THE ANTARCTIC CRYPTOENDOLITHIC ECOSYSTEM: RELEVANCE TO EXOBIOLOGY

E. I. Friedmann and R. Ocampo-Friedmann

Department of Biological Science, Florida State University, Tallahassee, Florida 32306

Abstract. Cryptoendolithic microorganisms in the Antarctic desert live inside porous sandstone rocks, protected by a thin rock crust. While the rock surface is abiotic, the microclimate inside the rock is comparatively mild. These organisms may have descended from early, pre-glaciation Antarctic life forms and thus may represent the last outpost of life in a gradually deteriorating environment. Assuming that life once arose on Mars, it is conceivable that, following the loss of water, the last of surviving organisms withdrew to similar insulated microenvironments. Because such microscopic pockets have little connection with the outside environment, their detection may be difficult. The chances that the Viking lander could sample cryptoendolithic microorganisms in the Antarctic desert would be infinitesimal.

Since the time of the Viking project, the Antarctic cold desert has been regarded as the closest terrestrial analog to Mars. New information gained during the last decade has changed earlier concepts about both: While on Mars no evidence of life was detected, in the Antarctic cold desert, an environment that was thought to be largely abiotic (10), a rich microbial community was found hidden under the surfaces of rocks (2, 4, 6). Although it is obvious that no direct comparison can be drawn between Mars and Antarctica, the new information can be helpful in assessing the possibilities for the existence of life forms in certain extraterrestrial environments as well as for their detection.

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We would like to review here some features of the Antarctic cryptoendolithic desert ecosystem that are relevant for our considerations. The ice-free region of Southern Victoria Land is frequently referred to as "dry valleys." This is a misnomer, as the area includes valleys as well as mountains over 2000 m high. In the valleys, there are streams and (mostly frozen) lakes; in the mountains, there is an extreme desert. The name "McMurdo Upland" is probably more descriptive of the general character of the region.

The climate of the high desert of McMurdo Upland is severe, characterized by low temperatures (between -15° and $0^{\circ}C$ in summer), extreme aridity (16%-75% relative humidity), and violent winds. Its most striking feature is the apparent absence of life: The exposed surface of rocks is practically abiotic, except for the very infrequent small patches of surface lichens in particularly sheltered microhabitats. Soil microflora is sparse: Most microorganisms that can be isolated from soils are atmospheric contaminants. Primary producers in the soil seem to be absent, and the few indigenous soil microorganisms are heterotrophs, utilizing organic matter carried in by winds.

The abiotic conditions on the rock surface seem to be due to its peculiar microclimate, charcterized by extreme aridity, high levels of solar radiation and temperature oscillations around $0^{\circ}C$, which result in a rapid sequence of freezing and thawing. The freezing and thawing cycle is caused by the frequent wind gusts; the surface, often warmed by solar radiation to temperatures above $0^{\circ}C$, freezes again at each gust (8, 15).

On the basis of these meteorological data, one could easily be tempted to conclude that in the hostile climate of the McMurdo Upland no life is possible (9). Biological observations on the rock surface would, of course, confirm this assessment, but would not detect the cryptoendolithic microbial community just a few mm underneath. These cryptoendolithic microorganisms grow under the surface of porous and translucent rocks, protected by a thin silicified rock crust. The key to the existence of this community lies in the physical properties of the rock substrate, which generate under the rock crust a microclimate that is very different from the outside environment and in which life can exist.

In this system, the rock substrate functions as an energy trap. Northern rock faces (which are reached by the sun) are warmed by solar radiation. At the same time in the southern faces, which remain in shadow, temperatures are near the ambient (2, 12, 15). Equally, if not more, significant is the fact that the freeze-thaw cycle prevalent on the surface is greatly dampened inside the rock, so in the lichen zone relatively balanced temperature conditions exist. During periods of insolation, temperature in the zone colonized by organisms ranges between about -4°C and about 10°C, which is close to the temperature range of metabolic activity of polar lichens (11, 13).

The thin rock layer above the organisms filters excessive radiation. Above the surface, radiation (quantum flux density) in the photosynthetically active range can reach up to 2000 $\mu E\ m^{-2}\ sec^{-1}$. Of this, about 1% reaches the upper level of the lichen zone and about 0.1% its lowest level (11, 16).

The porous rock also acts as a water trap. Snowfall, the only source of water, is highly irregular, and the snow mostly sublimes or is blown away by wind. Occasionally, however, snow melts on the surface, and the meltwater is imbibed by the porous rock (3). Although this process may occur only infrequently, the ensuing high humidity inside the rock is retained for several days and perhaps for weeks, even while relative humidity outside drops to extreme low levels (12). The rock substrate also serves as a nutrient trap, as shown in the case of nitrogen compounds formed in the atmosphere by abiotic nitrogen fixation. These nitrogen compounds reach the rock as dry fallout or are carried there by snow and are subsequently transported to the microorganisms by snow melt (5). Evidently, the endolithic environment also protects the organisms from mechanical abrasion by winds of high intensities.

It is necessary to consider here two points, both of which concern the dynamics of metabolic processes. The first is the limitation of space: In the rock substrate, the sharp lower and upper boundaries of the microbial zone are probably determined by physical gradients such as temperature and light, which set rigid limits to microbial colonization. Within these confines, the volume of airspace available for the organisms is necessarily finite. The second point is the question of time scale: The silicified rock crust under which the cryptoendolithic community lives is a result of geological processes, which are very slow compared to biological processes. Consequently, organisms living under such a rock crust are necessarily of considerable age. It is also necessary to assume that a steady state exists in which photosynthetic activity is balanced by respiration. These conditions correspond to a "closed ecosystem," a concept discussed in some detail by Maguire et al. (14). In such a system, the degree of closure may range from biological closure (closed to passage of organisms) to adiabatic isolation (closed to the flow of matter and energy). On this scale, the cryptoendolithic communities living under a rock crust may belong to the most closed ecosystems that exist in nature (7). Laboratory experiments seem to confirm this notion, and *in situ* measurements in Antarctica showed no measurable $^{14}CO_2$ uptake through the intact rock crust during a period of 27 days (11 and J. R. Vestal, unpublished).

These considerations indicate that conditions in the cryptoendolithic habitat can be largely independent of those outside, thus creating a microscopic niche that can support life in the midst of an abiotic macroenvironment. Because of the low metabolic activity of the organisms and the low rate of material exchange with its surrounding, such a "hidden" environmental pocket may be very difficult to detect, a point that may be significant for certain exobiological considerations.

Geological evidence (1) enables us to discuss the possible evolutionary history of the Antarctic cryptoendolithic ecosystem. Over 40 million years ago, the Antarctic continent supported a variety of life forms. When the continent moved to its present position, glaciation set in and the climate turned cold and dry. The present McMurdo Upland again became ice-free only within the last 4 million years. Yet geological evidence suggests that conditions resembling those in the recent ice-free area were always present on the Antarctic continent on the nunataks (mountain tops emerging from the ice sheath), which remained essentially ice-free during the entire period of Antarctic glaciation. At these places, remnants of the early Antarctic life forms could have found refuge. It is therefore possible that members of the cryptoendolithic lichen community are descendants of ancient Antarctic organisms that lived there before the onset of glaciation and that recent forms evolved during the cooling of the continent. If this is so, the cryptoendolithic microorganisms represent the last outposts of life in a gradually deteriorating environment.

On the basis of the evidence that Mars once possessed considerable quantities of water in its atmosphere, we may perhaps assume that during that time life evolved on the planet. If such was the case, it is conceivable that, following the loss of water and the cooling of the surface, the last of the surviving microorganisms may have withdrawn into insulated microscopic pockets comparable to those that now exist in the Antarctic desert. Although the analogy between Martian and terrestrial conditions cannot be pushed further, the possibility of the existence of fossil, or perhaps even active, microbial niches on Mars cannot be entirely excluded at this time.

Because such microscopic pockets may be highly insulated from the outside environment, their detection can prove to be very difficult. In this respect, it is perhaps interesting (or at least entertaining) to perform an imaginary experiment about the chances that the Viking lander could detect the cryptoendolithic lichens of McMurdo Upland. It is obvious from our discussions that a mechanical lander in search of cryptoendolithic lichens would have to make certain informed decisions about the mode of collection. First, it would have to land on a rocky terrain, perhaps on a mountain top, and not on soft soil. Then, it would have to select the proper rock type, taking into consideration color, transparency, and grade of porosity. Next, it would have to approach a rock boulder from the north, where it is warmed by insolation. Then, samples would have to be taken from the proper depth, between the narrow limits of the endolithic zone. Finally, this process would probably have to be repeated at various sites, as endolithic colonization in McMurdo Upland is frequent but by no means ubiquitous.

It is not difficult to see that the chances that a simple mechanical lander would find cryptoendolithic lichens in McMurdo Upland is infinitesimal. The morale of this imaginary experiment is, therefore, that, before any extraterrestrial life detection system can be developed, sufficient information is needed about the geology, chemistry, and climate of the area and about the biological problems involved. Without such informed planning, any attempt at life detection would be, at best, a shot in the dark.

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