WEATHERING AND COLONIZATION OF LIMESTONES IN AN URBAN ENVIRONMENT

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Weathering is the breakdown and alteration of material near the earth's surface to products that are more in equilibrium with newly imposed physico-chemical conditions. May rocks were originally formed at high temperature, high pressure and in the absence of air and water, and a large part of weathering is a response to low temperatures, low pressures and the presence of air and water /Ollier 1975/. Weathering of the initial materials precedes soil formation in hard rocks and accompanies it in soft rocks and soil materials. It is a continuous reaction during soil development, to the point where no more reactants are available.

The weathering of rocks and minerals is largely controlled by organisms, mainly bacteria, fungi, algae, lichens, plants and soil fauna. It has been reported that a soil starts to form from the moment organisms colonize the bare surface of rocks. At the earliest stages of soil formation the destruction and alteration of primary minerals and the formation of secondary minerals occur /Parfenova and Yarilova 1975/. While the role of algae, mosses and lichens in soil formation mainly consists of creating reserves of organic matter, the function of microorganisms is also important since they destroy the organic matter and participate in the synthesis of humus. In the processes of destruction of plant residues a predominant part is played by bacteria, fungi and actinomycetes.

In this paper the weathering and colonization of the limestones from the belfry of the Giralda tower are reported. The stone monuments are ideal locations for studying these
processes since, unlike the situation in the soil, the influence of single organisms on any one stone can easily be investigated.

RESULTS AND DISCUSSION

In the early phases of rock breakdown, physical weathering through frost, crystal growth, insolation, moisture swelling or abrasion causes a variety of changes such as cracking, expansion or shrinkage, disintegration or erosion. Further, chemical weathering by solution, carbonation, hydration, oxidation and reduction or hydrolysis can accomplish abiotic weathering.

Limestone is the only common rock in which the solution plays a major part. In natural environments, carbon dioxide may be an important factor in the process, however, in urban and industrial areas the air pollutants of concern in the solution of limestone are acidic oxides (carbon dioxide, sulphur dioxide and nitrogen oxides) produced by the combustion of fuels.

The atmosphere of Seville is moderately polluted with a mean annual sulphur dioxide level of about 90 μg/m³, whereas natural background sulphur dioxide levels are probably in the range of 0.3 to 3 μg/m³, therefore, atmospheric pollution adds a new factor to weathering of stones in urban environments.

The most aggressive agent is sulphuric acid that results from the dissolution and catalytic oxidation of sulphur dioxide in atmospheric water that is in contact with the stone. Acidic rain leaches out the calcareous matrix as well, causing it to crumble away, generating channels and cracks. The water dissolves and brings with it salts in solution to the interior of the stone. When a stone has imbibed water in which there are appreciable amounts of crystallizable solids in the solution, the drying-out of the stone results in the formation and growth of crystals at the surface. This enriches the substrate and creates favourable niches for biological colonization.

In the limestone that was studied, the first colonizers may be either algae or autotrophic bacteria. Ephemeral crusts of algae develop rapidly on the surface during brief periods of wetness. In sheltered sites, holes and crevices, water may
be retained longer, favouring the growth over a long period of time.

Phosphorus and nitrogen are most frequently cited as the main elements whose addition will stimulate increased growth of algae in soil. Certain soil algae may be nitrophilous, but factors such as pH and total salt content are likely to be responsible for their pattern of distribution /Lund 1972/. In our case, phosphorus, nitrogen and calcium are supplied by bird droppings since the belfry is a pigeon perch site.

Algal species on sheltered limestone sites consist of long olive-green to brown filaments covering the substrate. These were observed to be either free living /Fig. 1/ or in close relation to moss plants. The free living algae expand over the surface and form a hard crust that is constituted by the algal mucilage cementing sand particles and soot together at the surface. This results in the substrate exhibiting a longer retention time for moisture during the dry periods. Diatoms which are the most widespread of all algae and common from the surface of soils and wet rocks were also found.

In the initial stages of colonization of bare rocks, algae are the first humus formers and their organic matter serves as the primer for the development of other colonizers /Shtina 1968/. The living matter that accumulates rapidly under favourable conditions and the cells of algae that die become a nutrient source for heterotrophic microorganisms. Many bacteria and fungi presumably derive much of their carbon from organic substances of which algal products may form an appreciable proportion. Thus, the growth of algae is always accompanied by intensified microbiological activity of the substrate. In fact, in nature, algae always grow in association with other organisms, since axenic cultures do not exist under natural conditions. In the vicinity of algae, bacteria, fungi, mosses, ferns and higher plants often occur, and compete for available nutrients and thus indirectly may retard the growth of the algae present. However, algae flourish particularly well under conditions in which higher plants are sparse or absent.

It is noteworthy to find in limestone a close relationship between algae and mosses. Filamentous blue-green algae growing
in association with mosses is a commonly observed phenomenon on inhospitable lava sand and this association can explain the very early colonization and rapid distribution of moss plants on volcanic rocks /Henriksson and Rodgers 1978/.

Although no attempt has been made to study bacteria and fungi living on limestone, evidence of their activities was found. Figure 2 shows a hairy-spored streptomycete observed during the examination of the limestone surfaces. On the basis of the flexibility of the spore chains and the appearance of the spores, the *Streptomyces* species belong to the subgroup A of Dietz and Mathews /1972/ characterized by spores with large numbers of long hairs, generally joined together to form tightly coiled spiral chains. Representative cultures of the subgroup are *S. glaucus* and *S. pactum*.

The presence of actinomycetes, which colonize new substrates slower than bacteria and fungi and follow them in microbial succession would, in all probability, indicate a secondary colonization. Actinomycetes often seem to need previous fungal growth either to ameliorate the environment by altering its pH or to provide a suitable substrate with its hyphae /Lacey 1973/.

In certain sites, the surface of the stones was covered by a velvety, pink layer of fungal structures. The morphological study of conidia and mycelia revealed them to be *Trichothecium roseum* /pers./ Link ex S.F. Gray. This fungus has a world-wide distribution, is usually a saprophyte on decaying vegetable matter and has also been recorded on soil /Rifai and Cooke 1966/. Figure 3 shows a characteristic picture of *T. roseum* on limestone.

There are many other microorganisms living on limestone, but these two examples illustrate the diversity of the microbial flora. In this connection Webley et al. /1963/ reported that with increasing weathering and colonization of rocks, greater numbers of microorganisms are encountered, the highest numbers being found in the "raw" soil in rock crevices.

Organic matter synthesized and transformed by microorganisms tends to accumulate in crevices where dust and particulate matter is deposited by the wind, thus forming a shallow or
primitive "soil". These sites were colonized by the moss *Tortula muralis* /L./ Hedw. It was found that a network of rhizoids penetrate the limestone, probably through pores and microfissures /Fig. 4/.

A diversity of material accumulates underneath the moss forming a black layer varying from 1 to 10 mm. The layer consists of stem and rhizoids between which decaying organic matter, microorganisms, quartz grains of various sizes and air-borne carbonaceous particles were found. Humic acids could be extracted with a sodium pyrophosphate-sodium hydroxide solution, demonstrating that humification of the organic matter occurred.

Mosses with their delicate and uncuticularized plant bodies seem to have a great capacity for absorbing and accumulating polluting substances from the environment. It has been reported by LeBlanc and Rao that the different species of lichens and bryophytes show a considerable variation in their susceptibility to injury by air pollution, especially sulphur dioxide. Characteristically, few species can thrive in polluted areas, however, some manage to survive even under conditions of relatively high levels of pollution. Such species are toxitolerant and take advantage of the reduced competition. *T. muralis* is considered to be toxitolerant and obviously would be a pioneer colonizer of a variety of polluted habitats which may be inhospitable to other species.

The shady environment of mosses is not suitable for lichens, which tend to disintegrate under high humidity and low light conditions. Lichens occur on exposed limestone surfaces, where the supplies of water and nutrients are sporadic and, consequently, they may have to withstand periods of desiccation during the summer, when no water is available either as rain or fog. The distribution of species is not very homogeneous, due to environmental gradients which favour dispersion. Different distribution of nutrients and minerals also plays an important role in lichen colonization. Lichen establishment was encouraged by pigeon droppings, widely distributed all over the monument. In this connection the lichens are considered as ornithocoprophilous.
The most abundant lichen species was *Lecania erysibe* /Arch./ Mudd, followed by *Caloplaca decipiens* /Arn./ Jatta, *Xanthoria parietina* /L./ Betr., *Lecanora albescens* /Hoffm./ Floerke, *Candelariella medians* /Nyl./ A.L. Sm, *Lecanora dispersa* /Pers./ Rohl., *Phaeophyscia orbicularis* /Neck./ Poetsch, *Caloplaca flavovirescens* /Wulf/ DT and Sarnth., *Caloplaca dolomitica* /Hue/ Zahlbr. and *Lecanora muralis* /Scherb./ Rabenh. The community is a *Caloplacion decipientis* Klem. near to *Caloplacetum murorum* /DR./ Kaiser. The association occurs on a soft, decayed calcareous substrate enriched by bird droppings, and is very nitrophilous, photophilous, xerophilous and sulphur dioxide-air pollution tolerant /Sáiz-Jiménez 1981/.

Air pollution is the most important environmental factor in determining whether lichens will survive or perish in urban environments. Since lichens are slow-growing and long-living organisms with a special ability to accumulate substances from their environment, they are susceptible to many pollutants present in the atmosphere or brought down in the rain. However, the high pH of limestones provides a buffering effect on the toxicity of the urban environment /Seaward 1975/. Thus, behaviour of lichens in polluted areas is to some extent governed by the nature of the substrate.

The lichens cause stone weathering mainly through changes in volume during wet and dry periods and excretion of organic acids. It has been observed that hyphae of *Lecania erysibe* are involved in the disintegration and decomposition of stone, either through contraction which creates a pulling strain during dry periods or through dissolution by excreted lichen acids. Figure 5 shows a section of the lichen, demonstrating that the hyphae were attached directly to the limestone. Removal of the lichen also detaches a thin film of about 1-2 mm of substrate. The figure also displays a diatom frustule. Since diatomaceous algae are common on the surface of wet rocks and little growth occurs in the absence of light, the frustule found underneath the lichen would represent a primary colonizer. Similarly, it has been reported that the fine earth in moss mats, growing on rocks, contain many siliceous skeletons of diatoms /Parfenova and Yarilova 1975/.
The classic concept of the role of lichens in plant succession states that the colonization of bare rock surfaces begins with crustose species which are replaced by foliose species and/or by mosses /Syers and Iskandar 1973/. However, there is little evidence that they initiate a succession leading to vascular plants, and many successions do not involve lichens to any significant extent. In the limestone that was studied it appears that the lichen community does not develop further and it is the chomophytic community of mosses, exploiting crevices and the wind-blown material and organic matter which accumulates in them, the most important factors in a primitive "soil" formation. These sites are then invaded by vascular plants, such as Erodium malacoides /L./ L’Her., Hyoscyamus albus L., Misopates orontium /L./ Rafin. and Kickxia spuria /L./ Dumort.

Fig. 1. Scanning electron micrograph of algal filaments covering the limestone and cementing sand particles and soot. x 1000
Fig. 2. Scanning electron micrograph of coiled spiral spore chains from *Streptomyces* sp. on limestone. x 3000

Fig. 3. Scanning electron micrograph of *Trichothecium roseum* conidiophores on limestone. x 700
Fig. 4. Scanning electron micrograph of rhizoids from *Tortula muralis* penetrating limestone. x 150

Fig. 5. Scanning electron micrograph of hyphae from *Lecania erysibe* covered by slimy material and attached to limestone. A diatom frustule is also present. x 4000
SUMMARY

In the urban environment of Seville, soft, porous limestones from the Giralda tower are weathered by abiotic and biotic agents, mainly atmospheric pollutants and lichens. The most aggressive agent is sulphuric acid that results from the dissolution and catalytic oxidation of sulphur dioxide in the atmospheric water that is contact with the stone. Rain leaches out the calcareous matrix, causing it to crumble away, generating channels and cracks.

Colonization of weathered limestones is encouraged by bird droppings, which together with algae and microorganisms may provide an organic matter source. Organic matter tends to accumulate in crevices where dust and airborne carbonaceous particles are also deposited by the wind, thus forming a shallow or primitive "soil" colonized by the moss Tortula muralis.

Lichens occur on exposed limestone surfaces causing disintegration and decomposition of stones. The most abundant species was Lecania erysibe, followed by Caloplaca decipiens, Xanthoria parietina, Lecanora albescens, Candelariella medians, Lecanora dispersa, Phaeophyscia orbicularis, Caloplaca flavovirescens, Caloplaca dolomiticola and Lecanora muralis. The lichen community does not develop further and it is the chemo-phytic community of mosses which initiates a succession leading to vascular plants, such as Erodium malacoides, Hyoscyamus albus, Misopates orontium and Kickxia spuria.

REFERENCES