Deterioration of the Elephant Tomb (Necropolis of Carmona, Seville, Spain)

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The Roman Necropolis of Carmona, carved in a calcarenite bed, suffers different deterioration problems. The main alteration processes observed in the tomb walls and roofs are the result of powdering of the rock surface. This is due to the loss of calcite cement, leading to grain individualization and disintegration of the matrix into fine particles. Biological activity both inside and outside the tombs was observed, in some cases preventing disintegration of the calcarenite. The role of phototrophic organisms in the deterioration processes of the Elephant tomb is discussed.

La Necrópolis Romana de Carmona, excavada en calcarenita, presenta diferentes tipos de deterioro. El principal es el resultado de la arenización de la roca, debido a la pérdida de calcita cementante que origina la desintegración y liberación de los granos de cuarzo. Se discute el papel de los organismos fotótrofos en los procesos de deterioro de la tumba del Elefante, una de las más representativas de la Necrópolis, donde existe una abundante actividad biológica en el exterior de la tumba, y más limitada en el interior. En el exterior, la colonización de la calcarenita por líquenes evita su desintegración.

INTRODUCTION

The Roman Necropolis of Carmona was discovered and excavated at the end of the nineteenth century. This Necropolis was in use during the first and second century AD and resulted from the carving of different tombs in a bedrock. The main alteration processes observed in the tomb walls and roofs are the result of 'arenization' or powdering of the rock surface, with gravitational shedding of particles. This is due to the loss of calcitic cement of the rock, leading to grain individualization and disintegration of the matrix into fine particles. This phenomenon is more pronounced in areas of internal discontinuity of the rock. In addition, biological activity both inside and outside the tombs was observed, in some cases preventing 'arenization'.

In this paper, weathering of the building materials of the Elephant tomb (Fig. 1), as representative of the processes leading to deterioration in the Necropolis of Carmona, is investigated.

MATERIAL AND METHODS

Geology

The rock into which the Necropolis was carved is a calcarenite of the Messinian–Lower Pliocene period, with a depth of 30 m and layers of about 15–45 cm, sometimes reaching 1 m, separated by sedimentary discontinuities. The granulometry is variable, with bioclasts in which lamellibranchia predominate over oysters and small foraminifera. The matrix is calcite with 'equant' and 'drusy' textures. The rock is soluble, with high porosity and with medium to low cohesion, easily weathered and subject to microkarstification processes.

Environmental measurements

Measurements of temperature, relative humidity and radiation were taken on the surface of the calcarenite. Temperatures were also taken beneath the lichen thalli of *Diploschistes gypsaceus* and *Toninia sedifolia*.

Fig. 1. The Elephant tomb.

The temperature was measured by means of thermistors (Grant, Cambridge) placed on the rock surface. Relative humidity was measured 1 cm above the calcarenite surface with a hygrometer (Vaisala, Helsinki). Light irradiance was measured with a light sensor (Chauvin Arnoux, Paris) placed on the surface. All sensors were connected to a Squirrel Data Logger (Grant, Cambridge).

Sampling

Lichens were identified directly in the field and subsequently confirmed in the laboratory. Samples were taken by scraping the surface of the calcarenite or mortar. Where possible, small fragments were also removed with forceps.

For cyanobacterial and algal identification, samples were taken from zones with evident colonization. Enrichment cultures were made in Parafilm-sealed Petri dishes containing BG11 (Rippka *et al.*, 1979) or BBM (Chantanachat & Bold, 1962) solid media. Small fragments of calcarenite were placed on to the surface of the agar. Cultures were maintained at room temperature at 450 lx of continuous light.

RESULTS

Environmental parameters

Environmental parameters are shown in Fig. 2. In contrast to other tombs of the Necropolis, the Elephant tomb was relatively dry, with a relative humidity around 60%, but in some periods decreasing to 40%. This is a low value, and more so considering that the measurements were made after a period of autumn rainfall (November) and that the relative humidity outside in the shade was the same. The temperature inside the tomb showed some dependence on the outside temperature. Light levels were considerably diminished, reaching a maximum early in the morning when the sun was low, and light penetrated the chambers through the doors and windows.

To study the effect of the lichen cover on the calcarenite, a thermistor (0.5 mm in diameter) was inserted under each of two large epilithic thalli of *Diploschistes gypsaceus* and *Toninia sedifolia* colonizing the surface to measure the variation in temperature. A third one measured the temperature of the bare surface. The results showed that the temperature reached by the thalli was influenced by their colour: the white thallus of *Diploschistes gypsaceus* was 5–6°C lower than that of *Toninia sedifolia* (black). The temperatures of the bare rock and *Diploschistes gypsaceus* differed only by a few degrees, but the temperature of the bare rock suffered higher oscillations when compared with that of the lichen-covered rock (Fig. 3).

Biological colonization of the Elephant tomb

The Elephant tomb was a sanctuary devoted to the cult of oriental gods. The actual tomb comprises

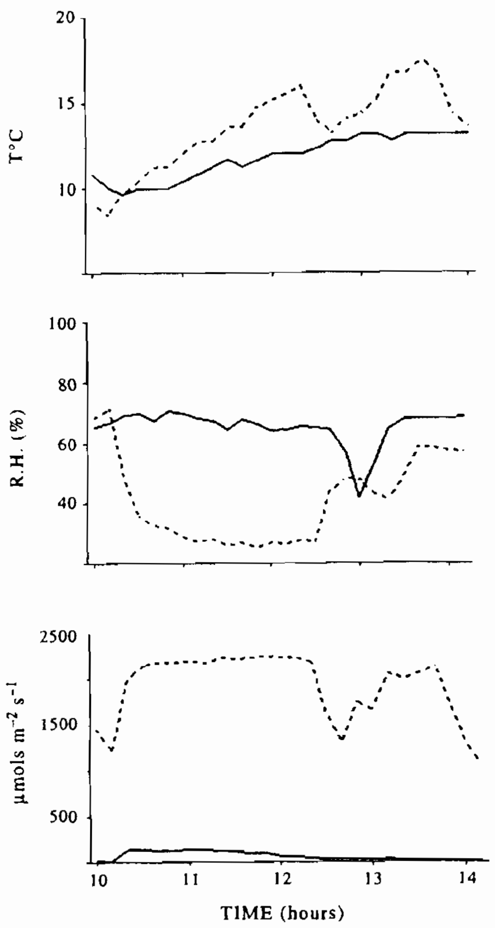

Fig. 2. Changes in environmental parameters inside (unbroken line) and outside (broken line) the Elephant tomb.

two main units: an exterior area or court with a central corridor with remains of columns of calcarenite and ornamental fountains coated with mortar; and an interior three-room chamber, excavated in the calcarenite, with several doors and windows.

The external walls of the tomb, below the level of the surrounding land, shows a large difference between the north and south sides. The biological colonization observed is a reflection of these differences. The distribution of organisms has been studied on both sides of the central corridor, the mortar of the fountains, and the external and internal tomb walls. The different communities growing on the calcarenite and mortar are shown in Table 1.

Central corridor

The sides of the central corridor include quadrangular ashlars of calcarenite, heavily colonized by lichens. The upper part of the blocks of the ashlars on the right side bears a lichen community typical of relatively xeric and nitrified horizontal surfaces. These accumulate large amounts of dust and soil particles, producing a protosoil that can sustain colonization by a great variety of organisms. In addition, rainwater runoff transports a considerable supply of nutrients, whereas a high amount of bird droppings gives additional nutrients and raises nitrification levels. In this situation, the lichens cover the rock almost totally, dominated by crustaceous and squamulose thalli, some of which reach a considerable size (*Diploschistes gypsaceus*, *Squamarina cartilaginea* and *Toninia sedifolia*).

The ashlars on the left side are blocks with the same characteristics as those on the right side, although exposed to less sunlight. The proportion of typically heliophilous species (particularly *Aspicilia contorta*, *Sarcogyne regularis* and *Caloplaca* spp.) is lower, and lichens of wetter and less exposed environments (*Lepraria* sp.) occur.

Mortar of the ornamental fountains

The mortar of the fountains shows a heavy covering of lichens on the right side with high sunlight levels. On the left side, colonization is much lower.

The lichen community, despite being under microclimatic conditions very similar to those of the ashlars, is very different. There are small, heliophilous crustaceous lichens without the large thalli that dominate the calcarenite community. Here, the most abundant are *Aspicilia contorta*, *Caloplaca variabilis* and *Verrucaria macrostoma*. The difference undoubtedly lies in the nature of the substratum since the irregularity of the calcarenite ashlars helps the accumulation of particles, giving rise to a surface that is more susceptible to colonization by a wide range of species.

Exterior walls of the tomb

Species distribution on the walls also depends on the exposure level. The right-hand wall, with a high level of sunlight, is dominated by xerophilous and heliophilous crustaceous lichens (especially of the genus *Verrucaria*). In the opposite wall, slightly wetter and with less light, most heliophilous lichens disappear, whereas a sciophilous lichen, *Lepraria nivalis*, is abundant.

On the extreme left, in an excavated niche protected from the rain and direct sunlight, there

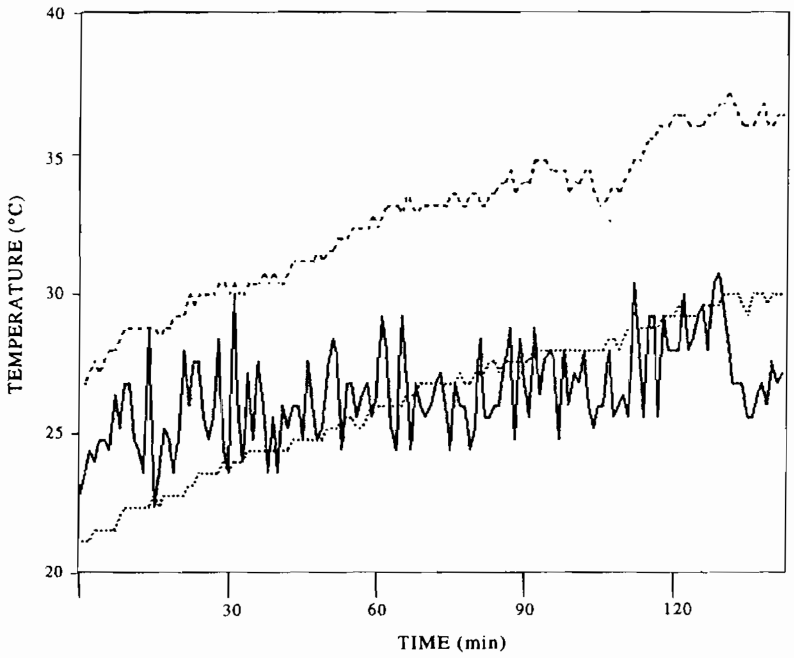

Fig. 3. Evolution of temperature on the bare rock surface (unbroken line), that colonized by *Diploschistes diacapsis* (dotted line), and that colonized by *Toninia sedifolia* (broken line).

are large patches of intense yellow colour caused by a monospecific population of *Leproplaca xantholyta*, a lichen with a leprarioid thallus (Table 2).

The instability of the substratum, which disintegrates readily, hinders the lichen communities reaching maturity. The lower contribution of rainwater and nutrients on the vertical walls produces restricted colonization, except in the water run-off tracks, where a thick

Table 1. Species Identified on the Calcarenite and Mortar of the Elephant Tomb

	Calcarenite	Mortar
Aspicilia contorta (Hoffm.) Krempelh.	+	+
Caloplaca aurantia (Pers.) Hellb.	+	+
Caloplaca citrina (Hoffm.) Th.Fr.		+
Caloplaca flavescens (Huds.) Laundon	+	
Caloplaca tenuatula (Nyl.) Zahlbr.	+	
Caloplaca teicholyta (Ach.) Steiner	+	+
Caloplaca variabilis (Pers.) Müll. Arg.	+	+
Caloplaca velana (Massal.) Du Rietz	+	+
Collema crispum (Hudso.) Web.	+	
Diploschistes diacapsis (Ach.) Lumbsch	+	
Endocarpon pusillum Hedw.	+	
Fulgensia fulgida (Nyl.)Szat.	+	
Lecanora albescens (Hoffm.) Branth and Rostrup		+
Lepraria nivalis Laundon	+	
Psora decipiens (Hedw.) Hoffm.	+	
Rinodina bischoffii (Hepp) Massal.	+	+
Sarcogyne regularis Körb.	+	
Squamarina lentigera (Web.) Poelt	+	
Squamarina cartilaginea (With.) James	+	
Toninia aromatica (Sm.) Massal.	+	
Toninia sedifolia (Scop.) Timdal	+	
Verrucaria hochstetteri Fr.	+	
Verrucaria macrostoma Duf. ex DC.	+	+
Verrucaria viridula (Schrader) Ach.	+	+

Table 2. Species Identified on the Walls of the Elephant Tomb

	Wet areas	Dry areas	Interior
Lichen			
Aspicilia contorta (Hoffm.) Krempelh		+	
Caloplaca aurantia (Pers.) Hellb.	+	+	
Caloplaca citrina (Hoffm.) Th.Fr.	+		
Caloplaca teicholyta (Ach.) Steiner	+		
Caloplaca velana (Massal.) Du Rietz	+		
Collema sp.	+		
Endocarpon pusillum Hedw.	+	+	
Fulgensia fulgida (Nyl.) Szat.	+		
Lepraria lesdainii (Hue) Harris			+
Lepraria nivalis Laundon	+		+
Leproplaca xantholyta (Nyl.) Harm.			+
Squamarina cartilaginea (With.) James	+		
Staurothele hymenogonia (Nyl.) Th.Fr.		+	
Toninia aromatica (Sm.) Massal.	+		
Toninia sedifolia (Scop.) Timdal.	+		
Verrucaria hochstetteri Fr.	+	+	
Verrucaria macrostoma Duf. ex DC.	+	+	
Verrucaria nigrescens Pers.		+	
Verrucaria viridula (Schrader) Ach.	+	+	
Cyanobacteria			
Chroococcus minor (Kütz.) Näg.			+
Nostoc sp.	+		
Plectonema sp.			+
Scytonema julianum (Frank) Richter			+
Symploca muralis Kütz	+		
Algae			
Chlorosarcina sp.	+		
Haematococcus pluvialis Flotow	+		

biofilm of cyanobacteria (mainly composed of the filamentous *Symploca muralis*) and rhizoids of mosses develops. The presence of areas of periodic wetting gives rise to the establishment of a community dominated by nitrophilous and terricolous lichen species (*Endocarpon pusillum, Squamarina* sp., *Toninia sedifolia*), though scarcely developed.

Internal walls of the tomb

Inside the tomb, the level of colonization of phototrophic communities is naturally very low or practically non-existent. A series of factors affects biological colonization, mainly the condition of the rock, with abundant disintegrative processes and surface precipitation of carbonates, giving rise to an unstable substratum.

The level of light does not itself cause any limitation, as it is sufficient for the growth of certain communities of organisms typical of low light environments. However, the low humidity and low light together do limit colonization. For instance, on the window- and door-frames, where there is a higher intensity of (indirect) light, certain leprarioid lichens (such as *Leproplaca xantholyta* and *Lepraria lesdainii*) occur.

Inside the tomb, only some green patches from the growth of a calcifying filamentous cyanobacterium (*Scytonema julianum*) can be distinguished (Saiz-Jimenez, 1995). This is restricted to small areas protected from air currents.

DISCUSSION

Biodeterioration processes are associated with the presence of water. A particularly wet zone, in the left-side chamber of the tomb, under a window, is heavily colonized by the lichen *Lepraria lesdainnii* and the cyanobacterium *Scytonema julianum*, but the rest is free from phototrophic communities. The deteriorating effect of the cyanobacteria and algae colonizing the interior chamber is possibly negligible, as the community is scarcely developed. The calcifying cyanobacteria, represented by *Scytonema julianum*, are enveloped in a calcareous crust of regular crystals of calcite, undoubtedly indicating mobilization of the calcium carbonate coming from dissolution of the rock.

In the exterior stones and walls, the presence of large crustaceous or squamulose lichen thalli is especially relevant to the degree of surface alteration of the calcarenite. Under drought conditions, the thalli are contracted, but when hydrated, their volume increases considerably. During this expansion, numerous particles to which the lower cortex of the thallus adheres are often broken away. A common phenomenon is that the central part of the thallus, on expanding, subjects the more peripheric parts to stress. When the thallus can no longer advance laterally, it rises from the substratum, forming a type of blister. This process can lift particles of the rock. A secondary effect of this alteration is that the empty spaces under the thalli are used by microfauna, such as small beetles and spiders, which are common inhabitants of these ecological niches generated by the lichens themselves. This means an increase in nitrification of the rock surface because of the constant supply of organic material, mainly from droppings and dead organisms. These remains then form the foundation for the establishment of an associated bacterial and fungal flora.

Lichens, bacteria and fungi are potential generators of large amounts of organic acids (Saiz-Jimenez, 1994). This has a considerable effect on the alteration of the calcarenite surface layer, mainly through the dissolution of carbonates. Thus, the layer comprising the first millimetres nearest the calcarenite surface, subjected to the continual action of the organisms, gradually disintegrates. The small crystals of quartz and calcite, which are more difficult to attack, lose the carbonate matrix that cements them together. These particles accumulate forming a protosoil where terricolous species of lichens, mosses and, at a later stage, vascular plants appear.

The chemical alteration taking place in the calcarenite surface has been demonstrated by analysis of the interface between a thallus of *Diploschistes gypsaceus* and the substratum. This lichen forms very large thalli—some 5–10 cm in diameter and of considerable thickness (1–2 mm) at certain points. Under hydration conditions, these often rise from the substratum to form the blisters described above. In such cases, the thallus often breaks, leaving the altered surface exposed and readily eroded by atmospheric agents. The study of the interface shows that the action of this lichen on the substraum is not only physical—its chemical activity is high since the thallus consists mainly of hyphae interspersed with crystals of calcium oxalate (Ariño & Saiz-Jimenez, 1996), resulting from the excretion of oxalic acid (Fig. 4).

However, the effect of biological agencies is small compared with the great physico-chemical processes taking place in the Elephant tomb. In fact, in the outcrops of excavated areas, the rock is subjected to the dissolving action of rainwater in the presence of atmospheric CO_2, attacking preferentially the cement joining the clasts. The daily mechanical effect of the pronounced change in temperature alternating between night and day—particularly in summer—contributes to surface disintegration of the rock. These processes are also favoured by wetting/drying during the rainy season or following nocturnal condensation. The combined action of these factors produces surface disintegration of the components of the rock, giving rise to its arenization. This detritus is subsequently carried by drainage water (barely organised in flat channels) to lower areas where it accumulates and sediments. Continual repetition of this process leads to gradual erosion of the rock surface. This process is prevented by lichen colonization, and the tombs subjected to the heaviest colonization of their walls are also those that have the greatest environmental stability and retain their structure best conserved. Covering of the calcarenite by lichen

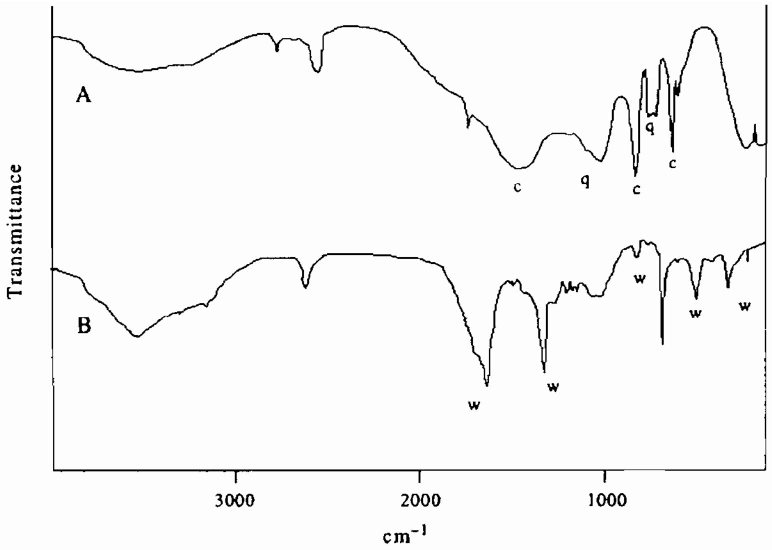

Fig. 4. Comparison between the IR spectrum of calcarenite (above) and that of the interface between the thallus of *Diploschistes diacapsis* and calcarenite (below). c, calcite; q, quartz; w, calcium oxalate.

thalli seems to give it a greater stability and resistance to disintegration when compared with bare rock. In the same way, lichen thalli buffer the oscillations of temperature, as shown by the white thalli of *Diploschistes gypsaceus* and *Squamarina cartilaginea* in comparison with the black thalli of *Toninia sedifolia*.

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