Origins of honeycomb weathering: The role of salts and wind

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ABSTRACT

Honeycomb weathering is a common surface phenomenon affecting a variety of rocks in a range of environments. It develops on building stones and it shapes ocean cliffs, rocks in hot deserts, and Arctic landscapes. Honeycomb weathering may also help alter rocks on other planets, such as Mars. Although first noted in the nineteenth century, its origins are still not well understood, and a dearth of laboratory experiments testing the many theories proposed for its development has added to the ambiguity. Incipient honeycomb weathering in a homogeneous limestone has been experimentally reproduced by wind exposure and salt crystallization. Our experiments show that heterogeneous wind flow over a stone surface is important in the development of this weathering pattern. Wind promotes evaporative salt growth between grains on a stone surface, resulting in the development of small, randomly distributed cavities. A reduction in air pressure within the cavities results in increased wind speed and rapid evaporation. A high evaporation rate and evaporative cooling of the saline solution in the cavity leads to more rapid and greater granular disintegration than in the surrounding areas. It seems that this local supersaturation and subsequent buildup of salt crystallization pressure ultimately result in the formation of honeycomb features. For the first time, these experimental results demonstrate the close relationship between salts, wind, and honeycomb weathering. They also offer new ways to understand the genesis of this striking and sometimes harmful weathering pattern.

INTRODUCTION

Honeycomb weathering (Fig. 1), also known as stone lattice, stone lace, and fretting (Mustoe, 1982), or alveolar weathering in the French literature (Grisez, 1960), is a common phenomenon in many rock surfaces with important implications in geomorphology, environmental geology, and stone conservation (Goudie and Viles, 1997). Frequently described in coastal areas (Trenhaile, 1987), honeycombed forms also develop in hot deserts (Blackwelder, 1929), cold deserts such as Antarctica (Prebble, 1967; Conca and Astor, 1987), and many historical buildings (Dragovich, 1978; Amoroso and Fassina, 1983). Indeed, this weathering form does not seem to be limited to Earth: a recent study (Rodriguez-Navarro, 1998) shows evidence of honeycomb weathering on Mars. Some of the best-developed terrestrial honeycomb features, however, have been noted in coastal areas (Trenhaile, 1987) in the spray zone above the level of normal wave action. These places undergo periodic heavy spray and splash during stormy weather, and hence are regularly exposed to both wind and salt deposition.

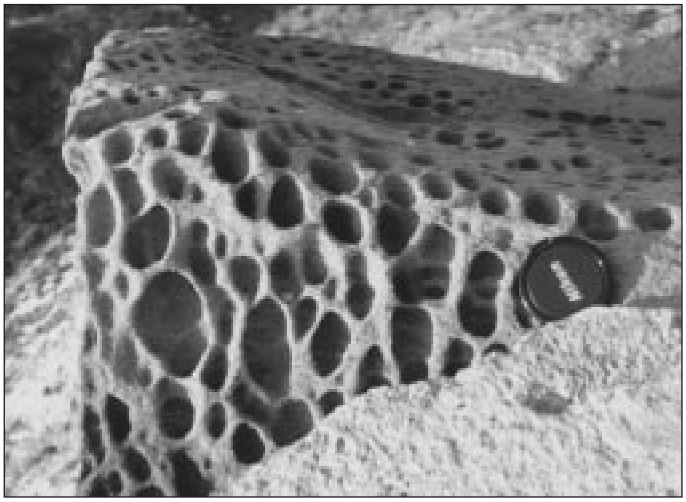

Figure 1. Honeycomb weathering developed on sandstones at Marina del Rey dock, Los Angeles, California, lat 34°3′N, long 118°15′W.

Since the first observations of honeycomb features (Darwin, 1839) many efforts have been dedicated to the analysis and understanding of the development of this weathering form. Recently, the loss of stone on historic buildings affected by honeycomb weathering has attracted the attention of both conservators and researchers seeking to understand its origins in order to develop mitigation methods. Despite these efforts, the origin of tafoni (large cavernous or alveolar weathering according to Dragovich, 1969) and honeycombs is still controversial (Smith, 1982; Goudie and Viles, 1997). The lack of laboratory experimentation has added to this situation.

Several mechanisms have been proposed to explain the origin of honeycombs, i.e., freeze-thaw (Cailleux, 1953), chemical weathering (Gill et al., 1981; Mottershead and Pye, 1994), thermal changes (Klaer, 1956), variation in moisture content in clay-rich rocks (Dragovich, 1969), wind erosion (Futterer, 1899), erosion of the core stone (or “core softening” according to Conca and Rossman, 1985), erosion of large clasts (Schattner, 1961), and salt weathering (Evans, 1970; Bradley et al., 1978; Mustoe, 1982).

In many cases, it has been very difficult to identify and isolate a single mechanism responsible for the development of honeycombs (Martini, 1978). Nevertheless, a ranking of the importance of the different decay

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mechanisms involved in the formation and development of these weathering forms has not been established.

Honeycombs and Salt Weathering

There is considerable evidence that salts are present in many cases where alveoli, honeycombs, and tafoni are formed, which suggests that these weathering forms are developed by salt weathering (Bartrum, 1936; Höllermann, 1975; Gill, 1981; Mustoe, 1982; Mottershead, 1994). Salt weathering, which has been demonstrated to be a major decay mechanism in a wide range of rock types and in many environments (Wellman and Wilson, 1965; Goudie and Viles, 1997), occurs primarily by salt crystallization (or hydration) pressure generation within the pores of a rock (Evans, 1970). At high supersaturation levels, a crystal can grow against confining pore walls, while a thin film remains between the two solids (a process closely related to diagenetic pressure solution, displacive crystal growth, and pseudomorphic replacement; Weyl, 1959). In addition, salts may also contribute to cavernous and honeycomb weathering development by inducing chemical weathering (McGreevy, 1985; Young, 1987) or by differential thermal expansion (Johannessen et al., 1982).

Wall Problem

The question of why the walls between honeycombed hollows are preferentially preserved is a key element in understanding the overall origins of honeycomb weathering.

Mustoe (1982), concluding that salt crystallization was responsible for honeycomb development on arkosic rocks in a coastal environment, proposed that the presence of organic colonies (mainly algae) acted as a protective coating and aided in the preservation of the walls. However, he considered that the organisms preferentially colonized the walls due to favorable microclimatic conditions. According to this statement, the organisms should colonize the wall after it is formed, not before.

Winkler (1994) suggested that the walls limiting the cavities of alveoli were formed by chemical deposition of different minerals. This so-called “case hardening” may explain some examples where iron oxides and secondary calcite precipitated along the pores of alveoli walls. However, in many cases no case hardening was found, and honeycombs were extensively developed (Mustoe, 1982).

Pauly (1976) observed localized wind speed fluctuations resulting in temperature and relative humidity variations in a monument where alveolar weathering developed on heterogeneous stones. In those conditions localized salt crystallization-dissolution cycling would result in the rapid development of initial cavities and the preservation of the surrounding walls. However, Pauly failed to explain why alveolar weathering is also a common phenomenon in homogeneous rocks (Mustoe, 1982). Torraca (1988) supported Pauly’s hypothesis and pointed to the effect of the acceleration of the wind in the cavities, which will result in a more rapid evaporation of the salt solution, if compared with the surrounding areas. Although a much more plausible and complete theory, these hypotheses were never supported by a successful laboratory simulation of the proposed decay mechanism.

The aim of this work is to assess whether the combined actions of wind and salt crystallization are sufficient conditions to the development of honeycomb weathering. We report results of a laboratory study that for the first time successfully reproduces incipient honeycomb weathering on homogeneous oolitic limestone. On the basis of the experimental findings we propose a general model for the development of honeycomb weathering. We stress that our model does not rule out other decay mechanisms; in particular locations, and with particular lithologies, other weathering processes may be active. We believe that the synergistic action of various decay processes in the weathering of a particular material can lead to honeycomb features. However, in this work we demonstrate that of all the possible factors, two are of key importance in the development of honeycomb weathering: salts and wind.

WEATHERING TEST

Rock Type and Properties

A fine-grained, homogeneous, buff-colored Middle Jurassic oolitic limestone (Bath stone from Monks Park, U.K.) was used in all experiments. The oolites, which compose almost 60%–70% of the rock, range in size from 300 to 600 μm, and are cemented by sparry calcite. The stone shows a high intergranular porosity, as revealed by optical microscopy and scanning electron microscopy analysis. The median pore radius is 0.25 μm, and the average porosity is 22.7% as determined by mercury intrusion porosimetry (MIP).

This stone type, commonly used for building and sculptural purposes, was chosen because it develops extensive and homogeneously distributed honeycomb weathering features in numerous monuments (Goudie and Viles, 1997), and it is microporous. The latter feature, as pointed out by Schaffer (1932), makes this stone highly susceptible to salt crystallization decay, and therefore a suitable substratum to study salt weathering phenomena.

Experimental Procedure

Homogeneous limestone blocks were cut into slabs ($25 \times 5 \times 2$ cm). Following drying in an oven to constant weight, each stone block was partially immersed in a beaker filled (to 4 cm high) with Na_2SO_4 saturated solution. The surface of the saline solution was covered with melted paraffin wax to promote the migration of the solution through the pore system of the stone, and to avoid “creeping” of the salt, as well as to minimize evaporation. Further solution was added with a syringe afterward to keep the beaker full. This experimental design simulates a very common decay process in building stone walls where saline solutions are supplied from the ground by rising damp (the wick effect, according to Goudie, 1986). Honeycomb features often developed in this situation (Pauly, 1976).

An electric fan (2 cm diameter, producing a wind flow of 6.20 m/s at 1 cm distance) was attached to the side of the beaker top edge (5 cm high and 9 cm in diameter) at an angle of 45°. The fan was placed facing one of the larger faces of the stone slab. To avoid any wind flow over the opposite face a piece of cardboard was placed in contact with the lateral sides of the stone slab. Immediately after immersion of the stone in the solution, the fan was turned on. Figure 2 illustrates the experimental setup.

To disclose the relation between wind and stone surface erosion, wind speeds were measured at different heights (interval of 1 cm) as well as at 0.3 cm and 2 cm above the surface using a TSI Model 8355 Velociclac air velocity meter. The environmental conditions in the laboratory were stable at 20 ± 2 °C and $50\% \pm 10\%$ relative humidity.

The amount of eroded stone was estimated by the material that fell off of both wind-exposed and unexposed broader surfaces. The material was weighed after extraction of salts by repeated immersion in distilled water and drying for 24 h at 110 °C. Scales formed on stone surfaces were examined by means of an environmental scanning electron microscope (ESEM, ElectroScan Model E-3) to observe salt growth in the pore system of the stone and to assess if chemical weathering occurred. The ESEM is especially useful in the study of salt decay problems because it allows direct observation of uncoated samples at high magnification, and it does not modify the salt state (a critical factor when hydrates are involved) (Doehne, 1994).

RESULTS

In the beginning stages of the experiment, the saline solution rose through the capillary system of the stone, leading to the evaporation of water and subsequent precipitation of mirabilite ($Na_2SO_4 \cdot 10H_2O$). Eventually, mirabilite dehydrated to form thenardite (Na_2SO_4).

Six days after the start of the experiment, a large quantity of salt efflorescence developed on the face protected from wind flow (Fig. 3A). No granular disintegration or scales developed on this face.

Efflorescence growth did not take place on the face exposed to the fan. However, stone flaking and granular disintegration occurred at different locations (close to the fan), and incipient (0.5 mm diameter) cavities were noted (Fig. 3B).

Significant changes occurred 24 days after the start of the experiment. Cavities (~1.5 cm diameter; ~0.5 cm depth) limited by well developed walls were evident on the face exposed to the fan (Fig. 3C). Only minor efflorescence growth was visible on the bottoms of the cavities facing the wind. Granular disintegration produced a significant accumulation of stone particles at the bottom of the slab face. No cavities developed on the wind-protected face where significant efflorescence growth occurred.

The experiment was terminated after 38 days. Figure 4A shows initial honeycomb weathering on the fan-exposed face at the end of the experiment. Maximum damage due to alveolar weathering takes place where the wind speed at 0.3 cm above the stone surface reaches a maximum (Fig. 4B). Minimum wind speed was measured at 2 cm above the same area. This indicates heterogeneous (turbulent) air flow over the stone surface where honeycombs developed. The amount of stone material lost off the wind-exposed surface was 30% (by weight) higher than that lost off the shielded face.

ESEM analysis of scales that fell off the stone face exposed to the wind identified dehydrated mirabilite and some small, anhedral crystals of thenardite (see Rodriguez-Navarro and Doehne, 1999). Crystals grew in the oolitic matrix, specifically in the interface between oolites and the sparitic cement. Anhedral salt crystals mechanically separated oolite grains, thereby generating and propagating fractures along the sparitic cement (Fig. 5A). No chemical attack or etching of the calcite grains was observed using ESEM. Mirabilite whisker-like crystals were found on the bottom of the stone face protected from the wind (Fig. 5B).

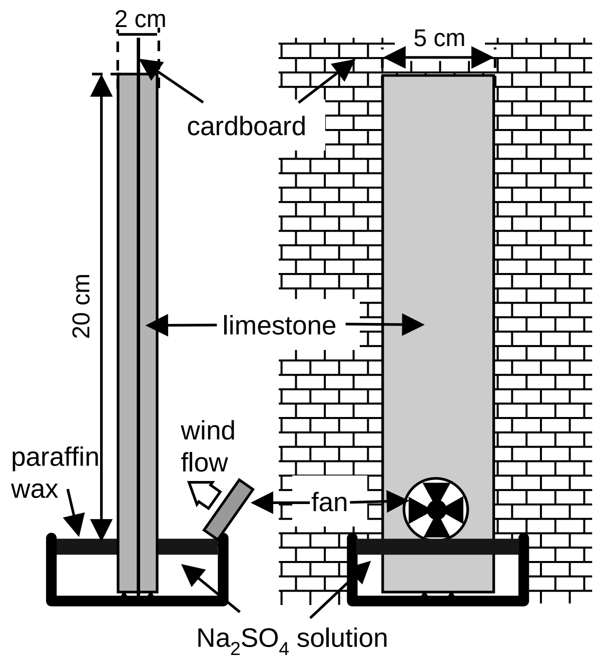

Figure 2. Lateral (left) and frontal (right) view of the salt decay test experimental design.

DISCUSSION

Experimental data show a clear correlation between incipient honeycomb formation and the crystallization of salt under windy conditions. Maximum erosion occurs where wind speed reaches a maximum on the stone surface.

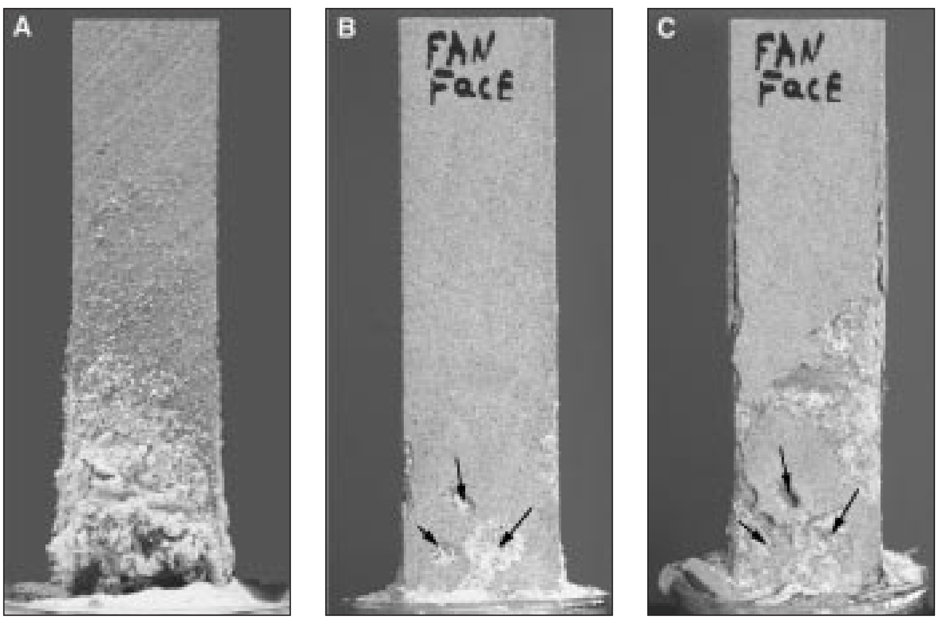

Figure 3. (A) Massive salt efflorescence growth on the non–wind-exposed face six days after the start of the experiment. (B, C) Incipient alveoles (arrows) formation on the wind-exposed face of oolitic limestone slabs after 6 (left) and 28 (right) days. Samples tested in the laboratory at Getty Conservation Institute, Los Angeles, California.

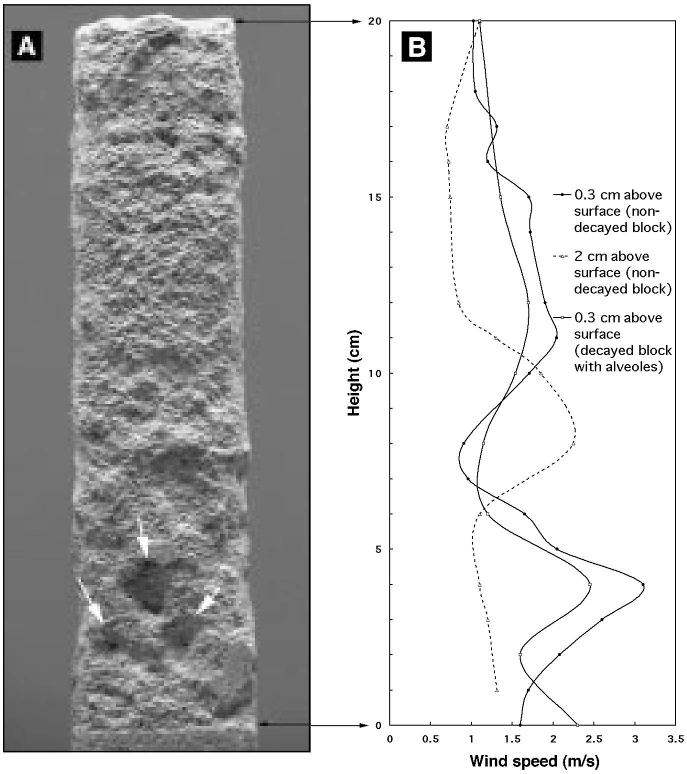

Figure 4. (A) Final appearance of the wind-exposed surface after decay test completion, correlated with (B) wind speed measured 0.3 cm (solid lines) and 2 cm (dotted line) from the surface. Note that maximum wind speed at the surface corresponds with maximum decay and alveoles (arrows) development on the bottom part of the stone block.

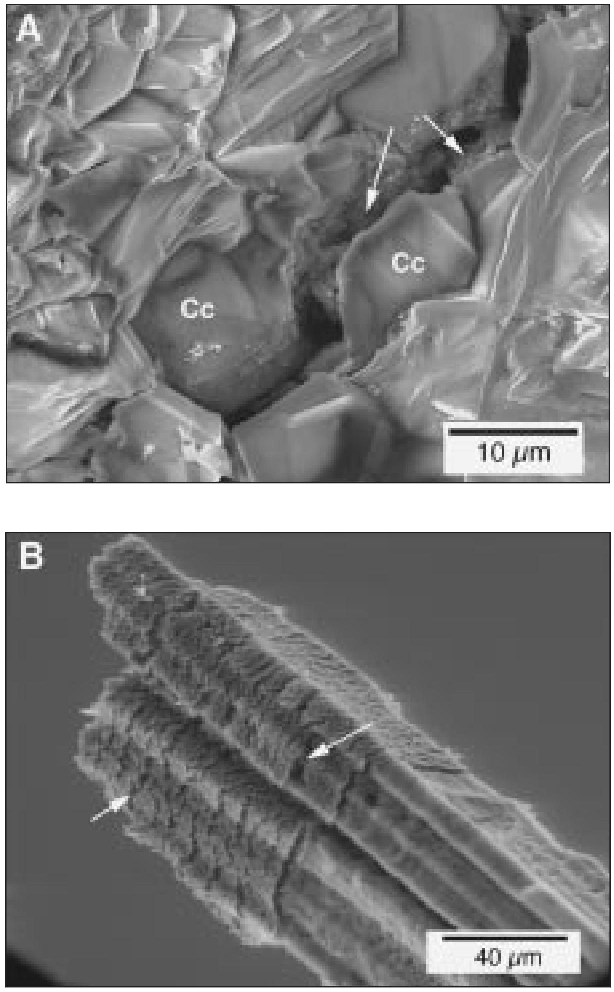

Figure 5. Mirabilite crystals developed: (A) generating fractures within the sparitic calcite cement (Cc) of the limestone on the wind-exposed face and transformed to thenardite (arrows) through a dehydration process occurring after mirabilite crystallization and growth; and (B) mirabilite efflorescence (whiskers) on the nonexposed face (arrows indicate incipient dehydration areas).

The style of erosion results in the formation of adjacent cavities (i.e., honeycombs). Conversely, efflorescence growth and little stone erosion occur in the sheltered face, where no cavities are formed.

Apparently, wind-enhanced evaporation of the saline solution induces the formation of subefflorescence, resulting in granular disintegration and, eventually, in honeycomb formation. Lewin (1982) proposed a model to understand why salt crystallization occurs either as destructive subefflorescence or as almost nondestructive efflorescence. He observed that as a saline solution migrates through the pore system of a stone by means of capillary forces, there is a point where evaporation from the liquid boundary occurs, followed by the saturation of the solution and the crystallization of the salt. If the supply of solution is more rapid than the evaporation rate, salts will precipitate outside the pores, on the stone surface (i.e., efflorescence). On the contrary, if the rate of replenishment of salt solution is slower than the rate of evaporation, the salt solution will evaporate and will reach supersaturation inside the pore system at some depth from the surface, and crystallization will take place below the stone surface (i.e., subefflorescence). The resulting crystallization pressure could damage the stone and produce material loss.

Under windy conditions, evaporation of water from a porous stone is promoted deep under the stone surface, as demonstrated in a similar porous limestone by Mossotti and Castainer (1990) using computer-aided tomography (CAT scan). If wind is blowing over a rough surface or a cavity, a decrease of pressure in the air takes place below the surface level (aerodynamic effect; Quayle, 1992), resulting in an increase of wind speed. The acceleration of wind speed results in increased evaporation (Bird et al., 1960).

Therefore, under windy conditions rapid evaporation of the saline solution will promote salt precipitation below the surface of the stone. As salt precipitation occurs, small holes will be randomly created on the stone surface. These heterogeneities will promote local acceleration of the wind into the hole and more rapid evaporation. Rapid evaporation will lead to high solution supersaturation ratios below the bottom of the cavity, thus concentrating the salt damage process in this location because salt crystallization pressure, and therefore damage, is proportional to the supersaturation ratio reached before crystallization begins (Correns, 1949; Winkler and Singer, 1972). The crystallization of salts will increase the porosity in the bottom of the initial cavity through the creation of microfractures, thus allowing saline solution to be readily available for successive crystallization (and damage) events that will deepen the initial cavity (i.e., self-propagating weathering processes; Dorn, 1995). In addition, more rapid evaporation in the cavities (if compared with the surrounding areas) will lead to evaporative cooling, which may contribute to rapid supersaturation of saline solutions with strongly temperature-dependent solubilities. This is the case for sodium sulfate, which has a solubility in water of 4.76 wt% at 19 °C and 33.40 wt% at 25 °C (data from Goudie, 1977).

The question why walls between cavities prevail remains unanswered. The oolitic limestone used in this work is homogeneous, thus any particular orientation, heterogeneity, or other characteristic of the stone should have little influence on the development of walls. However, as loss of material results in the formation of a small cavity, turbulent air flow results in the surrounding area. Turbulence will promote rapid evaporation of the saline solution in specific areas, leading to the formation of adjacent cavities. Between each cavity, a portion of material will stand where little or no salt solution ever arrives, because it will be preferentially suctioned to areas of rapid evaporation (Mossotti and Castainer, 1990); i.e., the cavity bottom. The final effect is the preservation of the walls between nearby cavities, where little or no salt crystallization (as efflorescence) and salt-related damage occurs.

Our model for honeycomb formation assumes that the supply of solution is slower than the overall evaporation rate and that supersaturation is reached only in the bottom of the cavities and not within the walls. The latter assumption agrees with independent observations by Heckmann et al. (1994), who found more rapid evaporation at the bottom of cavities in honeycomb features developed on sandstones, where a majority of crystallization occurred.

This theory for honeycomb formation also agrees with data from Höllermann (1975) and Bradley et al. (1978), who reported that tafoni and honeycomb features showed peak concentration of salts inside the cavities, where most of the erosion took place.

In agreement with Mustoe (1982) and many observations (e.g., Cooke et al., 1993), the salt weathering process resulting in incipient honeycombs does not produce any kind of chemical weathering in the limestone tested. ESEM analysis of calcite grains in contact with mirabilite crystals show no etching or corrosion pits on the carbonate crystals. We saw only crack development and grain disintegration. Salt damage in porous material is generally recognized to be mainly a physical weathering mechanism (Evans, 1970; Rodriguez-Navarro et al., 1996). In addition, salt crystal morphologies in the stone pores on the wind-exposed face are nonequilibrium, anhedral forms, while euhedral or whisker-like crystals are observed on the surface of the sheltered stone face. According to Sunagawa (1981), nonequilibrium forms result from crystallization under high supersaturation ratios, while euhedral or whisker-like salts are reported to form at low supersaturation ratios (Zehnder and Arnold, 1989; Rodriguez-Navarro and Doehne, 1999). The salt morphologies (nonequilibrium crystal habits) observed in the cavities confirm that very high supersaturation ratios were reached, resulting in a local concentration of the salt damage (Rodriguez-Navarro and Doehne, 1999).

CONCLUSIONS

For the first time, honeycomb weathering has been experimentally reproduced in a homogeneous stone. Wind-enhanced evaporation of a saline solution initially results in the random development of small cavities. Later, heterogeneous wind flow induces more rapid evaporation within the initial cavities, resulting in their deepening due to localized supersaturation and salt crystallization. Chemical weathering of the calcite grains is not observed. It is concluded that all damage is due to the physical action of salt crystallization.

The proposed model may help to put into perspective past studies on the origin of honeycombs and, we hope, it may help future geologists (and geomorphologists) in interpreting new occurrences. In addition, the knowledge acquired on the role of wind and salts in the origin of honeycombs may help to design and implement preservation measures in the field of building stone, and rock-art conservation to slow the progress of such weathering forms (e.g., wind deflectors or rows of trees). Nevertheless, there are several questions that are unresolved, such as understanding what controls the scale of honeycomb features.

Future work should address the influence of wind variability, stone type and homogeneity, salt composition, and humidity cycling on honeycomb weathering. Long term field testing and monitoring would also be beneficial in interpreting these features (perhaps using field web-cams [automatic cameras connected to a computer via the World Wide Web]). Future computer modeling of these phenomena could also offer new insights into these intriguing processes.

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