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BIODETERIORATION OF STONE IN RELATION TO MICROCLIMATE IN THE TA NEI TEMPLE – ANGKOR (CAMBODIA)

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Abstract

In the favourable tropical climatic conditions of Angkor, Khmer temples, which have been abandoned for many centuries, have been suffered from a wide range of biodeterioration processes. Ta Nei temple, which is still surrounded by a luxuriant forest, was selected as an appropriate site for testing the influence of microclimate on stone conservation. Not only big trees are growing on and all around the monument, but also different patinas of algae and cyanobacteria, lichens, mosses and higher plants are colonizing the temple stones. Field observations and laboratory analyses were carried out to establish the different phenomenologies of biodeterioration, their frequency and distribution in relation to water percolation, shadowing, ventilation and typology of stone. Data on the variations of these communities were collected in the field and evaluated on the basis of the ecology of the species. These data were related to temperature, light, ventilation and relative humidity measured in the site and gave rise to the identification of a clear ecological trend of different biological communities. The first colonizing community, which start to grow with minimum level of water in the substrate, is the *Trentepohlietum*, a pioneer coenosis widely spread in relatively xeric and shady conditions. It is followed by the *Scytonemo-Gloeocapsetum* in conditions of increasing water and light and then by various lichen communities (with dominance of *Lepraria* and *Pyxine*). With progressive higher water content of the substrate, communities of mosses and ferns colonize and grow on the stone. As noticed for other monuments, when the dynamism is blocked or limited by edaphic factors, these deterioration patterns change according to the environmental factors and not as successional stages. The knowledge of these relationships is very useful for evaluating the feasible use of indirect control methods against the various biological colonizers, and therefore for establishing the best microclimatic conditions for stone conservation.

Keywords: biodeterioration, tropics, microclimate, stone conservation, Angkor, ecology

1. Introduction

The Angkor monuments, close to the Tonle Sap Lake in Cambodia, represent the only remains of once thriving and powerful civilization, developed over a period of six hundred years (9th and 15th centuries). The magnificent remains of the different capitals of the Khmer Empire, inscribed in the World Heritage List in 1992, are distributed over about 400 sq km, including forested area and the archaeological park of Angkor. At this moment, part of the archaeological area has still to be excavated and great trees cover remains around the main monuments, giving to the place a suggestive impression, however causing also cracks and fall down of the constructive materials (Fig. 1).

Figure 1. Angkor site, aerial view. The Angkor Vat temple is visible due to the forest cutting. Many other temples, such as Ta Nei, are still covered by a thick tree cover.

The presence of the forest has direct and indirect effects on the conservation of the temples. In fact, the relevant tree cover can be a factor of risk for the conservation of the monuments, due to the problem of root damages on the walls, but this cover also greatly influences the microclimate of the site.

The effects of the changes in the environmental conditions can be sometimes positive, such as the protection from heavy rainfall or wind erosion, and in general from the reduction of rising of salts and water evaporation from the stone surfaces, and also for the protection against the stresses linked to the stone overheating during the day, and to their cooling during the night. Indeed, the changes induced here by tree cover can be sometimes negative, especially for the increase of humidity, due in particular to the shadowing and to the reduction of ventilation, which highly favours the biological growths.

Within the cooperation activity of the Japan team with the APSARA Cambodian authorities, in the field of the effects of microclimate on the stone of the monuments, Ta Nei temple (north east of Prasat Ta Keo in the Angkor Archaeological Park) was selected as a case study representative of stone conservation in shady conditions. This temple is still surrounded by a luxuriant forest and not only big trees are growing on and all around the monument, but also different patinas of algae and cyanobacteria, lichens, mosses and higher plants are colonizing the temple stones (Fig. 2).

The aim of this contribution is the definition of the relationships among biological colonisations and microclimatic conditions. In fact the knowledge of the relationships among the various biological deterioration patterns and the environmental conditions is useful for evaluating the possible use of indirect control methods against the various biological colonizers.

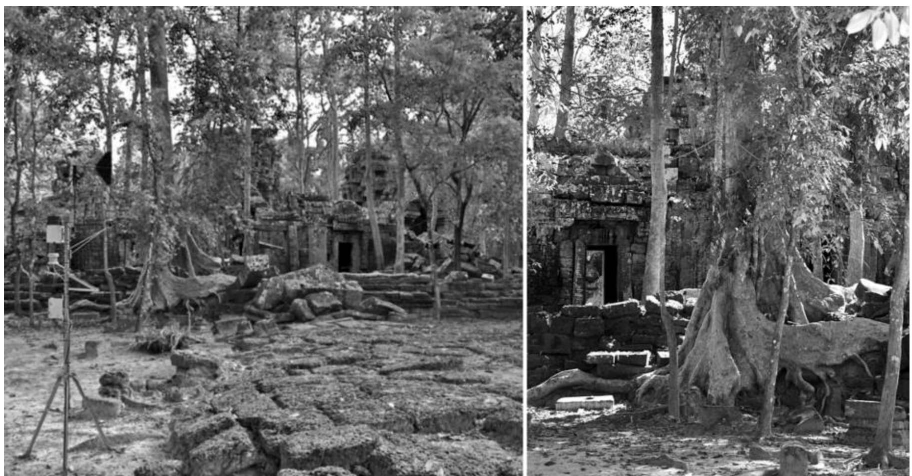

Figure 2. The West side of Ta Nei temple, where one of the microclimatic stations was settled. Note the diffuse collapses and cracks on the walls, and stone surfaces widely covered by different biological colonisations.

2. Material and Methods

2.1 The Site

The macroclimate of the site is characterised by "tropical monsoon", with a short rainy season, a prolonged dry season and irregular but generally plentiful rainfall, occurring between May and mid-October often with a two weeks dry period in July or August. Total annual rainfall is about 1200 mm; Siem Reap itself has an average daily rainfall of 1.4 mm, and in general no rainfalls occur between mid October and May. Ambient temperatures increase from December through April or May from an average of 24 to 36 degrees Celsius. The relative humidity is always high at the Ta Nei site, and in the rainy season its values are around 90% during the night, and around 70% during the day; in the dry season, these values are reduced until 50% only in the hottest hours. The direction and velocity of wind are affected by the arrangement of the buildings in addition to the monsoon winds. Even in the season when the wind velocity is highest, it is only around 1.5/2.0 m/s, and the prevailing wind blows from southwest in the rainy season and from the northeast in the dry season (Tomoko et al., 2006).

The historical information related with the selected temple attributes to Jayavarman VII its construction, at the end of the 12^{th} Century, as a Buddhist sanctuary. The temple was built with sandstone and laterite and comprises two enclosure walls with gopuras (Fig. 3). The sandstone is usually classified as feldspathic arenite or micaceous arkosic sandstone, it is a soft fine-grained sandstone weakly cemented by clay and calcite with a porosity of about 13-19 %.

2.2 Methods

Accurate observations were carried out on the Ta Nei temple to establish the different types of biodeterioration, their frequency and distribution in relation to the environmental factors. A general survey in the archaeological areas (Takeo, Ta Prom, Angkor Vat, Bayon) was also important to validate some correlations hypothesized in the site of study.

In particular, for each type of biodeterioration of stone, various quali-quantitative releves were carried out, repeating at minimum three times the observations, considering various expositions and shadowing effects.

The releves were carried out according to the phytosociological method (Braun Blanquet, 1964) and using the following scale to indicate the cover of the species: + = sporadic; 1 = 1-5%; 2 = 5-25%; 3 = 25-50 %; 4 = 50-75%; 5 = 75-100%.

For biodeterioration patterns in the shape of patinas and lichen growths, some samples were collected from the surfaces. For mosses and higher plants, other samples were also collected. The various phenomenologies of biodeterioration, the sampling areas and the locations of the releves were photographically documented.

All samples were observed under stereomicroscope, optical microscope and SEM at different magnifications. Specific taxonomic keys were used for the identification of species. Data on stone characteristic were also collected in the literature and observed under the microscope in thin sections.

Data collected in the field were evaluated on the basis of the ecology of the species, taking into account the microclimatic data collected by the Japanese team, and other data collected directly in the field as regards Temperature (of stones and air), Light and Relative Humidity. This information was used for establishing the ecological trends, suitable to explain the ecological meaning of the biodeterioration patterns' variation.

3. Results

The high temperatures and precipitations, typical of the tropical climate of the site, favour an abundant biological growth, and biodeterioration patterns on stone surfaces change in composition in relation to different shadowing, solar and wind exposition, and typology of stone.

Excluding few areas where the water input was very low, and stone appeared macroscopically free from biological growth, in the other areas, biological patinas, lichens and cushions tuffs on the surfaces were very evident. In fact, areas protected from rainfall, as incident water input or through percolation, are free from biodeteriogens, or their growth is very low (Fig.3). This means that water is here the main limiting (ecological) factor and the first step of biological colonization arises only starting from a certain water input in the substrate.

Figure 3. Stones protected from water percolation, and free from epilithic microflora.

Temperature and light have a certain relevance as ecological factors, but in a subordinate way with respect water. Temperature becomes a limiting ecological factor only during the hottest hours, when its values exceed 30-35°C. In this condition its influence is relevant for the increase of induced desiccation, which can be more or less tolerated by the various organisms: this tolerance is indeed higher for the poikylohydric ones, such as lichens and cyanobacteria.

The reduction of solar radiation due to the presence of trees or to N exposition is not so highly limiting for photosynthetic organisms to stop their growth; however the development of sciaphylous species, such as *Trentepohlia* and *Lepraria*, is favoured. Moreover the decrease of light often balances the reduction of other negative factors present in areas without a thick forest cover (e.g. conditions of very high temperature).
By the consequence, the combination among different ecological factors should be considered to reconstruct the Ta Nei ecosystem. These are in particular: *exposure* (to which the solar radiation, but also the different winds are correlated), *location and inclination of the surfaces* **(**that can favour water stagnation, percolation, effects of wind), *shadowing* (that reduces light, but overall water evaporation and salt rising), and *ventilation* (that, on the contrary, favours evaporation).

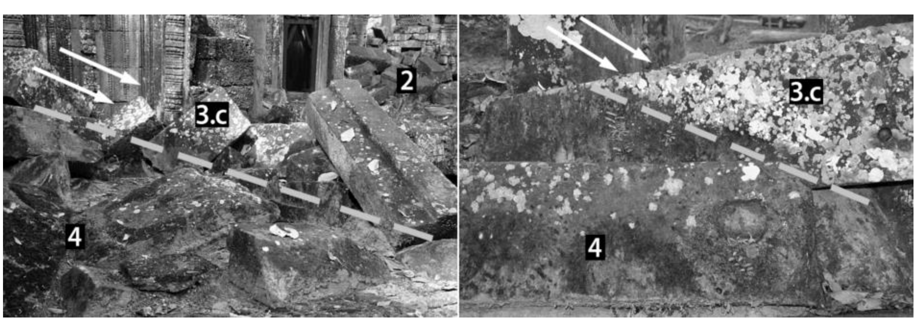

Figure 4. Stone blocks of Ta Nei temple showing a differential biocolonization resulting from different water content of stone due to the combined effects of shadowing and ventilation (moss communities in the wetter places and cyanobacteria and lichens in the dryer ones).

The different categories of biological colonisations can therefore be listed according to their correlation with a clear increase of water input of the substrate. They are numbered starting from the most xerophylous to the most hygrophilous communities:

1. reddish patinas
2. grey-blackish patinas

3.a grey-greenish lichen patinas
3.b grey crustose lichens
3.c white crustose lichens

4. green tuffs of mosses
5. ferns and flowering plants

The main pattern of species corresponding to each phenomenology of alteration is summarised in Tab. 1. The first step of biological colonization in Ta Nei is due to reddish patinas belonging to the green alga *Trentepohlia* sp. (Fig. 5). It was widely observed in tropical climates as first colonizers of stone, as reported in the literature of Meso- and South America

Table I. *Biodeterioration pattern in Ta Nei Temple*

Pioneer algae and Cyanobacteria				
Category	**1**		**2**	
Phenomenology	**Reddish patinas**		**Grey-blackish patinas**	
Association	***Trentepohlietum***		***Scytonemo-Gloeocapsetum***	
Species and rate	*Trentepohlia sp.*	5	*Scytonema javanicum*	5
			Gloeocapsa rupestris	4
			Basidia (lichen)	1
			Endocarpon sp.(fungi)	1
			Stigonema sp.	+

Lichens communities						
Category	**3a**		**3b**		**3c**	
Phenomenology	**Grey-greenish lichenic patinas**		**Grey crust of crustose lichens**		**White crusts of crustose lichens**	
Association	***Pixynetum***		***Leprarietum***		***Cryptothaecietum***	
Species and rate	*Pyxine sp.*	5	*Lepraria sp.*	5	*Cryptothecia cfr*	5
	Cryptothecia sp.	1	*Basidia sp.*	2	*Pyxine sp.*	2
	Basidia sp.	1	*Dirinaria consimilis*	1	*Enterographa zonata*	1
	Lepraria sp.	+	*Letroutia leprolyta*	1		
			Pyxine sp.	1		
			Cryptothecia	1		
			Enterographa zonata	1		
			Aspicilia sp.	1		

Mosses and Higher plants				
Category	**4**		**5**	
Phenomenology	**Green tuffs of mosses**		**Ferns and flowering plants**	
Association	**Moss communities**		***Adiantetum***	
Species and rate	*Trachyphyllum inflexus*	1	*Adiantum sp.*	4
	Hyophila rosea	-	*Asplenium sp.*	2-1
	Taxithelium nepalense		*Ceterach sp.*	1
	Fissidens spp. (F. ceylonensis et al.)	4	*Selaginella sp.*	1
	Ectropothecium dealbatum	r	*Hepaticae*	+
	Leptobryum pyriforme	r		
	Garckea flexuosa		*Tetrameles nudiflora*	1
	Pelekium investe		*Ficus sp.*	1
	Octoblepharum albium		*Peperomia pellucida*	1

(Caneva et al., 2005; Gaylarde et al., 2006), but also in wider geographic and edaphic conditions. These algae need a certain shadowing and their patinas were also observed in other monuments of Angkor, but never in condition of very high solar radiations.

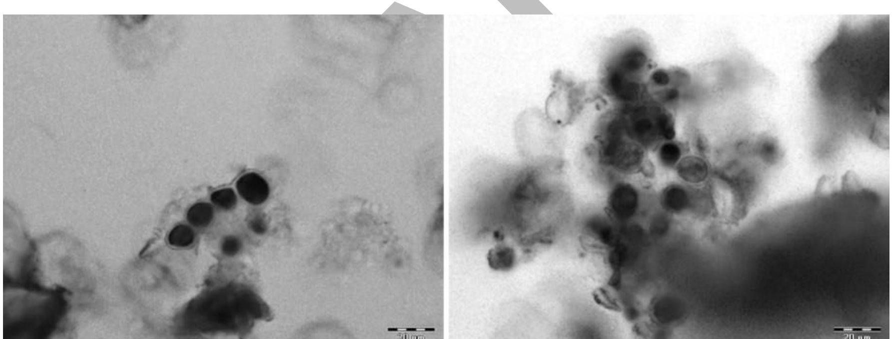

Figure 5. Reddish patinas (category n.1). Cells of *Trentepohlia* sp. packed with orange carotenoid pigment.

The second step of stone colonisation is made up by grey-blackish patinas, formed mainly by filaments of the genus *Scytonema* frequently associated with *Gloeocapsa* (Fig.6). The epilithic cyanobacterial association *Scytonemo-Gloeocapsetum* is widely developed on rock surfaces in tropical areas exposed to sunlight and sporadically wet.

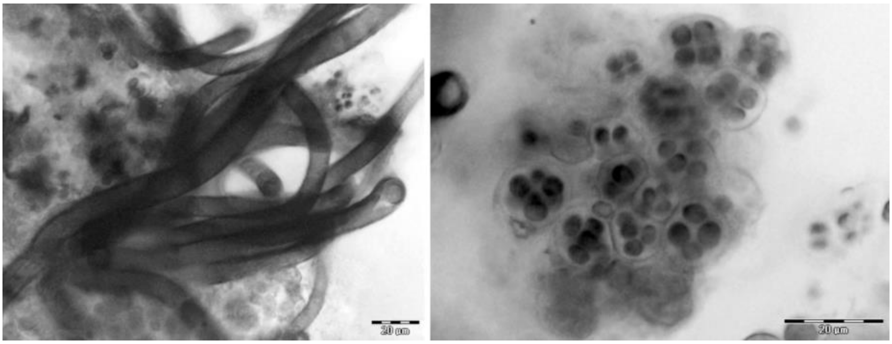

Figure 6. Grey-blackish patinas (category n.29. Filamentous forms of *Scytonema javanicum* with yellow-brown color and cyanobacteria (*Gloeocapsa* sp.) characterized by brown-purple glomeruli.

It is interesting to note that now at Ta nei a colonisation of *Trentepohlia* is arising in areas previously colonised by these cyanobacterial communities, after the treatment with water repellents to protect the stone. Some Authors considered this phenomenon as a undesirable "selective reinfestation by red-coloured green algae" due to the treatment (Warscheid and Leisen, 2011). In our opinion this has to be considered a positive result, in view of protection of stone surface, witnessing the effectiveness of the treatment, reducing the water content of stone, and finally shifting the biodeterioration pattern in a more xerophylous and less penetrating one, as our microscopic observations indicate.

Different lichen communities (category n. 3) are developed as a further step linked to a higher water content, with a relative dominance of *Lepraria*, *Pyxine and Cryptothecia* (see tab. 1) (Moon et al., 2009), respectively showing a preference for certain environmental conditions, especially for lighting levels.

When a progressive increase of water in the substrate occurs, due to environmental conditions or to a greater deterioration of stone with increase of its porosity, communities of mosses (category n.4) (mainly *Fissidens, Trachyphyllum*), ferns (*Adiantum, Asplenium, Ceterach* and *Selaginella)*, and also of flowering plants (category n.5) (*Tetrameles, Ficus, Peperomia)* became able to colonize the stone. These communities are obviously more developed in shadowed places, where water can remain longer; in fact, where ventilation occurs, they are suddenly substituted by lichen species following the direction of wind and creating precise linear oblique substation of such communities (see Fig. 5).

Dealing with conservation phenomena, it is important to note that different communities have different potential biodeterioration pattern. Notwithstanding the effect of lichens is well stated by a vast literature (Caneva et al, 2009), and is also observed for this stone temple (Moon at al, 2008), some Authors state for Angkor temples that "long-term developed microflora, i.e. lichens, has an important moisture-controlling function on the environmentally stressed stones…. and that lichens protect the stones from rapid water uptake"; they also note as "certain algal and blackened cyanobacterial films significantly increase it" (Warscheid and Leisen, 2011). However, in the cited paper this statement is only supported by limited *in situ* measurements of capillarity water absorption without a long-term observation of the behavior of stone after the wetting; information on experimental conditions (season, environmental conditions, number of repetition), and on the species checked in the measurements is lacking, as well as comments on the not non-negligible physical and chemical effects of lichens. Nevertheless other Authors suggest a protective action of some lichen communities based on their effect in reducing thermal stresses, or through other mechanisms, underlying the need to also consider bioprotection and not only biodeterioration (Carter and Viles, 2005). We therefore believe that these statements are not generalizable and more accurate analyses should be performed; a more critical evaluation of the deterioration effects of the different various colonizing species is also needed.

The plant communities (from moss to vascular plants) are the most dangerous ones, due to the most developed systems of roots and rhizines able to penetrate and crack the stone. Moreover certain communities evidently grow on substrata where water remains longer also due to an internal higher porosity. However the differential potential attack of the various species should be better established.

The ecological changes of the various biological colonisations in relation to the variation of the main environmental factors (water and light) are described in Fig. 7. It is worthy of note that, as observed for other monuments, in Ta Nei temple the natural dynamism of the biological colonisation is partially blocked or at least limited by edaphic factors (stone characteristics, such hardness and porosity, which are much lower than the soil). Therefore the various deterioration patterns change mainly according to the changes of environmental factors than as successional stages. This means that in dry and sunny conditions pioneer communities of cyanobacteria and lichens can remain for a very long time, and they evolve very slowly in communities of mosses and higher plants. That can happen only when the porosity of the deteriorated stone is so high to permit their establishment. Then, obviously they contribute to an acceleration of stone deterioration.

In more humid conditions or when the decay of stone is worst, the plant succession proceeds with higher speed and all the deterioration processes go faster.

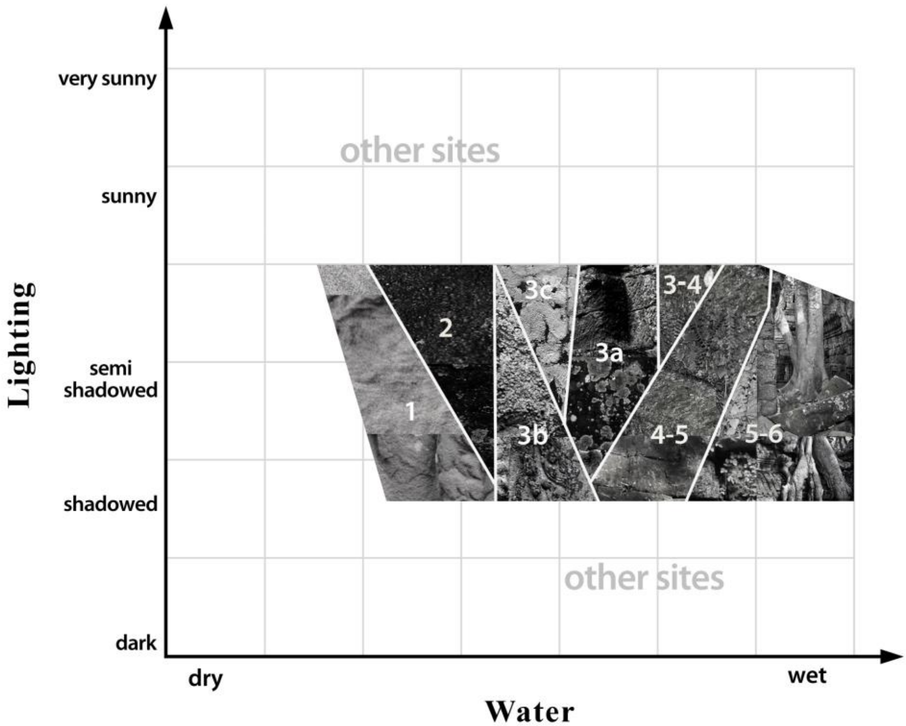

Figure 7. Relationships between the main ecological factors (water and light) and the biological growths in the Ta Nei Temple (archaeological site of Angkor). Numbers refer to the categories of Table 1.

4. Conclusions

It is well known that for an effective reduction of the biological growth, the better system is a change of environmental conditions to not favourable ones for the organisms. Considering the fundamental ecological value of water and its primary role observed in Ta Nei site, for a further reduction of the biological growths, any systems able to reducing the water content of stone should be considered the most effective.

However, the study of other sites in Angkor, such as Angkor Vat, or Takeo, shows that the reduction of humidity arising from the cutting of the forest does not completely stop the biological colonizers; this intervention causes a higher growth of cyanobacteria and algae, a reduction of certain sciaphylous lichen communities, and a drastic reduction of mosses and ferns.

This information is useful for establishing the better microclimatic conditions for the stone conservation, as regards the undesirable and potentially dangerous harmful biological growths on stones.

In order to plan the best conservative intervention, the effect of the tree cover on ventilation and on other microclimatic parameters should also be considered. In fact, the reduction of ventilation and the shadowing due to the tree cover gives rise to an increase of humidity, which is favourable for the biological growths. The increase of ventilation, which occurs after the tree cover removal, can however increase evaporation phenomena, with all the consequences coming from higher rapid water movements inside the materials. The better compromise between positive and negative actions induced on stone by the forest cover should be established after a more complete evaluation of different biological-chemical and physical phenomena.

According to the aim of this work, the relationships between the environmental factors and the biological growths, in order to know in advance what will be the consequence of human intervention on the biological colonisation, have been established. Further steps will be a more detailed assessment of the changes of biodeterioration patterns after the total tree removal, as it was done in other monuments in Angkor, and a more precise evaluation of the real aggressiveness of the different biological populations for the stone, through the estimation of the modality and depth of penetration of different biocolonizations, and the chemical interaction with the stone. The potential utility of some not highly aggressive biological community with respect other more aggressive weathering factors, or also the combination of consolidation or protection treatments aimed to reduce the porosity of materials, should be also considered in order to carry out the best conservative intervention for the stone of the temple.

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