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Biotic weathering of rocks by lichens in Antarctica

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Abstract Weathering process of rocks in Antarctica can be accelerated by the colonization of lichens, which dominate surface vegetation and endolithic communities respectively in the maritime Antarctic and in Antarctic cold deserts. The effects of lichens on their substrate rocks can be attributed to both physical and chemical causes. As the result of the weathering induced by lichens, the surface corrosion and exfoliation of colonized rocks occur. The mobilization of iron in the rock-forming minerals and the precipitation of poorly ordered iron oxides are investigated. Furthermore, the neoformation of crystalline metal oxalates and secondary clay minerals are identified in the colonized rocks. Due to unique climatic conditions, the biotic weathering process of rocks in Antarctica somewhat differs from that of other regions of the world.
Key words Antarctica, lichens, weathering, epilithic, endolithic.

1 Introduction

As the earliest colonizers of terrestrial habitats on the earth, the occurrence of lichens may be dated from the Early Devonian (Taylor *et al*. 1995). At present, it is estimated that around 8% of the terrestrial surface of the earth is covered by the lichen-dominated vegetation (Larson 1987). The lichens occupying substrate rocks generally known as saxicolous species, can be divided into three distinct group: crustose, foliose and fructicose (Jones and Wilson 1985; Carcia-Rowe and Saiz-Jimenez 1991). 75% of the approximately 15000 species of lichens belong to crustose. In the terms of the modes of attachment to the substrate rocks, lichens can be divided into epilithic (living on the surface of the rock) and endolithic (living in the interior of the rock) types (Golubic *et al*. 1981; Ahmadjian 1993; Bell 1993).

Lichens have long been renowned as pioneer colonizers of fresh substrate rocks in polar and alpine regions (Walton 1990). In Antarctica, lichen is the major component of the lower plant vegetation, and totally 340 - 400 species have been reported, some of which have been investigated even in the southernmost regions of Antarctica (86°06′S) (Larson 1987; Chen and Gong 1995). The lichen-formed oasises are found in the maritime Antarctic and the coastal areas of the continental Antarctica due to the relative warmer temperature and higher precipitation than on the continent. In these regions, the species are much more abundant and dominated by the epilithic communities of crustose and fructicose cryptogams. Whereas in the harsh climate of the continental Antarctica, the lichens are always associated with endolithic communities, which typically inhabit protective pores a few millimeters below the surface of rocks where are enough sunlight, nutrients, moisture, and thermal stability to sustain life (Mckay and Friedmann, 1985). According to Friedmann (1985), these endolithic lichens do not have their own shapes and forms, but in order to get into the safe protected depths of the rocks they give up their own shapes and grow in the available spaces within the rocks (Friedmann 1985).

The phenomena that lichens affect their substrate rocks have long been recognized and the role of lichens as biochemical weathering agents has been receiving special interest (Seaward 1997; Silva *et al.* 1997). As a substrate, undoubtedly rock is far more stable than other habitat environments such as treebark and soil, and lichen communities have a much better opportunity to develop to maturity over long periods. For example, a study has indicated that some communities of crustose and fructicose lichens have lasted for a period of one or more thousands years and, individually, an Usnea-thallus may reach 600 a in age in the maritime Antarctic (Lindsay 1977; Hooker 1980). The interface between lichen and rock is known to be a place of considerable physical and chemical activities, presenting a complicated heterogeneity in which primary and secondary minerals, organic acids and compounds, and living organisms involved (Jones and Wilson 1985; Wierzchos and Ascaso 1994, 1996). Therefore, the investigation of the interface has been of interest for many years. As a result, a vast amount of observational evidence of the lichen-rock interface showing the interaction between lichen thallus and mineral surface is accumulated in the field studies (Jones and Wilson 1985; Ascaso *et al.* 1995; Wilson, 1995). At the same time, a large number of laboratory studies assosiated with the weathering of rocks and minerals induced by lichens and lichen compounds have been conducted, and the experimental data obtained soundly support the observational evidence related to the weathering actions of lichens (e. g. Schatz 1963a,b; Iskandar and Syers 1971; Williams and Rudolph 1974; Eckhardt 1985).

Although the weathering ability of lichens started to attract attention nearly one century ago, it is only in the recent three decades when some attempts have been made to evaluate the contributions of lichens to the weathering process in Antarctica. As far as the authors are aware, the lichen communities to which most investigations have been detailedly made are the endolithic communities inhabiting the Beacon Sandstone in the Antarctic cold desert (e. g. the Ross Desert) (Vestal 1988). However, observable effects of epilithic lichens on the weathering process of various rocks have also been reported from regions including the maritime Antarctic (Campbell and Claridge 1987; Ascaso *et al.* 1990; Chen and Gong 1995).

2 Mechanisms of biotic weathering

Lichens can play an important role in both processes of physical and chemical weathering of rocks and mineral materials. In general, the physical weathering of rocks induced by lichens proceeds by the mechanisms including: (1) the penetration of hyphae through intergranular voids and mineral cleavage planes; (2) expansion and contraction of thallus by microclimatic wetting and drying; (3) freezing and thawing of lichen thallus and associated microenvironment; (4) swelling action of organic and inorganic salts originating from lichen activity; and (5) incorporation of mineral fragments into thallus. In some cases, if not many, the mechanical action of lichens on their mineral substrate dominates the bio-weathering process, especially in the early stages of colonization.

According to Duchafour (1979), all chemical weathering processes occurring in rock could be grouped into two types, one is geochemical weathering which is most completely expressed in a tropical climate and occurs in freely drained conditions in the absence of organic acid anions. Another is biochemical weathering, which is typical of humid temperature climates and is deeply influenced by the presence of organic matter and living organisms (Jones and Wilson 1985). By far it is known that the biochemical weathering of rocks is characterized by different solubilization mechanisms regarding mineral elements. These solubilization mechanisms include processes of acidolysis, complexolysis, alkalinolysis, corresponding to the formation of acidic, complexing, and alkaline metabolic compounds solubilizing rocks and minerals (Berthelin 1983). With respect to the chemical weathering induced by lichens, at least two of the above-mentioned solubilization mechanisms are widely demonstrated. Syers and Iskandar (1973) suggested that the main possible chemical processes by which lichens are able to solubilize minerals are (1) generation of respiratory CO_2; (2) the excretion of oxalic acid; and (3) the production of biochemical compounds with complexing ability.

The dissolution of respiration CO_2 in water held by lichen thallus results in the generation of carbonic acid, which is believed to be of importance in the process of solubilization by lowing the local pH values of thallus and the related microenvironment. As suggested by many authors, lichen thallus can create a characteristic chemical microenvironment and specific weathering conditions at the thallus-rock interface, particularly in the terms of water retention, where the chemical weathering by water, for instance, may be in progress during longer periods than on rare rock. The acceleration of this hydrolysis process of minerals by the dissolving of the metabolic CO_2 in water is to be expected (e.g. Creveld 1981; Seaward *et al.* 1989; Wierzchos and Ascaso 1996).

Oxalic acid secreted by the mycobionts of many species of lichens, extremely soluble in water, is commonly considered to play a crucially important role in the biochemical weathering of rocks and minerals. Generally, the considerable effect of oxalic acid on dissolution of rocks and minerals is attributed to the associated hydrogen ions and the formation of cation-complexes, namely the proton-promoted and the oxalate-promoted dissolution mechanisms (Song and Huang 1988; Ganor and Lasaga 1994). The structural cations, released form minerals as a result of the attack of hydrogen ions, tend to form cation-organic complexes with oxalic acid, which has OH and COOH groups in the ortho position. The chemisorption of the cation-organic complexes on the mineral surfaces causes a shift of electron density toward the framework of the mineral. This charge transfer increases the electron density of the cation-oxygen bonds and makes them more susceptible to hydrolysis (Eick *et al.* 1996a,b).

The organic compounds are abundant in lichens, as referred to lichen acids although not all of them are in fact acids; they have been shown to be likely responsible for the observable effects on rocks in some early studies (Schatz *et al.* 1954, 1956; Schatz, 1963a, b). The study of Iskandar and Syers (1971) revealed that lichen depsides and depsidones, commonly occurring in lichen compounds, are slightly soluble in water. This finding, in conjunction with the presence of polar groups such as OH, CHO, COOH in ortho positions in many lichen compounds, theoretically shows the chelating ability of these compounds. According to Schatz (1963b) and Syers (1969), the release of cations from silicates by lichen compounds is largely attributable to complex formation and not to reactions directly involving hydrogen ions.

3 Weathering process of rocks by endolithic lichen communities in the Antarctic cold desert

In the Antarctic cold desert, the endolithic lichens differ by mode of entry to the inhabiting rock. Cryptoendolithic forms occupy structure cavities and chasmoendolithic inhabit fissures and cracks within rocks, whereas euendolithic forms actively bore into rocks (Golubic *et al.* 1981; Bell 1993). Not all endolithic lichens, however, can be classified by the inhabiting location of rock. In fact, some species of lichens are partially epilithic and partially endolithic, others have an epilithic and an endolithic phase in the course of their life cycle (Golubic *et al.* 1981). Furthermore, it has been reported that some endolithic lichens may have their chasmo- and euendolithic phases at the different stages of colonization (Ascaso *et al.* 1995).

The biotic weathering of the Beacon Sandstone in the Antarctic cold desert was first investigated by Friedmann (1982), who suggested that the effect of endolithic lichens on the substrate rocks is twofold. First, iron compounds in the rock are mobilized by exudates from lichen hyphae, some of which move to the surface where they are precipitated and some may be moved deeper into rock, producing a well defined, leached, snow-white layer in the rock. Second, the cementing substance between sandstone grains in the upper level of the colonization zone of lichen community is dissolved by exudates, resulting in surface exfoliation. The biotic mechanical factors, such as growth of lichen pseudo-tissues and intermittent swelling during periods of hydration, as well as freeze expansion, may be attributed to this process. The exfoliation of surface crust exposes the endolithic lichens to the murderous climate of the Antarctic desert and then compels them penetrate further deeper into the rock, thereby the pattern of microbial growth is re-established, while a siliceous crust forms on the new surface (Friedmann 1982; Friedmann and Weed 1987).

Weed and Norton (1991) investigated the weathering phenomenon of the sandstone of the Palaeozoic Beacon Supergroup in the Dry Valley region of Antarctica (also known as Ross desert). According to their investigation, the typical colonized rock surface is a mosaic of tan- to orange-stained and more recently exposed white leached patches, indicating that the Beacon Sandstone in Dry Valley region undergoes at least three chemical weathering processes. (1) Mobilization and translocation of elements caused by exudation of oxalic acid and other chelating compounds by endolithic lichen communities, producing distinctive Fe pigment patterns and accelerating exfoliation in the colonized rocks. (2) Formation of thin siliceous crust by accumulation and in situ alteration of airborne dust composed of quartz, clays, and Fe oxyhydroxides. (3) Silicification of porous quartz sandstone by growth of quartz in optical continuity with host grains, producing impermeable rinds to several centimeters. The distribution of pigments in the rocks is the result of interaction of abiotic factors and lichen colonization.

The investigation of Weed and Norton (1991) indicated that the surface crusts of the colonized rocks are enriched in Fe over the unweathered rocks by 1 to 8 times. Ion chromatography of water extracts from lichen-colonized zones suggests that oxalic acid secreted by lichen hyphae is a major Fe mobilizing agent in the rocks. The finding of calcium oxalate monohydrate, a characteristic product of weathering process induced by lichen in the temperate regions, provides sound proof to the above conclusion. Furthermore, chromatography study also indicated that organic exudates other than oxalic acids may also enhance the leaching of iron.

4 Weathering process of rocks by epilithic lichen communities in the maritime Antarctic

With comparison to that of their biological and ecological aspects, very few investigations associated with effects of epilithic lichen communities on the weathering process of the substrate rocks have been conducted in the maritime Antarctic. Campbell and Claridge (1987) were believed to be the first investigators reporting the effect of epilithic lichens on the weathering of rocks other than sandstone in Antarctica. They noted that crustose lichens are attributed to the surface breakdown of weathered granite boulders and exfoliation of weathered dolerite in the maritime Antarctic. They pointed out, however, whether these lichens are responsible for much of chemical weathering of such rocks remains to be determined. In the other words, Campbell and Claridge (1987) tended to consider the effect of crustose lichens on these rocks to be physical. As known, the medulla of epilithic lichens is excellent hygroscopic substance and has a great water holding capacity up to 300% of the dry weight when enough moisture available. Therefore it can be expected that the physical impact, such as freeze expansion and freeze-thaw action of lichen thallus, plays a significant role in the weathering of rocks. This had been confirmed by the investigation conducted by Creveld (1981) in the alpine zone of South Norway where the climate is similar to that in the maritime Antarctic.

Chen and Gong (1995), however, reported that biotic weathering of volcanic andesite and basaltic rocks induced by epilithic lichens in the King George Island, South Shetland Islands, the maritime Antarctic. The obtained results revealed that the main chemical components in the bio-weathered surface layer of the colonized rocks are more or less altered. The weathering potential of the bio-weathered surface of the colonized rocks, known as important index indicating tendency of weathering process, evidently decreases by 4.7 percent, in comparison with that of the surface layer of bare rocks. A red-brown rind has formed as a result of mobilization and precipitation caused by lichen secretion. By means of the thin section examination, the ferruginization of some minerals of the bio-weathered layer at varying degrees was observed, and secondary products proved to be dominated by hematite, limonite, goethite and amorphous iron oxides. Also on King George Island, Ascoso *et al.* (1990) investigated the effects of epilithic lichens on the volcanic andesite and volcanogenoc sediment, by use of IR spectroscopy, energy dispersive X-ray analysis and transmission electron microscopy. They suggested that both cosmopolitan and endemic species of epilithic lichens could accelerate the weathering process of the colonized rocks. Feldspars are found to be present at the rock-lichen interface at a smaller degree than in the underlying rock. The presence of crystalline oxalate (weddellite), imogolite, carbonate (calcite), and amorphous materials which are not found in the bare parent rock, indicates that the weathering and bio-mineralization processes are attributable to the epilithic lichens.

5 Indirect effects of lichens on weathering and soil-forming processes

In Antarctica, besides the direct evidence discussed above, lichen colonization also may exert effects on the weathering process in indirect ways. For instance, lichen colonization can result in a considerable accumulation of organic matter. It was reported that the cryptoendolithic lichen community inhabiting sandstone could accumulate organic carbon from 10 g/m^2 to 100 g/m^2 in the Antarctic cold desert (Vestal 1988). In maritime Antarctica, low loss rates and the absence of grazing allow accumulation of a considerable standing biomass to values reaching nearly 2 kg/m^2 for Usnea himantormia (Kappen 1993). First of all, the organic matter and cell excretions enable a heterotrophic bacterial population to thrive, especially around the hyphae or closely associated with them, representing a synergism effect of the lichen thallus on weathering processes (Ariño *et al.* 1995). The study was conducted by Matsumoto *et al.* (1991) on the sample of Beacon Supergroup sandstooe from the McMurdo Dry valleys. A series of long chain *n*-alkanes (C_{20}– C_{36}) with near unity odd/even ratios and long chain *n*-alkanoic acids (C_{20}– C_{32}) with an even-carbon number predominance were detected in the rock occupied by lichen-dominated community. It is very likely that these components have originated from unidentified colorless bacteria associated with lichens. Second, the decomposition of some lichens, especially nitrogen-fixing species, may lead to the production of humic or fulvic acids, which are well known for their ability to form strong complexes with aluminium and iron (Jones and Wilson 1985). Furthermore, organic matter derived from lichen decomposition, together with detached particles of the substratum, and atmospherially-derived dusts trapped by thalli, all contributed to development of primitive soils (Seaward 1997).

6 Characteristics of biotic weathering in Antarctica

In comparison with the biotic weathering induced by lichens occurring in other regions of the world, this weathering process in Antarctica exhibits in the following aspects.

(1) The biotic weathering of rocks could be mainly attributable to lichens due to their predominance in both the surface vegetation and endolithic communities of Antarctica.

(2) Avoiding of human activities or succession to the higher plants, the interaction between lichens and their substrate rocks could go along a much longer period.

(3) For the cosmopolitan lichens, the weathering ability of the same species is generally smaller in Antarctica than that in the other regions of the world.

(4) Endolithic lichen communities play a very important role in the biotic weathering process in the Antarctic cold desert.

(5) The weathering phenomena of sandstone by endolithic lichen communities in the Antarctic cold deserts are somewhat similar to that of the other deserts of the world.

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