Adv. Space Res. Vol. 15, No. 3, pp. (3)243–(3)246, 1995

0273–1177/95 $7.00 + 0.00

A PRIMITIVE CYANOBACTERIUM AS PIONEER MICROORGANISM FOR TERRAFORMING MARS

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ABSTRACT

The primitive characteristics of the cyanobacterium Chroococcidiopsis suggest that it represents a very ancient type of this group. Its morphology is simple but shows a wide range of variability, and it resembles certain Proterozoic microfossils. Chroococcidiopsis is probably the most desiccation-resistant cyanobacterium, the sole photosynthetic organism in extreme arid habitats. It is also present in a wide range of other extreme environments, from Antarctic rocks to thermal springs and hypersaline habitats, but it is unable to compete with more specialized organisms. Genetic evidence suggests that all forms belong to a single species. Its remarkable tolerance of environmental extremes makes Chroococcidiopsis a prime candidate for use as a pioneer photosynthetic microorganism for terraforming of Mars. The hypolithic microbial growth form (which lives under stones of a desert pavement) could be used as a model for development of technologies for large-scale Martian farming.

INTRODUCTION

One of the key goals in terraformation of Mars--the engineered transformation of the Martian surface to resemble terrestrial conditions that support life--is the creation of an Earth-like oxygenated atmosphere. On early Earth, the evolution of such an atmosphere is the geologically recent result of biological activity, notably photosynthesis, by microorganisms. The problems and possible strategies of terraformation have been reviewed recently /1,2,3/. The introduction of a pioneer photosynthetic microorganism to Mars will be one of the basic steps in this process.

No terrestrial organism can grow under the conditions that prevail on the surface of Mars, and the establishment of such organisms there must therefore be preceded by engineered changes in the physical (and probably chemical) environment. Hence, we assume that prior to the introduction of a pioneer microorganism, the environment on the Martian surface will be modified to the point of approaching the lower limits of conditions under which that organism can survive. These values will, of course, vary according to organism. Those appropriate to the organism discussed in this paper are presented in Table 1.

Earlier studies /4,5/ developed computer models of Martian microbial communities. Two such models were proposed, one based on a lichen and another on a mat of filamentous cyanobacteria. We suggest it is unlikely that either system can be used as a Martian pioneer. Laboratory culture of lichens is difficult; it has been accomplished only a few times and never beyond a very small scale /6/. The reason is that, although lichens tolerate desiccation, they are adapted to narrowly specific environments, which are difficult to replicate. Cyanobacteria are more promising candidates but not in a microbial mat. Microbial mats were probably widespread on the water-rich primitive Earth, but on the surface of present-day Mars, the evaporative loss of water would eliminate microbial mats as pioneer growth forms.

CHROOCOCCIDIOPSIS AS A PIONEER ORGANISM ON MARS

To date, all considerations about pioneer microorganisms on Mars have been rather theoretical. Here we propose an actual organism--Chroococcidiopsis--as a candidate Martian pioneer and offer suggestions for development of technologies for large-scale Martian farming.

Chroococcidiopsis caldariorum was described from hot springs in Indonesia /7,8/. Other species or strains have been found in marine and hypersaline habitats /9/, nitrate caves /10,11/, extreme arid deserts around the world /12,13,14/, the Ross Desert of Antarctica /15,16/, high Alpine rocks (unpublished), and freshwater /17/, as well as in several lichens as cyanobionts /18,19/. At the Culture Collection of Microorganisms from Extreme Environments (CCMEE) at Florida State University and Florida A&M University in Tallahassee, over 240 strains of Chroococcidiopsis have been isolated from diverse extreme environments and are being maintained in culture. DNA/DNA hybridization of strains isolated from desert rocks indicate that all forms (including those from Antarctica) belong to a single species (/20/ and unpublished). Other forms are probably also members of the same large cluster. For this reason and also because of the unclear situation in cyanobacterial taxonomy, we will not assign species names to Chroococcidiopsis strains here.

CHROOCOCCIDIOPSIS, A PRIMITIVE CYANOBACTERIUM

We suggest that Chroococcidiopsis represents a primitive type of cyanobacteria, probably similar to the earliest forms of cyanobacteria that appeared on the surface of Earth.

The morphological characters of Chroococcidiopsis are, compared with those of other cyanobacteria, variable and even somewhat vague. The spherical unicells can divide by binary fission or produce two- to few-celled groups. Alternately, cells can grow into large baeocyte mother cells, which then divide by a rapid sequence of binary divisions (or by "simultaneous" divisions?) into baeocytes, enclosed in the mother cell wall. Baeocytes are released by the rupture or dissolution of the mother cell wall. Forms intermediate between these modes of reproduction are common. This variability in morphology exists not only between strains but also within the same strain growing under different conditions. We interpret this morphological plasticity of Chroococcidiopsis as an indication that it is undifferentiated and, in the evolutionary sense, primitive.

This range of forms shows a remarkable similarity, both in size and in morphology, with coccoid Proterozoic microfossils /21/. Without making an attempt at identification, we suggest that organisms morphologically similar to present-day Chroococcidiopsis were present on Earth in Proterozoic times.

Ecologically, the most conspicuous characteristic of Chroococcidiopsis is its unusually wide range of habitats, which includes several environmental extremes: extreme aridity, extreme salinity, extreme nitrate concentration, high temperature, extreme low temperature. In the most extreme of cold, arid, hot, and saline environments around the globe, Chroococcidiopsis is the dominant organism, forming mostly monospecific populations. In milder environments, however, it becomes less prominent, and in species-rich communities it is rare or absent.

We therefore suggest that Chroococcidiopsis:

(1) is a widespread and cosmopolitan organism, probably much more common than recorded but overlooked because of its small size and inconspicuous morphology;
(2) has a nearly unparalleled ability to live under a wide range of environmental extremes; and
(3) lacks the ability to compete with more discriminating, specialized, or aggressive species.

These characteristics would be consistent with those of an organism living on early Earth: primitive organisms were unspecialized, and success in survival depended on their ability to tolerate a wide range of environmental extremes, whereas competitiveness was of no advantage.

MARTIAN FARMING

We propose that Chroococcidiopsis be used for colonization of the Martian surface as a pioneer organism in initial stages of terraformation. Its resistance to desiccation and high salinity and its ability to grow at low temperatures render Chroococcidiopsis eminently suitable for this purpose. Among the strains maintained at CCMEE, several fast growers are available for this application.

Practical proposals for introduction and growth of terrestrial organisms on the surface of Mars must consider methods of large-scale Martian farming. For Chroococcidiopsis, microbial growth forms in extreme terrestrial deserts may serve as a model.

In deserts, Chroococcidiopsis grows either inside porous rocks (endolithic growth form) or on the lower surfaces of translucent stones partially embedded in the soil (hypolithic growth form) /22/. Of these, the hypolithic growth form seems the more appropriate model on which to base large-scale Martian farming technology.

Hypolithic microbial growth is common in deserts where the soil is covered by desert pavement, composed of small stones and pebbles on the surface half embedded in soil. Once formed, desert pavements are highly stable. They are common in many desert areas of the world, and in, e.g., the Gobi desert they constitute the dominant surface feature. Microbial life is possible under those stones, which are translucent enough to transmit light for photosynthesis; cyanobacteria, most commonly Chroococcidiopsis, grow on the lower surfaces of stones at the stone-soil interface. A diagrammatic representation of the hypolithic growth form is shown in Fig. 1.

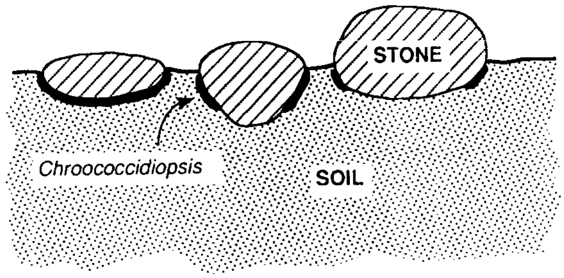

Fig. 1. Diagram of hypolithic microbial growth in deserts.

The translucent stones create a favorable microenvironment by reducing light intensity to favorable levels and by collecting and conserving moisture. The microorganisms occupy a well-defined zone at the stone-soil interface, the depth of which is apparently determined by light intensity. Model experiments showed that water from the surface penetrates along the stone-soil interface deeper than it does in the soil and that a small water reservoir is built up under the stone that persists for a long time (weeks) after the water has evaporated from the surrounding area /23/.

Future Martian farming technologies may be based on the creation of artificial desert pavements. The Martian regolith could serve as a porous base. Semi-translucent solid objects, such as glass strips with proper light-transmittance properties, manufactured on location, could be laid out over the surface in a parallel zebra pattern to create a solid cover. These glass strips would serve both as a dew trap and as a solid substrate for microbial growth. After inoculation with Chroococcidiopsis, only periodic wetting, perhaps a few times a year, would be needed to provide the conditions for hypolithic microbial growth. Such a pioneer microbial farming system could be most suitable for the arid conditions likely to be present on Mars in the initial stages of terraformation.

For design of large-scale farming methods, it is necessary to estimate the environmental requirements of Chroococcidiopsis (Table 1).

These environmental conditions will have to be created by planetary engineering prior to the introduction of life (ecopoiesis, /3/). The estimates of minimum duration and temperature conditions of metabolic activity are based on long-term recording and analysis of the nanoclimate (climate in the microbial range) in the cryptoendolithic microbial habitat in the Antarctic desert /24/, probably the closest terrestrial analog to Mars. The values in Table 1 probably represent minimum environmental parameters sufficient to maintain life at a very low growth rate. If higher yields are to be achieved, as would be desirable during the stage of terraformation, temperatures and duration of metabolic activity might have to be increased.

The temperatures listed in Table 1 refer to the temperatures of the solid substrate--stones in the case of natural desert pavements and glass strips in Martian farming. Under terrestrial conditions, rocks and stones in deserts are warmed by solar radiation to about 15°C above ambient /25,26,28/. Martian desert farming can take advantage of this warming. A temperature of 0°C can be reached in the hypolithic habitat even if the ambient temperature rises only to -15°C (= 258°K) during hours of solar radiation. At night, temperatures can drop significantly below freezing point without apparent damage: Chroococcidiopsis and other microorganisms are frozen each day, often more frequently, in the Antarctic desert, without apparent damage /24,26,27/.

The estimate of yearly total duration of metabolic activity in Table 1 is based on conditions prevailing in the Antarctic desert. At higher temperatures metabolic activity would be higher, and shorter periods of activity would suffice. The metabolically active "wet" periods, as in nature, can be induced by discrete events of moistening the soil (regolith). Observations in the field in Antarctica (with porous rocks that produce conditions that probably resemble those of the hypolithic habitat /27,29/) and in model experiments with the hypolithic system /23/ suggest that the porous substrate (rock or soil) retains liquid water for a period of weeks. Thus we estimate that a "wet" period of 500 hours of metabolic

TABLE 1 Estimated parameters for growth of Chroococcidiopsis in a low-temperature environment

Duration of metabolic activity (when liquid water is available)	500 h yr^{-1}
Range of temperatures during metabolic activity	from -10°C to +10°C
Mean temperature during metabolic activity	-5°C
Salinity	5%

activity (Table 1) can be a achieved by two, or perhaps even one, wetting event per year. For higher yields, more frequent wetting may be necessary. Between "wet" periods of metabolic activity, Chroococcidiopsis can survive, as in nature, in a desiccated condition and without apparent damage.

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