Reports

Microbial Trace-Fossil Formation, Biogenous, and Abiotic Weathering in the Antarctic Cold Desert

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In the Antarctic cold desert (Ross Desert), the survival of the cryptoendolithic microorganisms that colonize the near-surface layer of porous sandstone rocks depends on a precarious equilibrium of biological and geological factors. An unfavorable shift of this equilibrium results in death, and this may be followed by formation of trace fossils that preserve the characteristic iron-leaching pattern caused by microbial activity. Similar microbial trace fossils may exist in the geological record. If life ever arose on early Mars, similar processes may have occurred there and left recognizable traces.

THE EXPOSED SURFACES OF BEACON sandstone in the cold desert of southern Victoria Land, Antarctica [Ross Desert (*1*)], show characteristic patterns of exfoliative weathering, caused by microorganisms that colonize the porous rocks (*2*). In this extremely cold and dry environment, suitable conditions for microbial life can prevail inside porous rocks warmed by insolation (*3*). The continued existence of such favorable microbial environments in rocks depends on a precarious equilibrium of biological and geological processes that take place on overlapping time scales. A shift in this equilibrium can lead to extinction of microbial life and, as a further consequence, either to destruction of the rock surface or to its preservation and the formation of trace fossils.

The weathering of Ross Desert Beacon sandstone, colonized by microorganisms, has biogenous and nonbiogenous components. Among the abiotic weathering processes that act on the surface of Beacon sandstone in the Antarctic desert, some tend to preserve and stabilize the rock surface, whereas others contribute to surface destruction (*4*). Stabilizing weathering processes are the formation of siliceous crusts and resistant quartz rinds. Siliceous crusts consist of a brownish to orange amorphous silica-rich material that originates primarily from airborne particulate matter and coats and fills the spaces between near-surface rock grains (Fig. 1a). These crusts are similar to the rock varnishes, desert varnishes, or silica coatings that occur on exposed rock surfaces in semiarid and desert areas (*5*). Resistant rinds, which can attain a thickness of up to several centimeters, form as SiO_2 fills the pore spaces by precipitation of quartz that is optically continuous with the sandstone grains (Fig. 1b). Such macrocrystalline quartz growth in a low-temperature, nonaquatic, and near-surface environment is unusual. The mechanism of crystal growth, that of the inward migration of the "quartz precipitation front," and the source or sources of silica are unknown.

Disintegrative weathering processes include flaking by salt weathering, grain-by-grain disintegration by frost, salt, or wind action, and polishing by aeolian weathering (*4*). An additional geological process, the formation of primary weathering stains (*2, 4*), does not contribute to either preservation or destruction. The word primary refers to the fact that these stains are formed before microbial colonization by alteration of host rock minerals. They contain iron oxyhydroxides up to a few centimeters deep in the rock (*6*). Their hues vary and include a range of oranges, browns, and reds. The leaching of these stains is a telltale sign of microbial activity in the rocks.

The biogenous weathering of Beacon sandstone has been reported (*2*). This complex phenomenon involves both preserving and disintegrating weathering processes. It results from colonization by cryptoendolithic microorganisms (*2*) that inhabit the airspaces in the rock in a distinct zone, which is a few millimeters wide, 1 to 3 mm below and parallel to the rock surface (Fig. 2a). Cryptoendolithic lichens are the most prominent components of this microbial community (*2*). Their effect on the rock substrate is twofold. First, they mobilize iron compounds in the lichen zone, producing a well-defined, leached, snow-white layer in the rock, which often appears in sharp color contrast to the background stain.

Second, microbial colonization reduces the cohesion of sandstone grains in the upper level of the lichen zone, resulting in surface exfoliation. The exfoliating flakes are 1 to 3 mm thick, irregularly shaped, and up to 50 mm across. Growth of lichen plectenchyma (pseudo-tissue) between rock crystals and intermittent swelling during periods of hydration, as well as freeze expansion, may be factors in the flaking process. The loss of the protective rock layer exposes the cryptoendolithic lichen structures, which are then abraded by wind, leaving behind an exposed area of white, leached sandstone. The pattern of microbial growth is reestablished as organisms grow deeper into the rock, while a siliceous crust forms on the new surface. With progressive encrustation, the surface color deepens from white to orange to brown, and, at the same time, iron leaching takes place a few millimeters below the surface. Alternating flaking and encrustation produce a patchwork-like pattern of a white-orange-brown mosaic with a several millimeters deep relief (Fig. 2b) (*2*, figures 5b and 9).

Observations in the field show that the presence of a lightly to moderately silicified crust is a condition favoring continuing microbial colonization. The crust stabilizes the rock surface by preventing grain-by-grain weathering and also contributes to water retention. Such crusts are renewed in the course of the exfoliation cycle of actively colonized rocks. Unsilicified surfaces are not colonized. Heavily silicified crusts, on the other hand, preclude water absorption and thus resist microbial colonization.

Occasional observations of pioneer colonization suggest that, in rocks with heavy

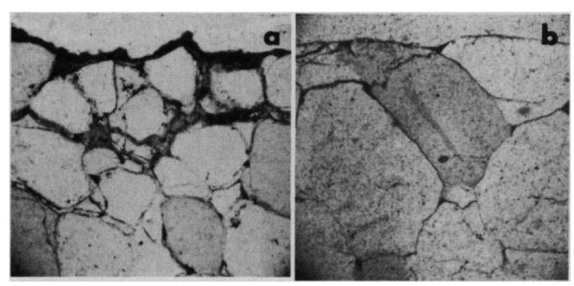

Fig. 1. Texture of Beacon sandstones in thin sections (×30). (**a**) Microbially colonized rock with well-developed, iron-stained siliceous crust and pore spaces. (**b**) Resistant quartz rind with thin crust on surface; pores have been filled by quartz overgrowth on sand grains.

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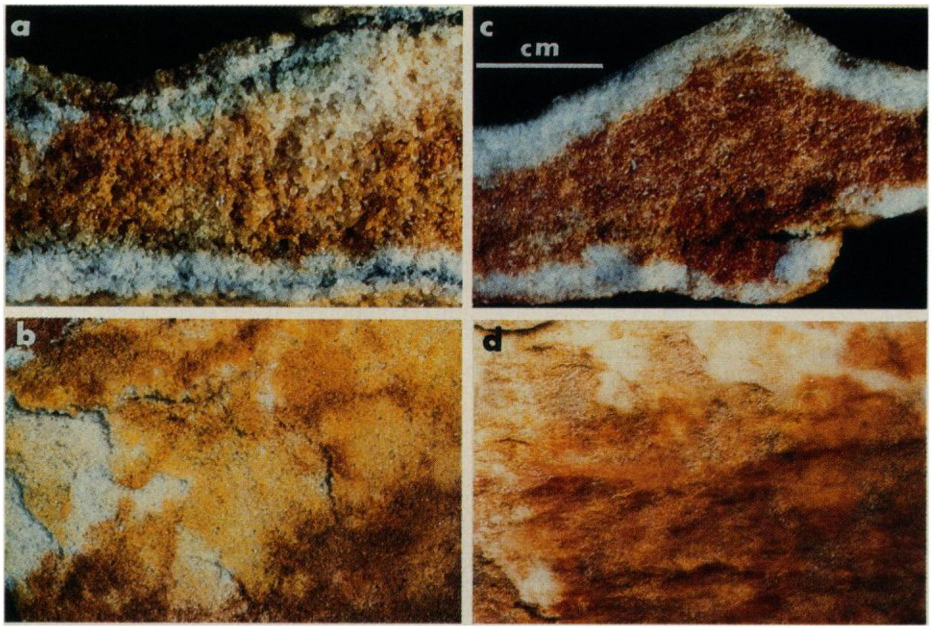

Fig. 2. (**a** and **b**) Microbially colonized Beacon sandstone and (**c** and **d**) trace fossils. (a) Fractured rock plate showing primary stain in the center and leaching in the microbial zone along both faces. (b) Exfoliative weathering; surface view of the rock in (a). (c) Fossil setting of past similar microbial colonization, pores are filled by quartz overgrowth on sand grains. (d) Surface view of the rock in (c) showing the color mosaic pattern of exfoliative weathering. This surface has been polished and fluted by wind action.

siliceous crusts, cracks can create openings for water and for microorganisms. Unsilicified surfaces may be colonized in sheltered and otherwise stable situations. Formation of iron stains in the rock typically precedes colonization, and a siliceous crust forms simultaneously with progressing colonization.

Once a rock surface is colonized, the biogenous exfoliation cycle starts. Its continuation depends on an equilibrium between preserving weathering processes (crust formation) and destructive processes (periodic loss of the protective rock crust). The maintenance of this equilibrium and the continued biological activity ultimately depend on sufficient insolation of the surface, as this warms the rocks to temperatures at which both metabolic activity and melting of snow are possible (*2, 7–9*). Insolation, in turn, is a function of surface orientation and slope; conditions are most favorable on sloping northern faces, whereas vertical southern faces are too cold for biological activity (*10*). Yet, even at the most favorable sites, conditions never reach the optimal temperature range for photosynthesis (*8, 11*), and the cryptoendolithic microorganisms of the Ross Desert exist near the limit of their tolerance. Change in the extent of insolation may critically affect the conditions for life. Should the balance tip too far, life and biogenous weathering come to an end, and abiotic, either destructive or preserving weathering processes take over. Thus, a particular rock surface can consecutively be subject to different modes of weathering when its orientation changes (for example, when a colonized bedrock ledge falls or a small clast is moved by wind) or when climate changes associated with glaciations occur. Thus a biogenously weathered surface may be silicified and later colonized again when conditions such as exposure or climate change. At the same time, different modes of weathering may dominate different faces of the same rock. The southern face of the bedrock boulder in Fig. 3, for example, is devoid of a siliceous crust and shows grain-by-grain weathering by wind and probably by frost and salt; the heavily silicified horizontal surface is fluted and polished by wind action, whereas the ledge facing north is colonized by microorganisms as indicated by the pattern of biogenous exfoliation.

Fig. 3. A boulder, showing three types of weathering. The vertical surface facing south (to the left) is weathered by wind. The polished and fluted horizontal surface is a resistant quartz rind. The surface sloping to the north (adjacent to the 10-cm scale) shows the mosaic pattern of active biogenous exfoliative weathering.

In this weathering cycle, the biological and geological processes involved act on comparable and overlapping time scales. This finding is consistent with the fact that the cryptoendolithic community is metabolically active for only several hundred hours per year, mostly below 0°C (*9*), and has an extraordinarily slow growth rate. Between episodes of loss of rock crust and ensuing new growth, the community persists for long enough for a new siliceous rock crust to be formed on the surface.

If biological activity in colonized rocks is interrupted and rock-preserving weathering processes take over, resistant rinds may develop that incorporate the characteristic biogenous weathering patterns. As a result, the exfoliation mosaic and the leaching pattern are preserved as a trace fossil of past microbial activity (Fig. 2, c and d). This fossilization process is taking place in a modern weathering environment, and transitional stages between viable colonization and complete quartzification of biogenous weathering structures coexist. Efforts to find either organic material or cell replicas in quartz rinds have not been successful, although the formation of silicified microfossils under these conditions cannot be ruled out.

Minimum ages for such trace fossils can be determined from the ages of the quartz rinds (*4*). Calibration of quartz-rind thicknesses was based on the study of sandstone boulders on a sequence of moraines of approximately known ages, ranging from about 70,000 to about 2 million to 4 million years old (*12*). These resistant quartz rinds range in thickness up to a few centimeters on the older boulder surfaces. Abundant quartz rinds with trace fossils suggest that the endolithic community has been present in the area for the last few million years. The relative chronology of colonization and glaciation provides additional evidence; the presence of trace fossils on glacially influenced landforms indicates that the endolithic community was present before the last glaciation of the area (*4*).

Formation of trace fossils of microbial colonization may not be limited to the case reported here. Similar processes may have occurred in the past and are preserved in the geological record.

Trace fossils of endolithic microbial colonization in a cold desert environment inspire speculations about possible scenarios for exobiology (*13*). Evidence for the presence of water during the early history of Mars raises the possibility of the appearance of primitive life forms there (*14*). If such forms were present, during loss of atmosphere, water, and concomitant cooling of Mars, these organisms may have withdrawn into porous rocks—the last habitable niche in a deteriorating environment. Under these conditions, trace fossils may have been formed. Because much of the surface structures of Mars is thought to have remained intact over geological time (*15*), the preservation of such near-surface fossils is a distinct possibility. The search for such structures is a legitimate goal for the future exploration of Mars (*13*).

REFERENCES AND NOTES

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Shocked Quartz in the Cretaceous-Tertiary Boundary Clays: Evidence for a Global Distribution

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Shocked quartz grains displaying planar features were isolated from Cretaceous-Tertiary boundary clays at five sites in Europe, a core from the north-central Pacific Ocean, and a site in New Zealand. At all of these sites, the planar features in the shocked quartz can be indexed to rational crystallographic planes of the quartz lattice. The grains display streaking indicative of shock in x-ray diffraction photographs and also show reduced refractive indices. These characteristic features of shocked quartz at several sites worldwide confirm that an impact event at the Cretaceous-Tertiary boundary distributed ejecta products in an earth-girdling dust cloud, as postulated by the Alvarez impact hypothesis.

THE FIRST MINERALOGIC EVIDENCE supporting the existence of an impact by an extraterrestrial body at the Cretaceous-Tertiary (K-T) boundary 66 million years ago (*1*) was the discovery of shock-metamorphosed quartz grains in a claystone at this boundary near Brownie Butte in the Hell Creek area of east-central Montana (*2*). This discovery was crucial to the confirmation of the Alvarez scenario (*3*) that a large meteorite or asteroid had struck the earth at the end of the Cretaceous period, throwing up a dust cloud that circled the globe for a substantial period of time and causing major extinctions of flora and fauna through blockage of sunlight and changes in temperature and climate.

Previously, the principal evidence for this scenario was the presence of anomalously high amounts of iridium and other siderophile elements measured in several boundary clay sites around the world. The number of sites with measured iridium anomalies has now increased to more than 75 (*4*), but the Montana location had been the only site at which shocked quartz had been unequivocably confirmed. Recently, Izett and Pillmore (*5*) and Badjukov *et al.* (*6*) reported the occurrence of shocked quartz and feldspar at the K-T boundary in the Raton Basin in the United States, and in the Soviet Union.

We now report the confirmed presence of shocked quartz at several K-T boundary sites around the world that also contain iridium anomalies. These data answer the objections of some investigators that shocked quartz at the Montana site may have resulted from erosion of localized shocked material from older impacts in the area (*7*). These data also suggest that shocked quartz and other shocked minerals are to be expected in every K-T boundary clay layer that contains a substantial iridium anomaly anywhere in the world.

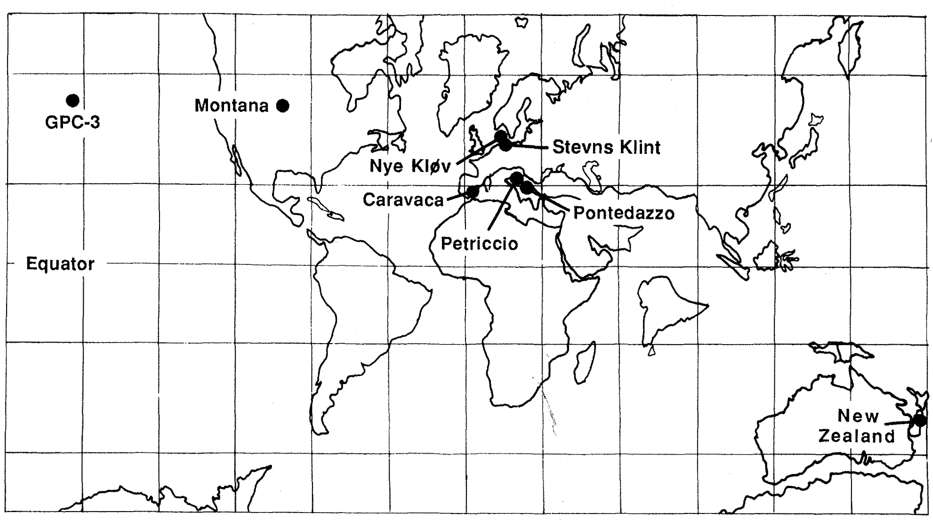

Fig. 1. Map (Mercator projection) of the world 60 million years ago showing K-T boundary sites where we have confirmed the presence of shocked quartz. The original discovery site in Montana is also shown. [Adapted from Smith and Briden (*25*)]

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