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The effect of rock strength on weathering rates of sandstone used for Angkor temples in Cambodia

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ABSTRACT

This study determined the weathering rates from the depths of hollows formed by the deterioration of sandstone blocks used to build Angkor temples in the 7th–12th centuries. Due to capillary processes, these hollows generally develop at the bases of building components such as doorframes, false doorframes, window frames, and pillars. In this study, 55 locations in 29 temples were selected to measure maximum hollow depth. Based on the ages of the temples, the weathering rate was calculated to be in the range 7–92 mm ka^{-1}. The weathering rate was found to be independent of building component type and aspect. The calculated weathering rate corresponds to the physical weathering rate of sandstone caused by the wetting-drying cycles that result from the tropical environment along with the dry season. An equation that can estimate the maximum depth of a hollow in a sandstone block was proposed based on temple age and the coefficient obtained from two types of rock hardness values. The equation coefficient is an effective index that can help predict the deterioration of stone cultural artifacts such as the Angkor temples.

1. Introduction

Because rock weathering processes are slow, it is generally difficult to estimate the weathering rates of rock or identify the beginning/duration of weathering. In recent years, many studies on weathering rate have been reported (Saunders and Young, 1983; Turkington and Paradise, 2005; Moses et al., 2014). In particular, weathering rate investigations have been reported for tombstones (e.g. Dragovich, 1981, 1986; Cooke et al., 1995; Inkpen and Jackson, 2000; Williams and Robinson, 2000; Wells et al., 2008) and stone architectures (e.g. Takahashi et al., 1994; Mottershead, 2000; Trudgill et al., 2001; Aoki and Matsukura, 2007b; André et al., 2014), for which zero-datum levels for the weathering duration can be easily obtained. Cooke et al. (1995) pointed out that tombstones are useful to determine weathering rates in various areas.

Most of the abovementioned studies aimed to determine weathering rates on a decadal or centenary time scale. However, weathering rates can change over time (Cooke et al., 1995). Namely, long-term weathering is often accompanied by various environmental changes (e.g. Little Ice Age, Medieval warm periods), which can change the mechanism and rate of weathering; thus, it is difficult to understand whether short-term weathering rates are representative of the long-term ones (Moses et al., 2014).

Weathering rate also depends on rock type as well as the current environmental conditions. The long-term weathering rates of ancient monuments in arid and tropical environments have been reported in some studies (Table 1). Table 1 shows that the reported long-term weathering rates range widely from 0 to 200 mm ka^{-1} due to differences in rock type, environment, and weathering process. Therefore, in order to understand the complexity of weathering rates, additional studies are still needed (Pope et al., 2002).

Since physical weathering generally implies a decrease in rock strength, the rock properties are thought to be the most important factor in controlling the weathering rate (Turkington and Paradise, 2005). In previous studies, the rock properties of stone architectures are often assumed to be the same as the typical properties of intact rock (i.e., such studies assumed homogeneous rocks and did not measure rock properties at different sites within the same rock type). However, although rock type is an important factor that can explain differences in weathering rate, the rock properties are not always the same for the same type of rock. Thus, when different weathering rates occur within the same rock type, it is difficult to determine whether these differences stem from environmental conditions or rock heterogeneity. In addition, in the case of long-term weathering, it is not possible to determine the degree of decrease in rock strength.

To address the abovementioned problems, it is necessary to determine the degrees of weathering in individual building stones in consideration of the heterogeneities in rock properties. This may help to clarify the relationships between weathering rate and the rock properties that control it. In particular, studies on physical weathering rates associated with tropical and subtropical environments in which chemical weathering is thought to prevail are lacking. Therefore, this present study based on weathering rate considers the rock properties of Angkor

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Table 1
Some weathering (recession) rates of millennial-scale monuments.

Name & location	Climate	Building age	Rock type	Weathering rate, mm/ka	Reference
Great Pyramid, Giza, Egypt	Semi-arid	2800 BCE	limestone	Ave. 200	Emery (1960)
Alberuela Castle, Ebro basin, Spain	Semi-arid	850–1550 CE	sandstone	Max. 84	Sancho et al. (2003)
Ancient quarry, Petra, Jordan	Arid	100 BCE–100 CE	sandstone	13–80	Paradise (2002)
Roman Theater, Petra, Jordan	Arid	50 BCE–100 CE	sandstone	10–70	Paradise (2005)
Roman Theater, Petra, Jordan	Arid	50 BCE–100 CE	sandstone	7–66	Paradise (1995)
Ta Keo temple, Siem Reap, Cambodia	Tropics	975 CE	sandstone	26.2–53.1	André et al. (2008)
Angkor monuments, Siem Reap, Cambodia	Tropics	9 –13th	sandstone	7.6–46.9	André (2006)
Great temple, Amman, Jordan	Semi-arid	165 CE	limestone	0–15	Paradise (1998)
Granite sanctuary, Luxor, Egypt	Semi-arid	318 BCE	granite	Max. 5	Barton (1916)

temples that were built approximately 800–1400 years ago under tropical conditions. Preservation activities have widespread in recent years at the Angkor site because the temples have deteriorated due to natural degradation over long time scales. The results of this study may make significant contributions to the methodology used to estimate the stone deterioration and weathering rates of historical structures.

2. Site descriptions

2.1. Selected temples and sandstone weathering

The selected monuments in this study are 29 Angkor temples that are mostly sited around Siem Reap city in Cambodia (Fig. 1). A temple complex in the city, including masterpieces of Khmer architecture such as Angkor Wat and Bayon (Fig. 2a and b), was registered with the World Heritage List (UNESCO) in 1992. The Preah Vihear, Sambor Prei Kuk, Koh Ker (Fig. 2c–e), and Beng Mealea temples are located farther from the city (Fig. 1b). In 2008, Preah Vihear temple was named an outstanding masterpiece of Khmer architecture.

The studied temples were built from 618 CE to circa 1200 CE (Table 2), as determined by chronological studies based on epigraphs, construction styles, and the reigns of Khmer kings as well the radioactive carbon ages (e.g. Uchida et al., 1999, 2005). Ages determined by the construction style and the reigns of Khmer kings are reported as ranges (Table 2; #1–3, 6–9, 13–15, 23, 26–27, 29–32). The construction of the Preah Vihear temple (#23) is thought to have begun in the 9th century; however, the main part of the temple was constructed between the reigns of Suryavarman I (1002–1050 CE) and Suryavarman II (1113–1150 CE). Thus, the combination of the reigns of these two kings is listed as the age of this temple.

These temples have a building-block construction in which sandstone and laterite blocks and bricks were used as the primary building stones. Sandstone was used for a period of over ~1300 years as a principal building stone for the construction of structures such as sanctuaries, galleries, and gates. The natural degradation on such sandstone blocks

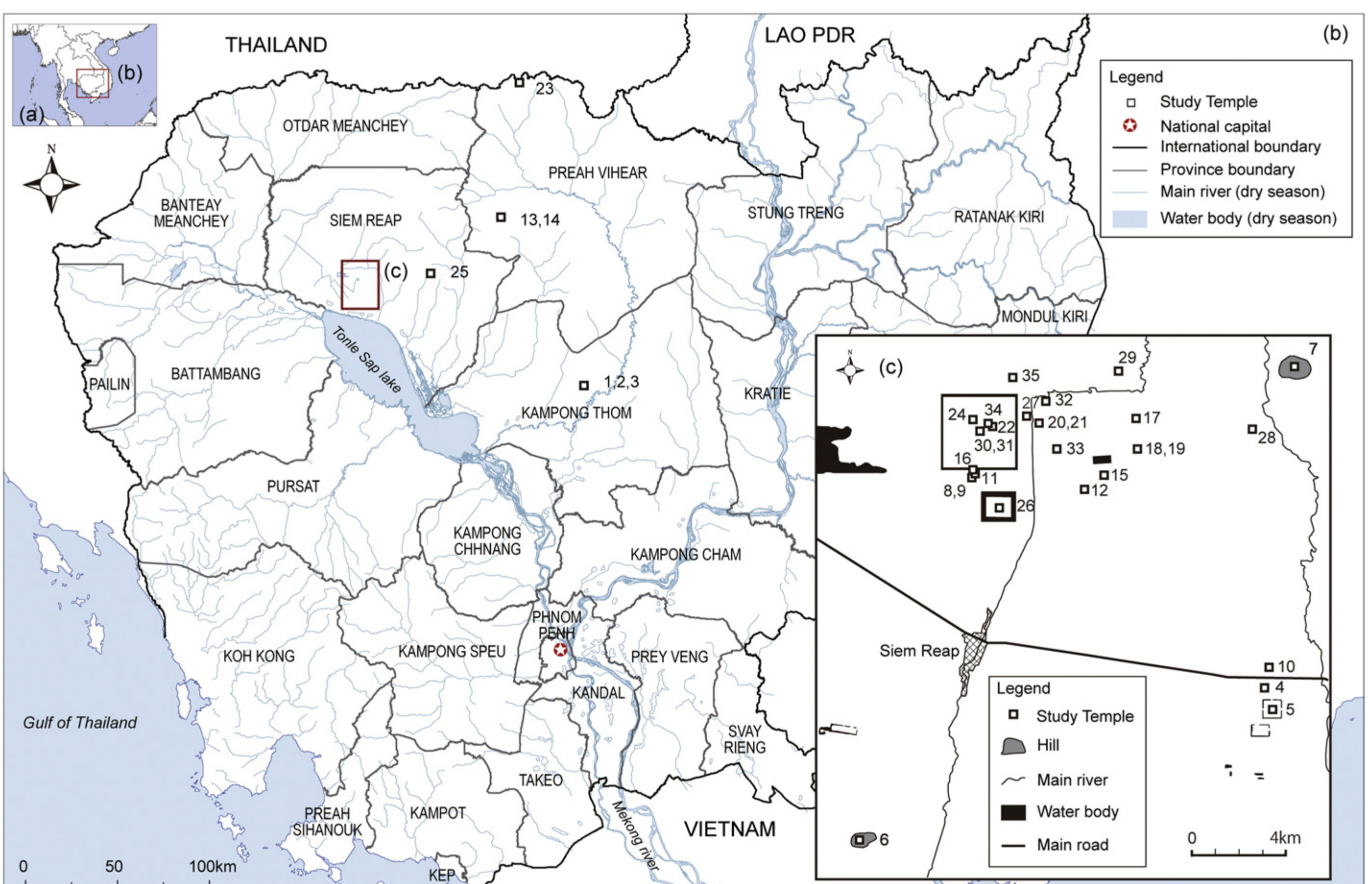

Fig. 1. Locations of studied temples. (a) and (b) were based on the map produced by WFP Cambodia (2013). Numbers correspond to the temple name in Table 2.