampong Cham city (Figures 1 and 2f). This temple was constructed by Jayavarman VII at the end of the 12th and early 13th centuries [13]. At its center, there is a sandstone central sanctuary and laterite northern and southern libraries. Surrounding these structures, in sequential order from the outermost, there are an outer wall with gopuras to the east, west, north, and south; an inner wall with gopuras to the east and west; an outer gallery with gopuras to the east, west, north, and south; and an inner gallery with gopuras to the east, west, north, and south. All of these structures were built of laterite blocks, but the gopuras of the inner wall and inner gallery were constructed from sandstone blocks. The sandstone used is pale brown siliceous sandstone.

Pale brown siliceous sandstone and laterite blocks were used as construction materials in the Wat Nokor Bachey temple. These stone blocks have rectangular cross-sections and are irregular in shape. They were randomly stacked. These observations indicate that this temple was built in the Bayon style period [15].

3.7. Outcrops of the Phra Wihan Formation along the Road Leading to the Preah Vihear Temple

As reference data, the chemical composition and magnetic susceptibility of four outcrops of the Phra Wihan Formation along the road leading to the Preah Vihear temple were measured. The measurement locations are shown in Figure 5.

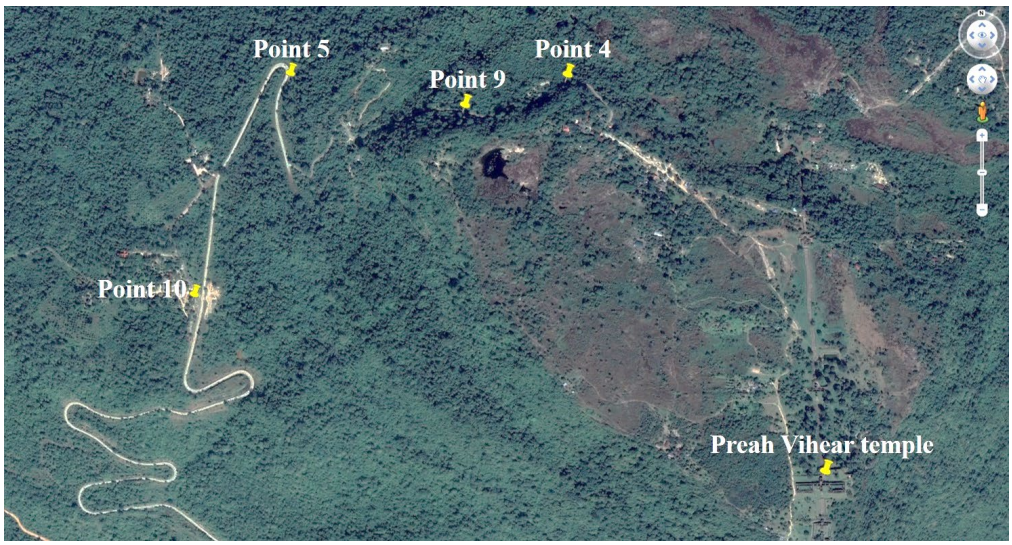

Figure 5. Locations (points 4, 5, 9, and 10) of chemical composition analyses and magnetic susceptibility measurements on a Google Earth image conducted for the Phra Wihan Formation along the road leading to the Preah Vihear temple.

4. Materials and Methods

In this study, chemical composition analysis was conducted using a portable X-ray fluorescence analyzer equipped with a Rh target and a silicon-drift detector (pXRF: Delta Premium, Innov-X Systems, Waltham, MA, USA) (e.g., [17]). The measurements were conducted at a tube voltage of 15 kV for light elements and 40 kV for heavy elements. The pXRF was set to measure for 1 min in "soil mode". The calibration of the measurement results was performed using the fundamental parameter method. Magnetic susceptibility measurement was performed using a portable magnetic susceptibility meter (SM30, ZH Instruments, Brno, Czech Republic) (e.g., [18–20]). Sandstone types were visually identified at each temple, and measurements were conducted on 10 stone block surfaces for each rock type. In the pXRF analysis and magnetic susceptibility measurement, a flat surface that is unaltered and free from algae or lichen coverings was selected. Among the elements measured by pXRF, particular attention was given to Rb, Ti, Zr, Y, and Sr in pale brown siliceous sandstone, red siliceous sandstone, and gray sandstone. These elements are believed to be primarily concentrated in potassium feldspar, rutile, zircon, apatite, and plagioclase, respectively. The analysis precision for each element is 1.4, 35, 5, 1.5, and 6 ppm, respectively. Significant differences in the concentrations of these elements were observed in the Phra Wihan Formation (sandstone blocks used in the Preah Vihear temple [6] and outcrops along the road leading to the Preah Vihear temple) and Sao Khua Formation (sandstone blocks used for the construction of the Banteay Srei temple and other temples in the Angkor monument) [5] of the Khorat Group (Figure 6). The differences in these elemental contents can be used to estimate the sources of the stone blocks used in the construction of the investigated temples. However, the Phra Wihan and Sao Khua formations showed a similar range of magnetic susceptibility (less than approximately 0.7×10^{-3} SI units) and were not useful for distinguishing between the two (Figure 7).

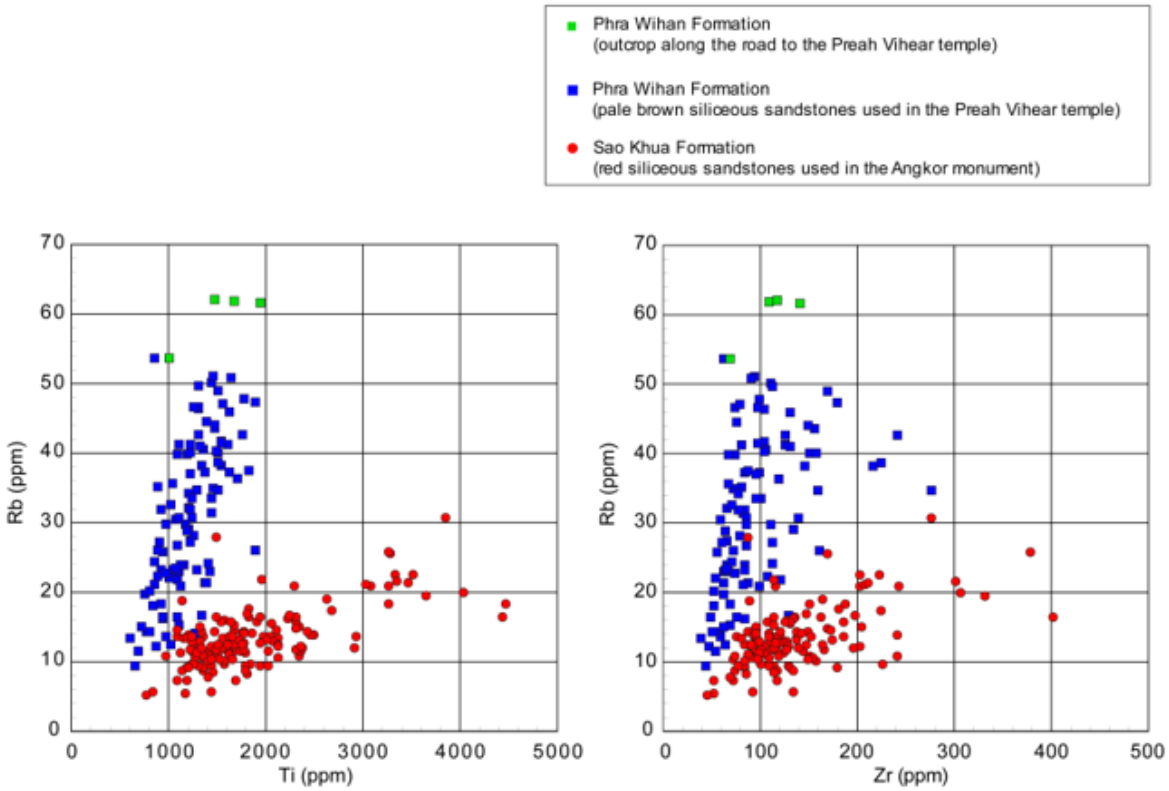

Figure 6. Relationships between minor element (Rb, Ti, and Zr) contents in sandstones from the Phra Wihan [6] and Sao Khua [5] formations, determined using pXRF.

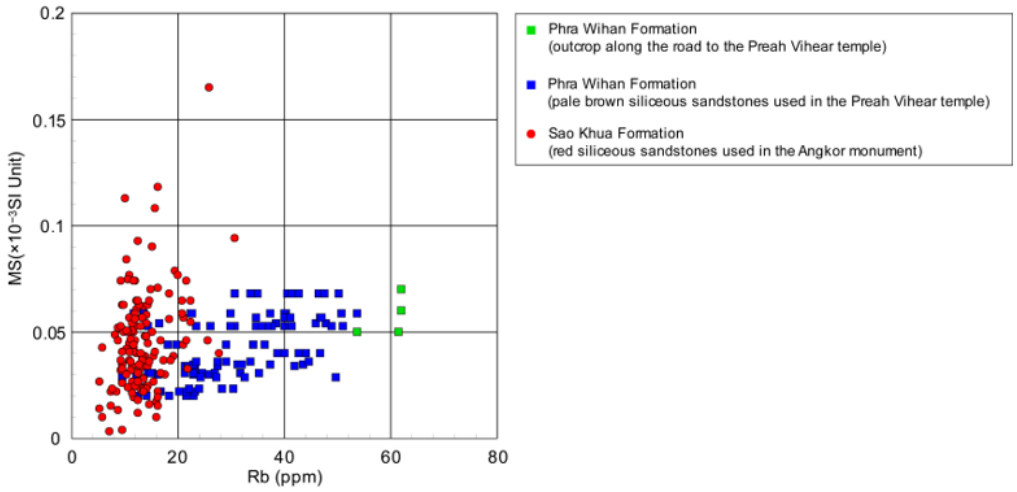

Figure 7. Relationship between magnetic susceptibility and Rb content for the Phra Wihan [6] and Sao Khua [5] formations.

5. Results

Siliceous sandstone was observed in all the temples investigated in this research. The results of the chemical composition analyses and magnetic susceptibility measurements in each temple are summarized in Supplementary Materials (Table S1). The results obtained in this investigation are shown in Figures 8–10.

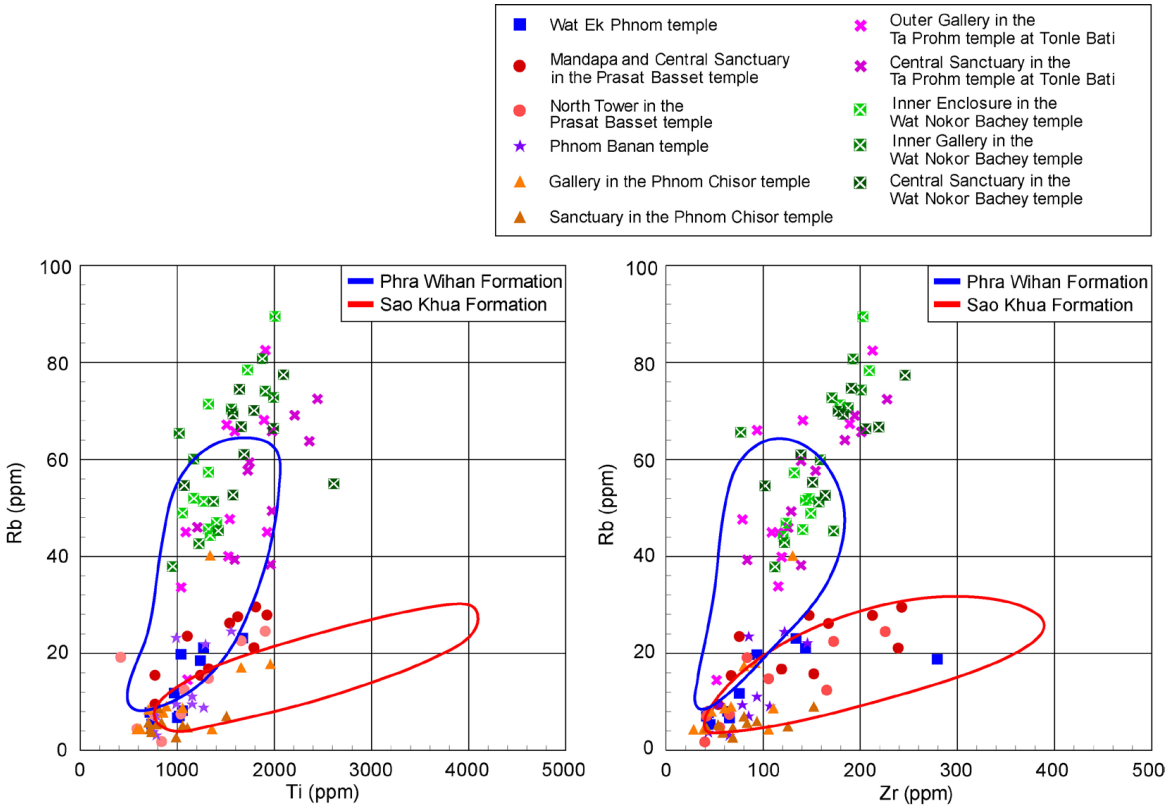

Figure 8. Relationships between minor element (Rb, Ti, and Zr) contents in pale brown siliceous sandstones used in the investigated temples.

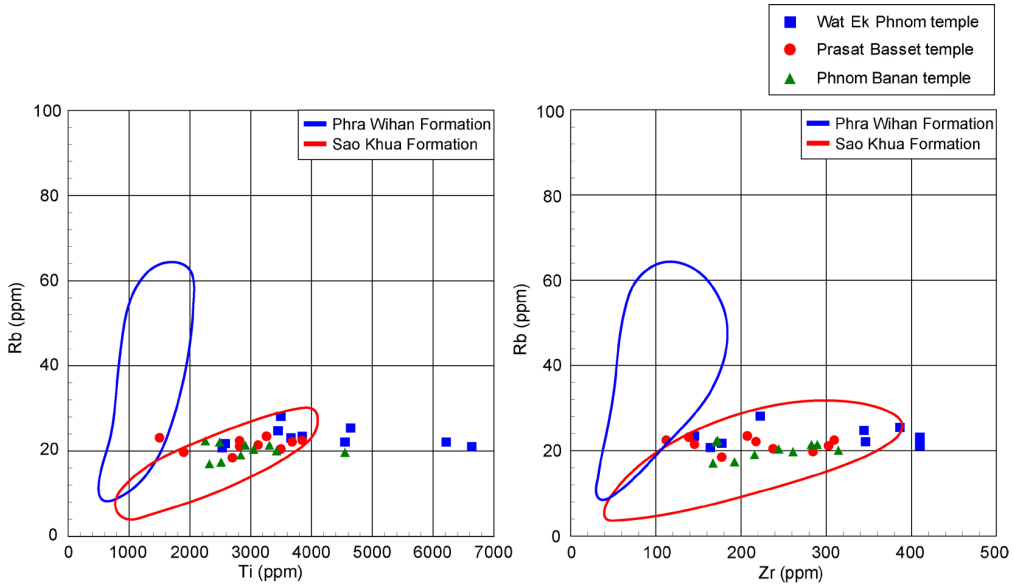

Figure 9. Relationships between minor element (Rb, Ti, and Zr) contents in red siliceous sandstones used in the investigated temples.

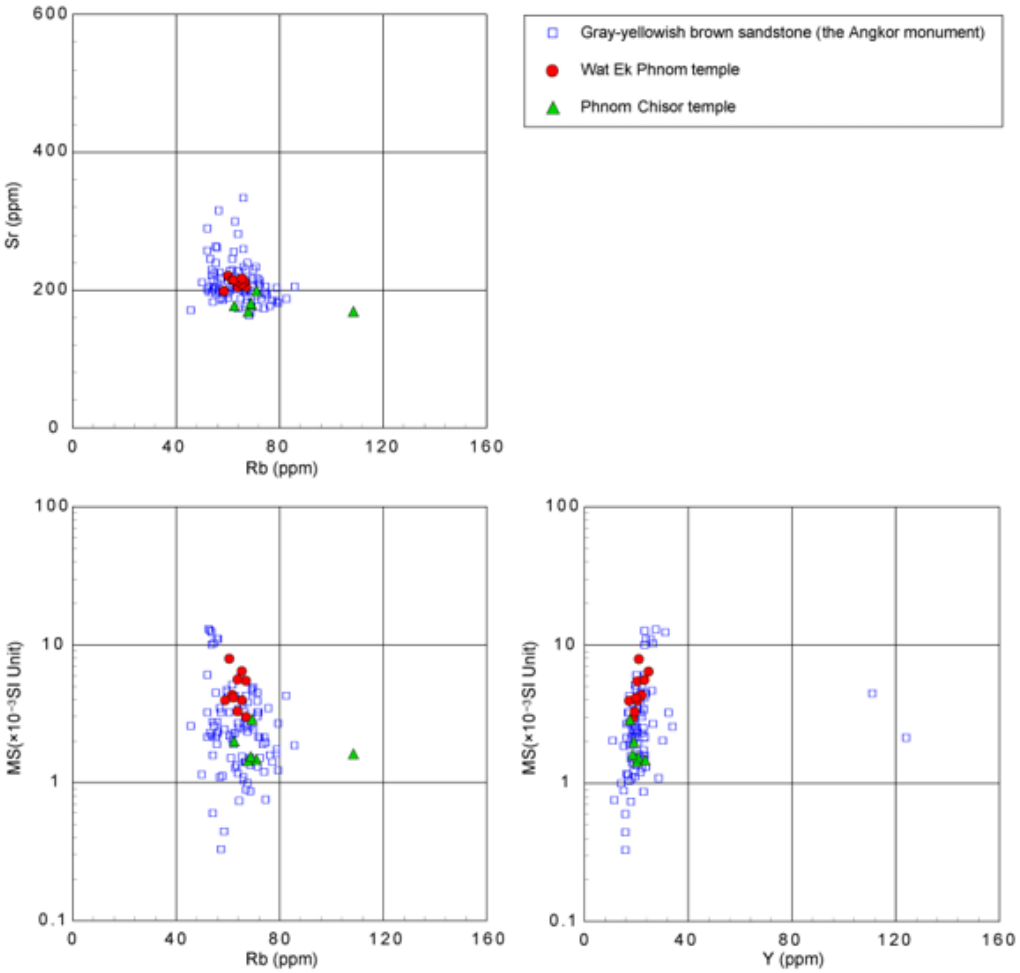

Figure 10. Relationships between magnetic susceptibility and minor element (Sr, Rb, and Y) contents in gray sandstones used in the investigated temples and the Angkor monument.

The Rb, Ti, and Zr contents in the pale brown siliceous sandstone investigated in this study and those of the Phra Wihan Formation (the Preah Vihear temple) are shown in Figure 8. Similarity was observed, especially in the Rb vs. Ti diagram. The Rb concentration in the Ta Prohm temple at Tonle Bati and the Wat Nokor Bachey temple tended to be high compared with the other investigated temples and the Preah Vihear temple. In the Phra Wihan Formation along the road leading to the Preah Vihear temple, Rb, Ti, and Zr contents tended to be high (Figure 6), suggesting that impurities including these elements in the Phra Wihan Formation increase toward the underlying Phu Kradung Formation.

Red siliceous sandstone was found at three locations: the Wat Ek Phnom, Prasat Basset, and Phnom Banan temples. Red siliceous sandstone was used as a major construction material in the Banteay Srei temple in the Angkor monument. The Rb, Ti, and Zr contents in the red siliceous sandstone analyzed in this study and those of the Sao Khua Formation (the Banteay Srei and other previously analyzed Angkor temples) were closely aligned (Figure 9). The relatively low Rb content in the pale brown siliceous sandstone used in these temples suggests that they were quarried from the upper level of the Phra Wihan Formation (Figure 8).

Gray sandstone (gray to yellowish brown sandstone [1]) was used for parts of two temples, the Wat Ek Phnom and Phnom Chisor temples. The gray sandstone used in these two temples exhibited a similar distribution of magnetic susceptibility and similar concentrations of Sr, Rb, and Y to those of the gray sandstone used in the Angkor temples (Figure 10) [5].

6. Discussion

6.1. Pale Brown Siliceous Sandstone

The Rb vs. Ti diagram is particularly effective for differentiating between the Phra Wihan Formation and the Sao Khua Formation. (Figure 6). The pale brown siliceous sandstone used in the investigated temples is inferred to belong to the Phra Wihan Formation based on the results of the chemical composition analyses and magnetic susceptibility measurements (Figure 8 and Supplementary Materials (Table S1)). The concentration of Rb in the pale brown siliceous sandstone blocks used in the Ta Prohm temple at Tonle Bati and Wat Nokor Bachey temple appears to be higher compared with those in other temples investigated in this study and in the Preah Vihear temple. Furthermore, the Ta Prohm temple at Tonle Bati and the Wat Nokor Bachey temple were constructed later (the end of the 12th to early 13th centuries) compared with the other temples (11th century). This result implies the possibility that the locations of the pale brown siliceous sandstone quarries changed over time.

The chemical analysis of the Phra Wihan Formation along the road leading to the Preah Vihear temple revealed higher Rb, Ti, and Zr contents. This indicates that the pale brown siliceous sandstone in the Ta Prohm temple at Tonle Bati and the Wat Nokor Bachey temple, which is rich in these elements, was sourced from the lower level of the Phra Wihan Formation. In contrast, the pale brown siliceous sandstone poor in Rb used in the Prasat Basset, Wat Ek Phnom, Phnom Banan, and Phnom Chisor temples was presumably sourced from the upper level of the Phra Wihan Formation.

6.2. Red Siliceous Sandstone

The red siliceous sandstone used in the construction of the Wat Ek Phnom, Phnom Banan, and Prasat Basset temples is inferred to belong to the Sao Khua Formation, as indicated by the results of chemical composition analyses (Figure 9 and Supplementary Materials Table S1). Because there were no significant differences in chemical composition between the temples, and considering their proximity in terms of locations, there is a possibility that the red siliceous sandstone blocks used in the three temples were sourced from the same quarry. This quarry may have been located near the boundary with the underlying Phra Wihan Formation, and it may be that red siliceous sandstone blocks were mixed in during the quarrying of pale brown siliceous sandstone blocks.

6.3. Gray Sandstone

The gray sandstone found in the Wat Ek Phnom and Phnom Chisor temples may have been transported from the Angkor region, on the basis of the results of magnetic susceptibility measurements and chemical composition analyses (Figure 10). It is assumed that this gray sandstone originated from the Phu Kradung Formation. In the Muang Tam temple on the Khorat Plateau, Thailand, some lattices are made of gray sandstone [9]. Because there is no locality where gray sandstone occurs on the Khorat Plateau (Figure 1), it is likely that the gray sandstone was transported from the Angkor area. It is suggested that the Wat Ek Phnom temple, for which gray sandstone was used exclusively, is one such site. In the Phnom Chisor temple, gray sandstone was used only in the shrine located between the central sanctuary and the southwestern shrine. The shrines and libraries that used pale brown siliceous sandstone are symmetrically arranged along the east–west axis in pairs, whereas the shrine for which gray sandstone was used lacks such symmetry (Figure 4). In addition, small amounts of gray sandstone blocks are found in the East Sneng temple in Battambang Province and the Prasat Khmau temple in Ta Keo Province. These temples were built mainly of bricks. The lack of gray sandstone in these areas and the limited use of gray sandstone blocks in these temples suggest that the gray sandstone blocks may have been transported from the Angkor area.

7. Conclusions

The following conclusions were obtained from this study:

(1) The pale brown siliceous sandstone frequently employed in the temples examined in this study is believed to have originated from the Cretaceous Phra Wihan Formation within the Khorat Group.

(2) In the Preah Wihan Formation, the Rb, Zr, and Ti contents in the sandstone tended to be high toward the underlying Phu Kradung Formation. The Rb, Zr, and Ti contents in the pale brown siliceous sandstone used in the Ta Prohm temple at Tonle Bati and the Wat Nokor Bachey temple also tended to be high. Thus, it is suggested that the pale brown siliceous sandstone blocks in these temples were sourced from the lower level of the Phra Wihan Formation. In contrast, for the Prasat Basset, Wat Ek Phnom, Phnom Banan, and Phnom Chisor temples, the pale brown siliceous sandstone blocks poor in Rb content were presumably sourced from the upper level of the Phra Wihan Formation.

(3) Small amounts of red siliceous sandstone blocks are observed in the Prasat Basset, Wat Ek Phnom, and Phnom Banan temples. It is believed that these sandstone blocks were quarried from the Sao Khua Formation within the Khorat Group. The quarry for the red siliceous sandstone blocks might have been situated close to the boundary with the underlying Phra Wihan Formation, and it is proposed that red siliceous sandstone blocks were potentially blended in during the quarrying of pale brown siliceous sandstone blocks.

(4) The gray sandstone used in small amounts in the Wat Ek Phnom and Phnom Chisor temples may have been transported from the Angkor area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/heritage7020029/s1, Table S1: Magnetic susceptibilities and chemical compositions determined by pXRF for pale brown siliceous sandstone, red siliceous sandstone, and gray sandstone.

Author Contributions: Conceptualization, E.U.; methodology, E.U.; formal analysis, E.U. and Y.K.; investigation, E.U. and Y.K.; data curation, E.U. and Y.K.; writing—original draft preparation, E.U.; writing—reviewing and editing, E.U. and Y.K.; visualization, E.U. and Y.K.; supervision, E.U.; project administration, E.U.; funding acquisition, E.U. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All data are included/referenced in this article.

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Conflicts of Interest: The authors declare no conflicts of interest.

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