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Pitting of calcareous rocks by organisms under terrestrial conditions

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ABSTRACT

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The establishment of microorganisms such as fungi, cyanobacteria, and lichens at the calcareous rock surface leads to a decrease in the coherence of rock particles. The increasing rate of dissolution and removal of particles leads to the creation of depressions near the lithobionts. The much faster rate of weathering near the lithobionts is expressed in the formation of pits 1–5 cm in diameter and depth. Microscopic fungi in extreme desert areas are the most drought-resistant lithobionts developing in the mist desert of Namibia. Lichenized and free-living cyanobacteria are some of the most common organisms that induce biological pitting. There are special situations where calcareous rocks are subjected to the colonization of endolithic lithobionts and to snails grazing on the lithobionts. The latter type of ecosystem leads to pitting too.

Each type of pit has particular recognizable features enabling the use of these weathering patterns as guiding fossils that may assist us in interpretation of past environmental conditions.

INTRODUCTION

Our joint publication (Danin, Gerson, Garty, and Marton, 1982) dealt, among other subjects, with "pitting", one of the most important forms of biodeterioration of calcareous rocks under terrestrial conditions. We considered "pits" as depressions in the rock surface that are 1–5 cm deep and with a diameter of that order of magnitude.

The processes of biodeterioration of various types of substrate have been studied by many authors during the last few decades. Several hundred studies were carried out on various aspects of the biodeterioration of stone monuments. A rather complete list of references on the effect of microbial activity on stone monuments is that of Krumbein (1987). From this extensive bibliography only a few of the more general papers are mentioned here: Hueck van der Plas (1968), Pochon and Jaton (1968), Curri and Paleni (1973), Krumbein (1973), Schneider (1976), Krumbein and Jens (1981), Bech-Anderson (1984), Eckhardt (1985), Koestler et al. (1985), Caneva and Salvadori (1987), Gehrmann, Krumbein and Petersen (1988). A comprehensive review of several life forms active on the marble of ancient monuments in Greece is that of Anagnostidis et al. (1983). The ubiquitous and extensive nature of biodeterioration of many types of substrata by many microorganisms forming biofilms was discussed by Flemming (1992). He stressed that the majority of microorganisms on earth live in biofilms. In sites where the microorganisms did not form a continuous film they appear as circular groups of cells. The biogenic weathering they induce leads to the formation of pits.

The aim of the present paper is to discuss the processes

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of biologically-induced pitting, — their similarities and differences in shape and in the environmental conditions under which they develop.

HOW TO DISTINGUISH BIOLOGICAL PITTING

Hard and homogeneous calcitic rocks that are exposed to a certain kind of terrestrial environment are expected to weather at about the same rate all over the surface. When an organism that establishes itself among the rock crystals grows, its respiration releases CO_2 to the water when the rock is wetted, forming the weak acid, carbonic acid, (H_2CO_3), which dissolves the rock parts that are in direct contact with the organism. The coherence of particles to the rest of the rock decreases, and their erodibility by splashing raindrops increases. The weathering rate near such an organism is accelerated, and if it is faster than that of the entire surface it leads to the formation of a depression in the rock, in the vicinity of the organism. In a homogeneous rock the lateral growth rate of the organisms is expected to be the same in all directions, thus forming a circle. The results of localized faster weathering near the organisms is the formation of a circular pit. The deepest point in the pit is the locus of the first establishment of the organism.

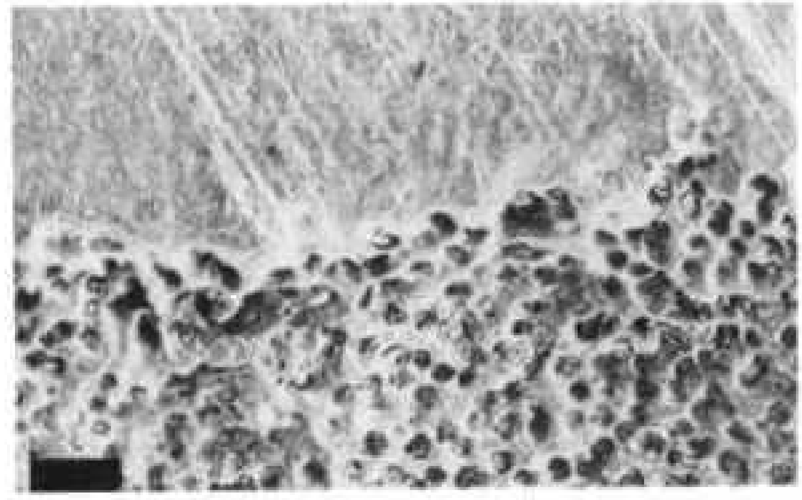

Fig. 1. Margins of a shallow pit on crystal face of Precambrian calcite from near Swakapmund, Namibia. (Bar = 300 µm.)

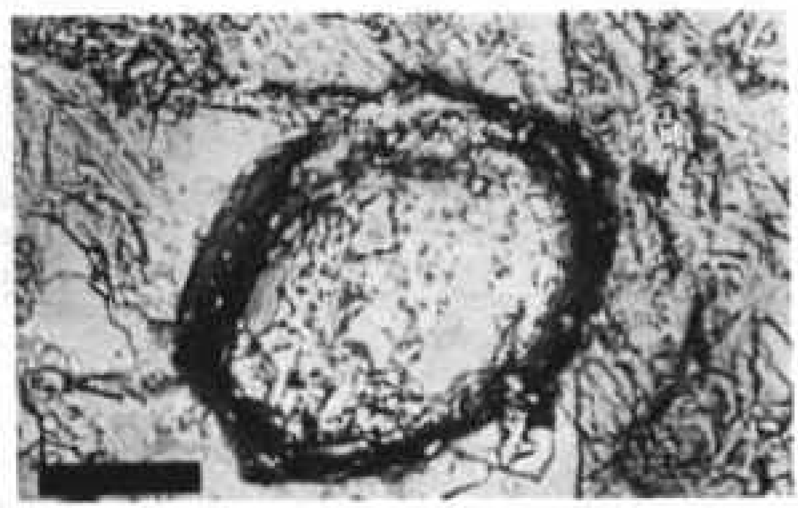

Fig. 2. A back-scatter micrograph of a micro-pit from the floor of the pit in Fig. 1, that was populated with *Lichenothelia globosa*. The dark strips are of a sediment rich in clay minerals. (Bar = 30 µm.)

PITS IN DRY ENVIRONMENTS

The common life-form strategy in most of the lithobionts (organisms that live inside or on the rock; Golubic, Friedmann, and Schneider, 1981) involved with pit formation is their being poikilohydric, i.e., they change the water content of their body in accord with their close environment. These organisms can tolerate desiccation to air humidity values, while entering a status of drought dormancy. They start their biological activity shortly after being wetted. Those that photosynthesize consume CO_2 during the daylight hours but release it to the water during the night wetting by rain or dew. Non-photosynthesizing lithobionts release CO_2 whenever wetted sufficiently to start respiration.

THE ORGANISMS ASSOCIATED WITH PITS AND THEIR TYPICAL HABITATS

Microscopic fungi

Lichenothelia globosa, a non-lichenized microscopic fungus, having a rather globular, ovoid, or funnel-shaped thallus, is involved with the weathering of a Precambrian calcite outcrop in the mist desert of Namibia near Swakapmund. It is a pioneer colonizer that establishes itself in natural microscopic cracks, dissolving microscopic holes (micro-pits) in the hard rock (Figs. 1 and 2). The fungi induce sedimentation of airborne clay in the periphery of the holes, thus locally increasing the moisture-holding capacity of their own niche (Fig. 2). The life cycle of this organism is not known yet, but because of its appearance in clusters of individual holes, forming together shallow pits (Figs. 1 and 2), it is assumed that there might be some vegetative reproduction in this fungus. The rate of pit formation here is not known. However, the fact that pits are found proves that the rate of weathering near the fungi is faster than the regular atmospheric weathering processes. Old *Lichenothelia* pits become populated with organisms such as cyanobacteria or lichens, the successional relationships of which with the fungi should be studied.

Other species of *Lichenothelia* in the Judean Desert, the southern Negev, and Crete (Greece) induce pits as well. *L. intertexta* Henssen (det. Prof. A. Henssen) is the most common species in Israel that starts the weathering process of hard limestones. In our previous study (Danin et al., 1982, Figs. 7 and 8), we erroneously presented this fungus as a colony of cyanobacteria. A very rough and preliminary rate of weathering associated with these organisms could be estimated by a study of the 700-year-old Mausoleum of el Kebkebi in Jerusalem (Danin and Caneva, 1990). In this site there are a few building stones with *Lichenothelia* in micro-pits. Since the common depth of pits was ca. 200 µm and the age of the site is ca. 700 years, these fungi may indicate a rate of dissolution of ca. 1 mm in 3500 years. In extremely dry habitats such as limestones in the southern Negev (30–50 mm mean annual rainfall) or marble in wetter areas (southeastern Crete, near Preveli) pits populated with *Lichenothelia* seem to be the final stage of lithobiont succession. In moister areas or softer rocks the fungi are replaced by lichenized and non-lichenized cyanobacteria (Danin, 1986a). The process goes on when neighboring micro-pits join together, thus forming larger micro-pits that may hold higher quantities of water and may be better protected from desiccating winds.

Typical features of the pits associated with *Lichenothelia* species are the separated micro-pits created by dissolution of the rock around the funnel-shaped thallus of the fungi.

Cyanobacteria

Pleurocapsalean cyanobacteria developing on marble surfaces in Italy (probably *Myxosaracina* sp., Danin and Caneva, 1990) start the formation of pits in the following way (see figs. 7–14 in Danin and Caneva, 1990). The cyanobacteria establish themselves among the crystals and thus function as epiliths (sensu Golubic et al., 1981). Then, their physiologic activity causes the area in contact with them to dissolve. Their growth there leads to a decrease in the coherence of the crystal to the rest of the marble body. A few cyanobacteria cells grow below the crystal and lead in time to its dislodgment by raindrops associated with the imbibition of the cyanobacteria cells. As the colonization of the marble by cyanobacteria proceeds the number of crystals detached in this way increases and pits are formed, becoming deeper with time. Highly significant correlation was found between pit diameter and their depth in marble columns found in Forum Traianum in Rome (Danin and Caneva, 1990, fig. 8). Cyanobacterial growth leads to lateral and vertical weathering of the marble at a faster rate than the non-biogenic deterioration among the pits. The rate of pitting in Rome should be carefully studied. However, since the deepest pit in column No. 2557 in Forum Traianum was 2.6 mm (Danin and Caneva, 1990) and it was exposed some 100 years ago, the rate of pitting in this habitat is in the order of ca. 1 mm in 25–100 years. Pits in marble populated with cyanobacteria were observed in Forum Traianum and Forum Romanum in Rome (Danin and Caneva, 1990), in old marble quarries in Carrara, Italy (Danin and Caneva, unpublished), and in a marble monument in Didim, Turkey (Danin, 1992).

Typical features of the pits associated with pleurocapsalean cyanobacteria are their white-bleached floor with relatively wide fissures among the crystals.

Lichenized and free living cyanobacteria

The pitting by this kind of organisms was dealt with in several of our previous papers (Danin et al. 1982; Danin and Garty, 1983; Danin, 1983, 1986a, 1989; Danin and Caneva, 1990). Since the organisms that function in this ecosystem and dissolve the limestone in contact with their body at the floor of the pit are small, they form a spongy rock layer there. It is ca. 100 µm thick and unless covered by a crust of recrystallized calcite (Danin, 1986a) the spongy floor and pit walls are easy to recognize. If the crust formed under less than 100 mm annual rainfall is removed, a spongy layer with holes 5–150 µm in diameter can be observed. An early stage of the establishment of lichenized and free-living cyanobacteria that replace *Lichenothelia* and induce a faster rate of weathering is presented in Fig. 3. Mature surfaces in desert areas of Israel have an elevated light-colored level that is populated with *Lichenothelia* and a

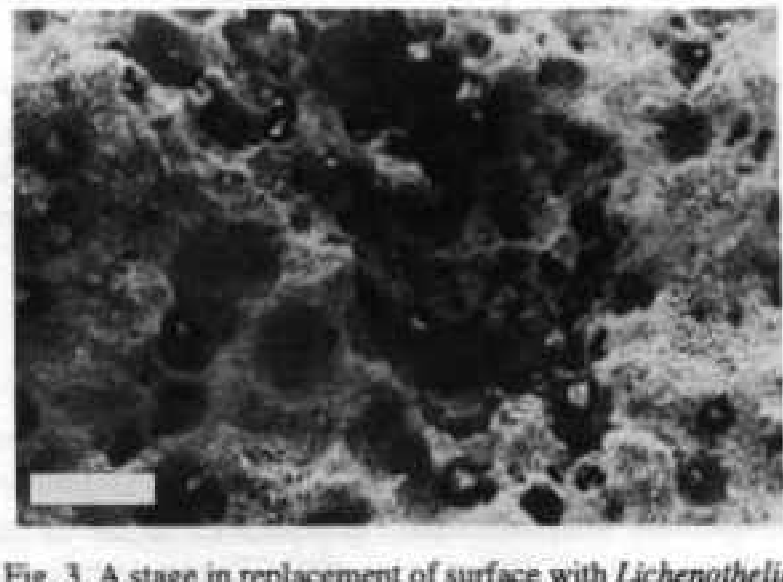

Fig. 3. A stage in replacement of surface with *Lichenothelia* by lichenized and free-living cyanobacteria. The fungal micro-pits above the bar have a floor perforated by the much smaller endolithic cyanobacteria that developed below it. The oblique depression has already a spongy floor. (Bar = 200 µm).

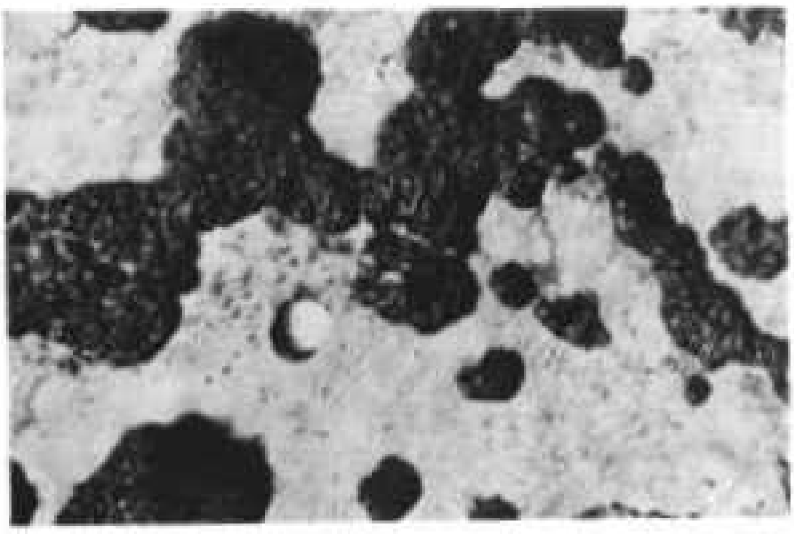

Fig. 4. Pitted limestone from near the Dead Sea. The light-colored surface is populated with *Lichenothelia*, the dark-colored pits or connected pits are populated with lichenized and free-living cyanobacteria.

lower level with pits. These pits may be connected in old surfaces or when developing along joints in the rock (Fig. 4). The pits are populated by lichenized and free-living cyanobacteria.

The rate of weathering of walls and cliffs around Jerusalem by this lithobiont community was estimated to be 1 mm in 200 years (Danin, 1983). This rate is one order of magnitude faster than that of the rough estimation of the *Lichenothelia*-induced dissolution. The difference in rates may explain the development of steep pit walls in the areas where both lithobionts coexist each in its specific microhabitat. The distribution of pits caused by these organisms was discussed already (Danin, 1986a). Generally speaking, these pits are found on inclined rocks in the deserts of Israel and Sinai, and on walls and cliffs of the Mediterranean zone of Israel. I have seen these phenomena also on limestone and marble cliffs in Crete.

Typical features of the pits associated with cyanobacteria and cyanophilous lichens are their spongy floor with holes 5–150 μm in diameter. A rather smooth crust may cover the spongy layer, which is revealed when this is removed.

Endolithic lichens

Shallow pits with a gradual transition from the pit's floor to the surrounding non-pitted surface are found on detached stones in the Negev Highlands. The pits are populated with endolithic lichens with algae of the Chlorophyceae (Krumbein, 1973; Danin and Garty, 1983) and their floor has a jigsaw puzzle-like pattern (Danin et al., 1982). The surface of the higher level of the stone is populated in most cases with *Lichenothelia* sp. Endolithic lichens of the same species as in the Negev Highlands grow on south-facing slopes of rocks or on detached stones in non-desert areas as well. Under the latter conditions they are not associated with the formation of pits.

Fig. 5. A pit formed by abrading snails (15 mm from the left margin and 57 mm from the top of the photo) within the thallus area of an endolithic lichen. (Scale in millimeters.)

A rare type of pit in rock faces that are covered by endolithic lichens in the non-desert areas of Israel was presented by Danin (1986b, figs. 5 and 6). Snails that regularly graze and thus remove the surface of the area covered by endolithic lichens, occasionally cause pits as well. Such pits are always isolated and are found in surfaces covered with the jigsaw puzzle-like pattern (Fig. 5).

Typical features of the pits associated with endolithic lichens under climatic conditions of the Negev Highlands are their gradual transition to the *Lichenothelia*-dominated surface and floor with jigsaw puzzle-like pattern or with microscopic features of lichens at the upper 100 μm layer. These features may assist in differentiating this pattern from a similar pattern formed in pitted faces that became exposed to

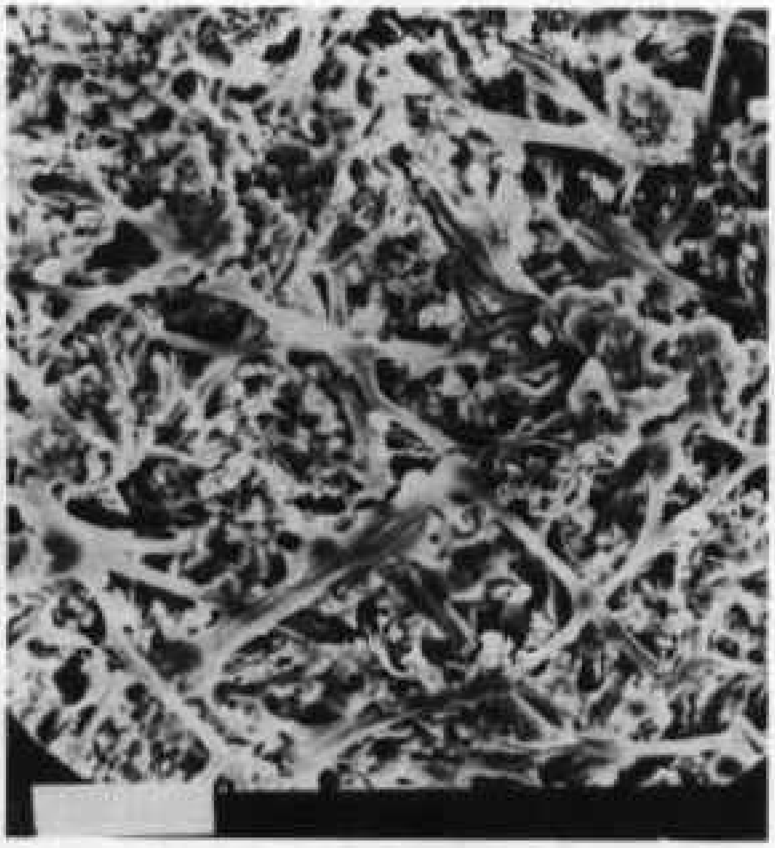

Fig. 6. Filamentous cyanobacteria and remains of the perforated rock in a pit floor from a pebble found on the beach of Lake Kinneret. (Bar = 40 μm.)

climatic conditions that enable the dominance of endolithic lichens.

Pinhead holes induced by the ascocarps of fungi of endolithic lichens occur as patches of many such holes on a flat surface or slightly below or above the area surrounding it (photos 2 and 3 in Danin and Garty, 1983; Danin 1985, fig. 2). This is known as the "foveolate" pattern (Smith 1921; Fry 1922; Danin, Gerson, and Garty 1983). The holes are 0.5–2 mm in diameter and depth, and never join together to form a pit as described above. The occasions where such groups of pinhead holes occur at a level slightly different from that of the surroundings result from the history of abrasion by grazing snails or slugs (Danin, 1986b). In cases that the specific individual lichen thallus was more tasty to grazers than the neighboring lichen thalli, its level was lowered, and vice versa. However, such grazing does not lead to the formation of pits.

PITS IN WET ENVIRONMENTS

Filamentous cyanobacteria and fresh water snails

Corrosion of limestone pebbles by boring endolithic filamentous cyanobacteria and abrasion of the corroded surfaces by gastropods are the principal components of an ecosystem which induces biogenic weathering at the littoral zone of Lake Kinneret (Danin and Dimentman, unpublished manuscript). The endolithic filamentous cyanobacteria belong to the genera: *Plectonema*, *Dalmatella*, *Hyella*, *Schizothrix*, and *Entophysalis* (det. Dr. I. Dor). They grow perpendicularly to the stone surface and bore into the upper 1–3 mm of the pebbles (Fig. 6). This corrodes the surface layer by the cyanobacterial metabolic activity. Gastropods, mainly the freshwater snail *Theodoxus jordani*, abrade the corroded pebble surface and remove stone particles and cyanobacterial filaments, thus pitting the pebble surface (Fig. 7). The growth of cyanobacteria takes place in these pits, which then become preferred microsites for the gastropods as well as for the cyanobacteria.

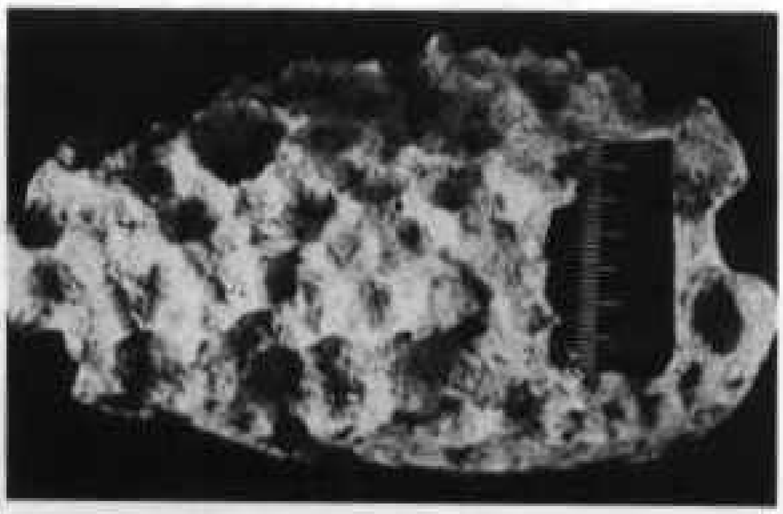

Fig. 7. A pitted pebble from the beach of Lake Kinneret. (Bar = 3 cm.)

The rate of pit formation by this feedback ecosystem, as it was studied in exposed ancient piers, is 1 mm/100 years.

A feature typical of the pits associated with endolithic filamentous boring cyanobacteria and freshwater snails is the floor of the pits microscopically perforated perpendicularly to the pit floor by the cyanobacteria. Pebbles that have undergone this pitting and have become smoothened by wave activity near the beach have shallow pits with blunt crests and endolithic cyanobacteria or remnants of their boring activity in the depressions.

Endolithic coccoid algae and land snails

An ecosystem similar to that of pebbles in Lake Kinneret, but with endolithic green and blue-green algae (cyanobacteria) and grazing-abrading snails was observed along temporary water streams on cliffs of a marble quarry in Carrara, Italy (Danin and Caneva, unpublished). Vertical lines where water streams after the rain are populated with epilithic, dark colored cyanobacteria. Pits with steep walls, 5–10 mm in diameter and depth are populated with dark-colored small land snails (*Pyramidula* sp.). The pit's floor is populated with endolithic coccoid Chlorophyceae and a few species of coccoid or pleurocapsalean cyanobacteria, including a species of *Chroococcidiopsis* (det. Dr. I. Dor). These lithobionts grow in a layer 50–200 μm deep. The floor is rather white when dry, becoming green when wetted, and contrasts in color with the dark surrounding surface. Intestinal content of the snails was not analyzed yet.

A typical feature of the pits associated with endolithic cyanobacteria, green algae, and land snails is their occurrence in vertical lines on cliffs, parallel to water streams. Fossils of the grazing snails may be found in sites with carbonate sedimentation.

DISCUSSION

Processes of limestone dissolution by water are often associated with karstic activity. In dry regions where there is not sufficient water for karstic dissolution, communities of microorganisms accelerate carbonate dissolution processes by releasing CO_2 and other compounds into the water. Thus the metabolic activity of lithobionts function as a catalyst for dissolution processes that otherwise would not proceed as fast.

Each of the 7–8 kinds of pits dealt with above develops under typical environmental conditions and by typical organisms that leave their impression in the supporting rock. When the rock or stone containing such pits is buried by natural or artificial causes, its peculiar structural features may remain in the rock for a long time. They may be used as guiding fossils, indicating the environmental conditions that prevailed when they were alive. Some of these weathering patterns were already used as indicators for climates of the past (Danin et al., 1982; Danin, 1986a). Others were used as evidence for the aeolian origin of Terra Rossa (Danin, Gerson, and Garty, 1983). Better understanding of the ecology of pit-forming organisms may assist us to preserve stone monuments or at least understand what affects them (Danin and Caneva, 1990; Danin, 1992).

The significance of pitting induced by microorganisms is displayed in the mist desert of Namibia, where rain comes in rare events and cannot be regarded as sufficient to dissolve the rock. It is through the nature of these organisms to use minute quantities of water during events of dew condensation and mist that they grow and dissolve the rock. It is here where one can separate the role of microorganisms in pitting from that of the rain. In other cases lichenized and free-living cyanobacteria decrease the coherence of rock particles and make them vulnerable to being splashed by raindrops.

Pitting is prominent where the environment and organisms induce a much faster rate of weathering than that of the regular surface processes induced by atmospheric agents (rainwater, dust, or sand abrasion). In such pits, the transition from the area populated with the pit-inducing organism to the area not populated with it is sharp and the pit walls are steep. When the pitting organisms cease, the rate of weathering of the entire rock surface becomes similar throughout, and the sharp edges of the pits become blunt (Danin et al., 1982). One can use this to estimate the relative rate of weathering by various organisms. It is clear that one of the lowest weathering rates is that induced by species of *Lichenothelia*. A faster rate is that of the endolithic lichens that cause the jigsaw pattern on detached stones in desert areas. The latter have a slower rate than that of the lichenized and free-living cyanobacteria, the pits of which have sharp edges and perpendicular walls with the inter-pit area populated with *Lichenothelia* sp.

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