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Weathering of limestone in Jerusalem by cyanobacteria

by

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with 2 figures and 3 photos

Zusammenfassung. Die Verwitterung durch Kolonien von poikilohydrischen coccoid euendolithischen Cyanobakterien an den Wänden von massiven Kalken und monolitischen Grabsteinen, bis zu 2600 Jahre alt, wird untersucht. Unmittelbar nach der Durchfeuchtung beginnen die Cyanobakterien, aktiv zu werden. Sie schwellen und geben während der Nacht CO_2 ab, was punktuell Lösung von $CaCO_3$ in der Nähe dieser Kolonien bedingen kann. Durch Auflockerung des Zusammenhangs des Mineralverbandes in der Umgebung der Kolonien beschleunigen die Cyanobakterien die Absplitterung von Gesteinspartikeln. Das bedingt eine Verwitterung mit der Geschwindigkeit von 5 µm/Jahr. Dasselbe Gestein verwittert selbst nach Hunderten von Jahren nicht, wenn es nicht von Cyanobakterien besiedelt ist. Die Verwitterungsrate kann an anderen Stellen hilfreich sein, um archäologische Lokalitäten zu datieren durch die folgende Gleichung:

$$\text{Alter der Lokalität (Jahre)} = \frac{\text{maximale Verwitterungstiefe (mm)}}{0.004825}$$

Summary. Weathering induced by colonies of poikilohydric euendolithic coccoid cyanobacteria on walls of massive limestone and monolithic tombs up to 2,600 years old is studied. After being wetted, the cyanobacteria resume activity immediately, swell and release CO_2 during the night and may cause local dissolution of $CaCO_3$ near their colonies. By decreasing the coherence of rock crystals around their colonies, the cyanobacteria accelerate detachment of rock particles, thus leading to weathering at the rate of 5 µm/yr. The same rock when not populated by cyanobacteria does not weather even after hundreds of years. This rate of weathering may be useful elsewhere for dating archaelogical sites by the following equation:

$$\text{age of site (years)} = \frac{\text{maximal weathering depth (mm)}}{0.004825}$$

Résumé. La désagrégation provoquée par des colonies de cyanobactéries coccoide euendolithiques poecilohydriques sur des parois de calcaire massif et des tombes monolithiques remontant jusqu'à 2.600 ans a été étudiée. Après avoir été humidifiées, les cyanobactéries entrent immédiatment en activité; elles gonflent et libèrent du CO_2 pendant la nuit, ce qui peut causer une dissolution locale du $CaCO_3$ autour de la colonie. En diminuant la cohérence des cristaux de la roche autour de leurs colonies, les cyanobactéries accélèrent le détachement de particules rocheuses, ce qui conduit à une désagrégation à la vitesse de 5 µm/

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an. La même roche ne se désagrège pas, même en plusieurs centaines d'années, si elle n'est pas colonisée par les cyanobactéries. Le degré d'altération peut être utile partout où des sites archéologiques doivent être datés; l'équation est la suivante:

$$\text{âge du site (années)} = \frac{\text{profondeur maximum de la zone désagrégée (mm)}}{0.004825}$$

Introduction

Weathering of limestone in the Mediterranean region is assumed to be a predominantly chemical process of dissolution by rainwater (YAALON 1959; BEN-YAIR, 1960; GERSON 1974). Biogenic weathering of massive limestone in coastal areas was studied by SCHNEIDER (1976, 1977) who found that "different microorganisms produce partly specific boring patterns". A similar kind of weathering induces by cynobacteria (= blue-green algae) and endolithic lichens should be regarded as an important factor in the decomposition and disintegration of limestone in areas far from the coast with 100 to 600 mm mean annual rainfall (DANIN et al. 1982; DANIN & GARTY 1983).

The present article deals with the process and rate of weathering induced by cyanobacteria in limestone walls and monolithic tombs, up to 2,600 years old, in Jerusalem.

Study rocks, sites and organisms

Jerusalem is about 5,000 years old (AVIGAD 1980). For more than 3,000 years (PICARD 1956) hard Turonian massive limestone rocks have been the main source of building stones. The water holding capacity of such limestone is 0.2–1.2 % (BEN-YAIR 1969 and DANIN, unpublished). The permeability is negligible (BEN-YAIR 1960). Jerusalem is situated at the divided of the Judean Mountains, 60 km east of the Mediterranean coast at elevation of 700–800 m above s. l.. Annual rainfall, measured in Jerusalem since 1846, fluctuates from 206 mm to 1,091 mm (ASHBEL 1956, and Meteorological Service of Israel). The mean annual precipitation for the entire period is 611 mm. The sliding decade average for 1888 to 1898 is 808.9 mm, whereas that of 1924 to 1934 is 435.0 mm. The mean annual number of rainy days (defined as days with over 0.1 mm) for 1950–1981 is 58. There is a small decrease in rainfall quantities within the boundaries of Jerusalem from west to east and from north to south (ASHBEL 1956). The rainstorms are predominantly with west to south-west winds. This influences the moisture regime; the west facing walls become wetted more efficiently than the east facing ones. Solar radiation has also an important impact on water regime of walls (ASHBEL 1942; HOLLAND & STEYN 1975). South-facing walls receive much higher load of solar radiation than the northern ones. As a result of the direction of rainstorms, winds and solar radiation the total time of the walls being wet, in an increasing order, is: southern, eastern, western and northern walls.

Dew is not formed on walls of houses even in nigths with heavy dew formed on other surfaces.

The mean annual temperature in Jerusalem is 17°–18 °C (Atlas of Israel 1970).

The most common organisms inhabiting the stones in west, southwest and north-facing walls are colonies of spherical cyanobacteria enveloped in a yellow-brown common sheath. These cyanobacteria are poikilohydric (Evenari 1981 = desiccation tolerants, Bewley 1979). Their principal adaptations to dry conditions were summed up by Evenari (1981). The most important property related to our study is the ability of their thallus to absorb humidity as either vapor, dew or rain. When water becomes available, they immediately resume their metabolic activity which terminates when they become dry. They can pass any number of times from the dry to the wet state and back again.

Once the cyanobacteria become wet during showers, they become active photosynthetically, in excess over respiration, consuming CO_2 during the day. During the night they release CO_2 to their wet environment. The most important environmental factor influencing the prevalence of a certain group of poikilohydric cryptogamic lithophytes is the cumulative imbition time (Danin & Garty 1983).

Cyanobacteria prevail in the driest habitats of the area of the present study. Moister habitats, such as softer stones with a higher water holding capacity, north-facing walls, horizontal faces of rocks and walls, are populated by epilithic or endolithic lichens. The typical impact of lichens on weathering has been described elsewhere (Danin et al. 1982; Danin & Garty 1983).

Methods

The stone weathering and its lithobiont plant populations were studied using dissecting microscope, transmitted light microscope and Scanning Electron Microscope (SEM) after gold coating.

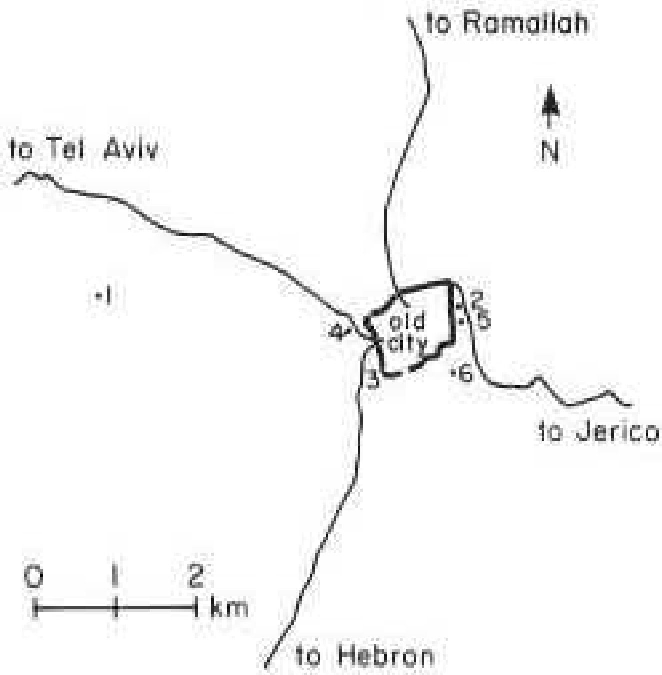

Fig. 1. Locations map in Jerusalem. 1. Beit Hakerem (a 50 years old wall). 2. Moslem cemetery (10–34 years old grave stones). 3. Walls of the Old City (erected 440 years ago). 4. Mausoleum in Mamila cemetery (693 years old mausoleum). 5. Tomb of Zachariah (ca. 2,000 years old). 6. "Tomb of Pharaoh's Daughter" (ca. 2,6000 years old).

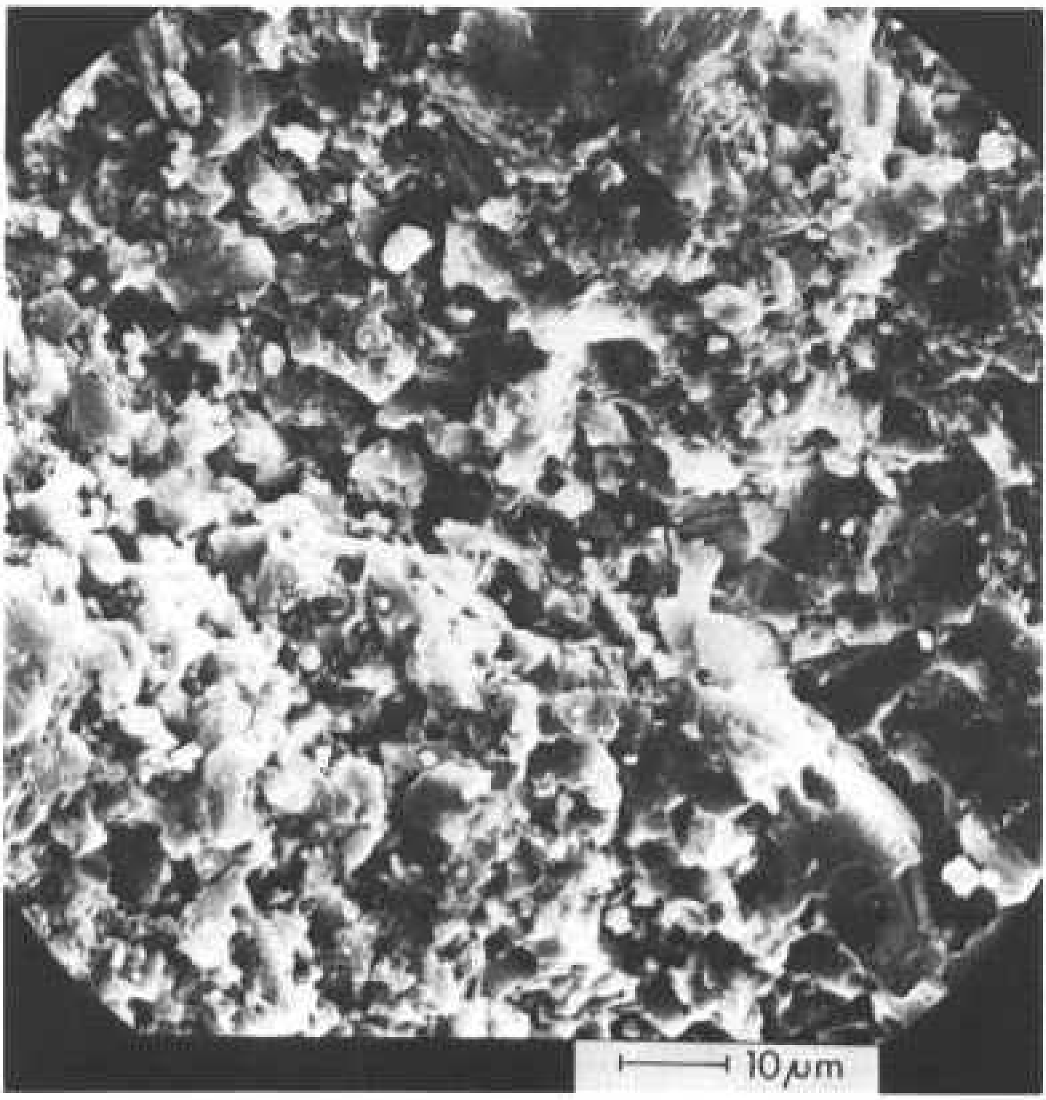

Photo 1. Scanning electron micrograph of unweathered limestone faces.

West-facing walls of houses, graves, tombs and walls of the Old City were studied. At the time all the sites were free of shading trees or higher buildings. Stones bearing marks of quarry tools or of chiselling were preferred. The maximal depth of depressions below the level of the cutting marks, which are populated with cyanobacteria, was measured.

Results

A wall of a house in Beit Hakerem, built in 1932 (No. 1 in fig. 1) is relatively densely populated by colonies concentrated in already existing micro-depressions. There is no prominent weathering resulting from the activity of cyanobacteria.

The second stage of cyanobacteria-induced weathering was hard to locate on walls 100–400 years old. Some of the dated houses are built from soft rocks, others are situated in air-polluted sections of the city or have been cleaned to restore their white colour. To complete the missing stage in the weathering of the stone, tomb-

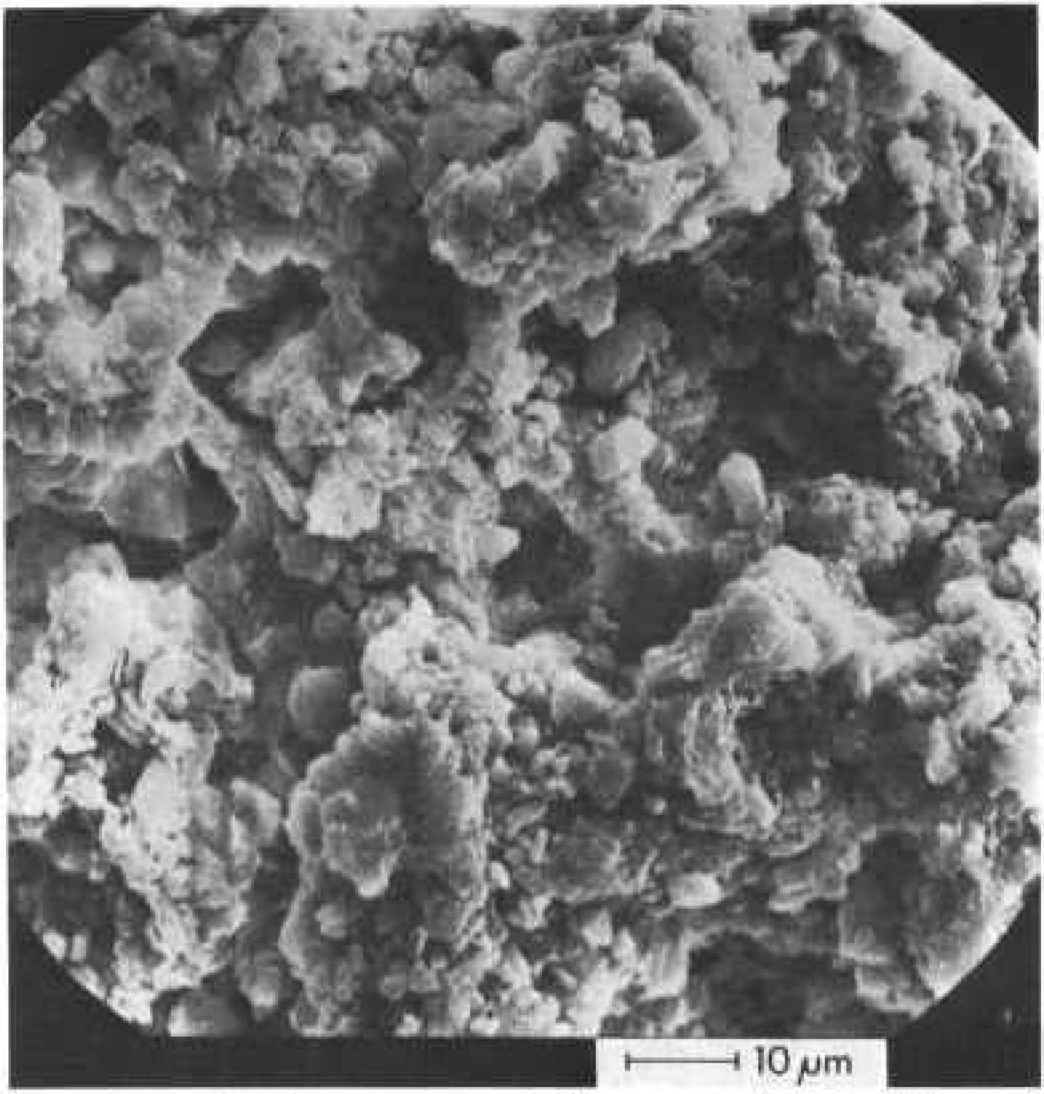

Photo 2. Scanning electron micrograph of the spongy structure of limestone surface induced by cyanobacteria.

stones at the Moslem cemeteries, along the eastern wall of the Old City (No. 2 in fig. 1), were studied. Western faces of tombstones nearly 50 cm wide, 10 cm thick, projecting more than 60 cm from the edge of the main slab of the grave were analyzed. Here, a 10 years old tombstone was already populated with colonies of cyanobacteria, mainly in the chiselling micro-depressions. In 30 and 34 years old tombstones, the rock at the micro-depressions which are populated with cyanobacteria looks spongy, as a result of weathering induces by the cyanobacteria (Photo 1 and 2). In the spongy surface, colonies occur at a maximal depth of 200 μm.

The walls of the Old City of Jerusalem were built in 1538 by sultan SULAIMAN THE MAGNIFICENT (Israel Guide 1980). The maximal depth of pits with cyanobacteria in stones between Jaffa Gate and Zion Gate (No. 3 in Fig. 1) is 2 mm. Large stones in corners of towers with south faces have no prominent weathering marks; their west faces have pits 1–2 mm deep.

The mausoleum of EMIR ADUGHDI EL KUBAKI (No. 4 in fig. 1) was built in 1289 (Israel Guide 1980). The maximal depth of pits and weathered faces below the

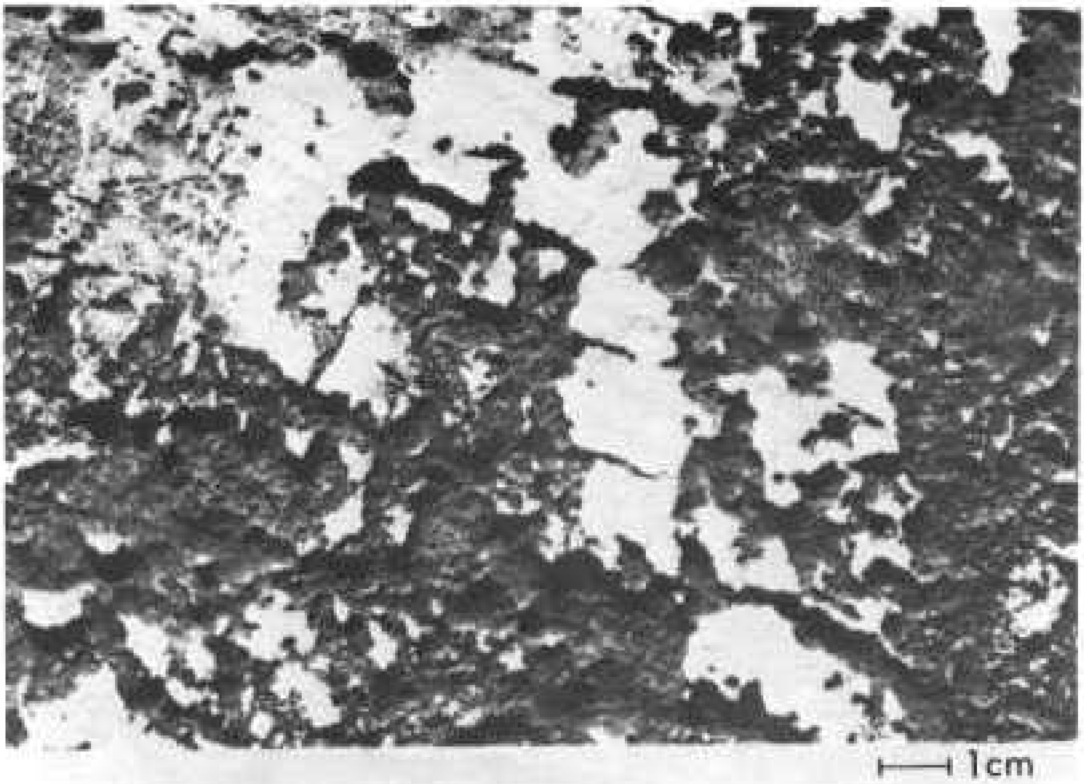

Photo 3. Pitting of a limestone wall of EMIR ADUGHDI EL KUBAKI's Mausoleum due to the acitivity of cyanobacteria. Note the chiselling marks on the white elevated faces. The black lower faces are populated by cyanobacteria.

chiselling marks on the west-south-west wall is 4 mm. All the lower faces are densely populated with cyanobacteria (photo 3). The south-south-east wall is nearly intact, there are no weathering signs and the marks of chiselling look fresh.

The "Tomb of Zachariah" in the Kidron Valley (No. 5 in fig. 1) "may be assigned to the second half of the 1st century B. C." (AVIGAD 1954). In the course of the cutting of this monument an extensive rock facing south-south-west has been formed. The entire area of this rock face is pitted as a result of cyanobacterial activity. Here and there the chisel marks may still be detected. The maximal depth of pits is 15 mm, mostly within the depressions carved by chisels over 2,000 years ago. Other deepest pits are 10 mm below the unweathered remnants of the rock faces.

The "Tomb of Pharaoh's Daughter", at the northern edge of Silwan village (6 in fig. 1), is a nearly 2,600 years old monolith (AVIGAD 1954). Here, 11 mm deep pits occur on the west and on the south facing walls of the tomb. The rock faces cut north of the tomb is not vertical here: the cyanobacteria-induces pits are 14 mm deep.

The coefficient of correlation between the depth of weathering and age of the walls or rock faces for the six samples is $r = 0.984$ ($P < 0.01$ %; fig. 2). The relevant equation is:

$$\text{Weathering depth} = 0.004825 \cdot \text{age} + 0.0678$$

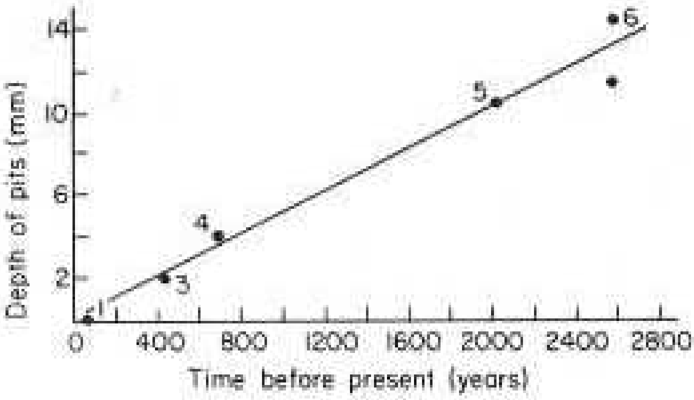

Fig. 2. Depths of pits resulting from cyanobacteria-induced weathering in comparable limestone walls of varying age in Jerusalem. Numbers of sites as in fig. 1.

Thus, the mean rate of weathering is ~ 5 microns (4.825) per year, or 1 mm in 200 years.

Discussion

The results of the present study lead to the conclusion that the "chemical weathering" of limestone described by previous authors (YAALON 1959; BEN-YAIR 1960; GERSON 1974) is, in fact, negligible. Thus, stones in walls not populated by cyanobacteria bear distinct chiselling marks; even after seven hundred years appear almost unweathered. If these faces were subjected to weathering at rates of 10 microns (YAALON 1959) or 20 microns (GERSON 1974) by rainwater, this should be clearly visible. The unweathered east- and south-facing walls of the Old City and the KUBAKI Mausoleum in the Mamila cemetery (440 and 693 years old) resemble the old unweathered east-facing hard limestones of the Great Pyramid in Egypt (EMERY 1969). These results corroborate those of SCHNEIDER (1976): "no inorganic solution of $CaCO_3$ by pool water could be demonstrated".

Stone faces populated by cyanobacteria have a constant rate of weathering. It is assumed that this rate is an important factor in the biogenic weathering of limestone rock in the entire Mediterranean region.

The processes of "chemical erosion" of beach rocks in tropical coasts, undercutting the blocks thus leading to the formation of nips (REVELLE & EMERY 1957; CLOUD 1965; NIR 1971), also seem to be relevant. They assumed that CO_2 released to intertidal basins at nigth decreases the pH, and favors solution. Precipitation of $CaCO_3$ during daytime is facilitated by warming of the water and by the concomittant decrease in CO_2 due to the excess of plant photosynthesis over respiration. Such processes were measured on the coast of Sinai, 20 km south of Elat, and subsequently simulated in the laboratory (KRUMBEIN 1979). Similar day and night processes may be presumed to take place in the proximity to the cyanobacterial colonies on walls. Night rainfall may increase dissolution of the rock near the cyanobacteria colonies. A similar process was attributed to lichen-induced chemical dissolution (SYERS & ISKANDAR 1973). In the course of time, the decomposition of the substrate near the colonies results in a "spongy" structure of the rock (photo 1 and 2). A similar pattern of spongy rock faces was attributed to the activity of endolithic algae and fungi (SCHNEIDER 1976). The cyanobacteria become contracted when dry and swell when wet. This expansion may cause some pressure on the surrounding rock particles, as described for lichen-induced weathering (FRY 1924). Subsequently, raindrops may split off rock particles which are not bound tightly to the main rock body. The continuous growth of cyanobacteria on the wall causes this weathering process to go on.

The rate of cyanobacteria-induced weathering, so closely correlated with time of exposure, may be used as a tool for dating archaeological sites: age of sites (in years) = $\frac{\text{maximal weathering depth (mm)}}{0.004825} - 0.0678$.

The weathering rate of stones or thin walls such as the 10 cm thick tombstones of the Moslem Cemetery may be faster than that of walls. This may be due to the formation of dew on this substrate, thus increasing the mean cumulative imbibition time (DANIN & GARTY 1983) available for the cryptogamic lithophytes. Their increased activity may result in a higher dissolution rate.

Conclusions

Weathering of limestone stones in walls of old buildings and cut rocks of monoliths in Jerusalem is induced by the activity of cyanobacteria. Stones 400 and 700 years old, not populated by cyanobacteria because of harsh microenvironmental conditions are not weathered. However, stones of the same parent rock populated by cyanobacteria have pits 2 mm and 4 mm deep accordingly.

The statistically significant rate of weathering of 5 microns/yr is a result of biogenic activity. Carbon dioxide released by the cyanobacteria during rainy nights cause local dissolution of $CaCO_3$ thus decreasing the coherence of rock particles which are easily dislodged from the stone surface by rain drops. The pitting of rock or stone surface by cyanobacteria create better microenvironmental conditions for these organisms which continue the corrosion of the surface mainly in the pits. In time the microelevations between the pits also become populated by cyanobacteria and the rough microtopography becomes level.

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