

High Arctic cryptoendolithic microorganisms in a polar desert environment

C.R. Omelon & F.G. Ferris

University of Toronto, Department of Geology, Toronto, Ontario, Canada

W.H. Pollard & D.T. Andersen

McGill University, Department of Geography, Montréal, Québec, Canada

L. Whyte

Biotechnology Research Institute, National Research Council, Montréal, Québec, Canada

ABSTRACT: The recent discovery of cryptoendolithic microbial communities (prokaryotic, microalgal, or fungal assemblages living within structural cavities of porous rocks) in sandstone outcrops on northern Ellesmere Island in the Canadian high Arctic provides an important opportunity to explore a unique microbial habitat in one of Canada's most extreme environments. Preliminary reconnaissance in 2001 revealed a relative abundance of cyanobacterial communities in lithic environments; their presence in the subsurface in areas with limited epilithic growths appears to be controlled by the thermal capacity of the host substrate to maintain overall warmer temperatures during periods of insolation, as well as to moderate short-term temperature fluctuations. Comparisons to Antarctic cryptoendoliths reveal that Arctic microbial endoliths have much longer active growth periods resulting from an overall warmer climate.

1 INTRODUCTION

For life to exist in polar climates, microorganisms must find strategies to minimize environmental stresses imposed by the harsh climatic conditions that effectively limit growth and development of complex ecosystems regularly observed in more temperate biomes. In addition to low annual average temperatures and limited precipitation, microorganisms in polar environments are subjected to long, continuous day/night periods that effectively control their metabolic activity, as well as rapid temperature oscillations around 0°C that impose stresses both on biological function as well as the physical environment.

Cryptoendolithic microbial communities are considered to have found such a niche in pore spaces only millimetres beneath the surface of suitable rock substrates. For these organisms, being insulated from the outside environment is advantageous in that (1) the porous nature of the rock matrix enables the flow of air, water and nutrients into and out of the endolith environment, (2) the thermal capacity of the rock maintains warmer temperatures and provides an effective moderator against diurnal climatic extremes, and (3) the translucent character of the mineral grains allows for adequate penetration of photosynthetically active radiation necessary for phototrophs. Despite extremely slow growth rates (Johnston & Vestal 1991) the lack of higher consumers and predators permits their persistence.

2 BACKGROUND

The majority of research on cryptoendolithic microbial communities has focused on those in the Antarctic Dry Valleys. Starting with the first identification of this habitat and the microorganisms found within them (Friedmann & Ocampo 1976), studies have since explored both the physical and biological components of microbial endoliths. Field-based studies examining important environmental characteristics of the lithic substrate have included measurements of temperature, relative humidity, snowfall, and photosynthetically active radiation (McKay & Friedmann 1985, Friedmann et al. 1987). Much work has been done on the interaction between cryptoendolithic microbes and their surrounding environment, including the availability of water (Friedmann 1978) and photosynthetically active radiation (Nienow et al. 1988), mineral solubilization (Johnston & Vestal 1989), rock weathering (Friedmann 1982, Friedmann & Weed 1987, Johnston & Vestal 1993), and carbon metabolism, primary production and element cycling (Vestal 1998a,b, Banerjee et al. 2000). Identification of lichen symbionts and the role of heterotrophic bacteria as decomposers are also documented (Friedmann et al. 1988, Siebert et al. 1996). More recently, studies have examined how these organisms adapt to environmental stresses, most notably the effects of increased UV radiation (Wynn-Williams et al. 1999). The potential for microbial biosignature preservation in the cryptoendolithic environment

(Friedmann & Weed 1987, Wierzchos & Ascaso 2001) is of significant interest to astrobiology studies.

This work, however, has not been followed up with comparative research in northern polar deserts. Although at similar latitudes, the Arctic generally experiences more moderate climates than the Antarctic, and similarities and differences between these two cryptoendolithic microbial communities are bound to exist. This paper presents the first results of such an initiative, providing environmental, geologic and microbial observations of cryptoendolithic microhabitats in the Canadian high Arctic.

3 STUDY AREA

3.1 Location and geology

Current work focuses on cryptoendolithic microbial communities observed in sandstone outcrops around the Eureka area (80°00'N, 85°55'W) on Ellesmere Island, Nunavut (Fig. 1). Field reconnaissance in July 2001 revealed numerous examples of endolithic microbial environments in outcrops and associated boulders located along ridge crests structured around a synclinal basin where resistant bedrock composed of Upper Triassic – Upper Jurassic sandstones and Lower Cretaceous shales and sandstones reach the surface (Figs 2–3).

3.2 Climate

The climate of the area is classified as a polar desert with an average air temperature of -19°C and ranging

from -36°C (January) to $+6^{\circ}\text{C}$ (July) (Atmospheric Environment Service 1984). Average annual precipitation rates are low ($<65\text{ mm}\cdot\text{yr}^{-1}$) however this may be underestimated due to snow redistribution (Woo et al. 1983). The majority of this precipitation falls as snow ($\sim 65\%$) that collects around obstructions as drifts, but most exposed surfaces are blown clear. Precipitation as rainfall is restricted to the months of June–August. Wind speeds are moderate (average $9.9\text{ km}\cdot\text{h}^{-1}$) and are predominantly from the west-southwest. Due to the high latitude of this site,



Figure 2. Example of exposed Tertiary sandstone ridge crest containing endolithic microbial communities. Rock hammer for scale.

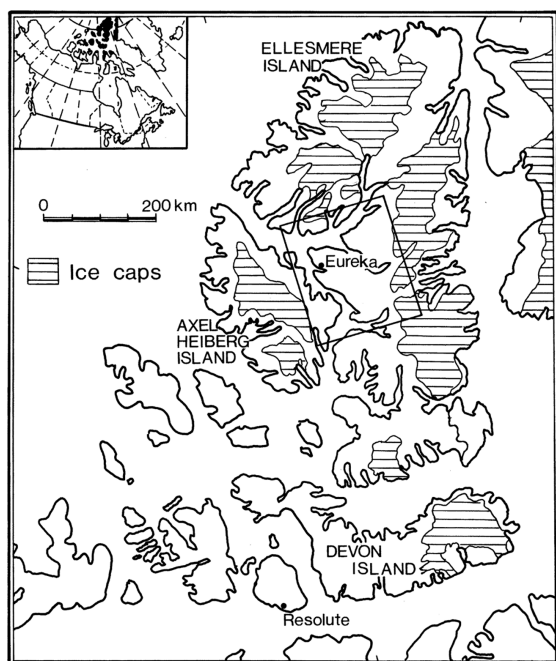


Figure 1. Location of study area.

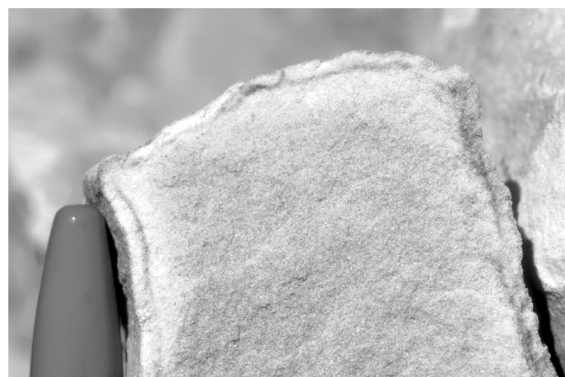


Figure 3. Cryptoendolithic “zone” observed in fractured rock sample. Note discolouration of rock around endolith colony. Pen cap for scale.

insolation is restricted to between mid-February and mid-October peaking in May and June, after which higher atmospheric moisture inputs leads to increasing cloud cover and a reduction in the amount of unrestricted solar radiation reaching the surface (Atmospheric Environment Service 1984).

4 METHODS

Air temperature was measured with a temperature probe (Campbell Scientific) fixed in a Stevenson screen; rock surface temperatures as well as temperatures at varying depths within the rock were measured using copper-constantan thermocouples (Omega Engineering Inc.) that were placed both directly on the rock surface as well as within drilled holes measured to depths of 5 mm, 10 mm, 15 mm, and 20 mm beneath the surface. Temperatures were recorded every 60 seconds, averaged hourly and stored using a CR10 datalogger (Campbell Scientific) with an accuracy of $\pm 0.1^\circ\text{C}$.

Rock samples containing cryptoendolithic microbial communities were collected in July–August 2001 from several different sites around the Eureka area identified for their varying physical properties (colour, porosity, friability). At each site the samples were obtained using geological hammers and placed in sterile roll-top bags, subsequently stored under cool, dark conditions until further analysis.

Subsamples for microbial identification were removed from endolith “zones” (areas showing visual presence of microbes) of freshly cleaved rocks using a high-speed tungsten carbide bit in a Dremel tool. 2.0–3.0 g of this material was inoculated in BG11 nutrient liquid media and incubated under continuous light at 25°C . Cultures were viewed on a Nikon Microphot FX-A light microscope under differential interference contrast with cyanobacterial identifications based on morphology (Rippka et al. 1979).

5 RESULTS

5.1 Diurnal temperature regime

Temperature measurements were taken in July 2001, normally the warmest time of year. Continuous temperature measurements of the ambient air, 0 cm and 1.0 cm depths (see methods) within a colonized south-facing vertical rock face over a sixteen-day period are shown in Figure 4. Weather for the majority of the monitoring period was typically sunny with periodic overcast conditions.

The maximum averaged ambient air temperature measured was 15.9°C , and the minimum 0.1°C . The daily temperature average was 6.0°C with an average diurnal variation of 10.0°C . A clear diurnal temperature

pattern due to the height of the sun over the horizon and associated shading of the study area is observed overlying normal temperature variations reflecting regional weather systems. Periodic overcast conditions are differentiated from unrestricted sunshine by the temperature difference between air and rock during daytime hours.

Rock temperatures generally followed ambient air temperature trends, but direct insolation has considerable influence on measured temperatures both on the surface as well as at shallow depths with the rock. Maximum temperatures were consistently higher both on the surface as well as within the rock, with a maximum peak rock-air temperature difference of 7.52°C at a depth of 1.5 cm below the surface. Temperature maximums were generally observed in late afternoon/ early evening as a result of prolonged heating of the rock surface. This was normally followed by a cooling trend as the rock face fell into the shade and the sun angle decreased. Air and rock temperatures decreased concurrently down to comparably low values around 0300 h, after which time increased solar radiation began to heat the air and rock surface as the sun traversed the sky.

Figure 5 shows temperature measurements for ambient air, rock surface (0 cm), and depths of 1.0 cm and 2.0 cm over a three-day period. The high thermal conductivity of the rock substrate is important in controlling subsurface temperatures: variations in temperature with depth are small compared to rock-air temperature and rock temperature amplitude is greater than air temperature. In addition, temperatures at deeper points (2.0 cm) experience a lag time during cooling as a result of heat retention in the mineral matrix.

5.2 Microbial colonization

Microorganisms are generally observed between depths of 1–3 mm beneath the rock surface (Fig. 3). The variability of organisms is diverse, ranging from green-pigmented cyanobacteria to red-pigmented bacteria and fungi. Physical rock property appears to have no influence on their relative presence and spatial distribution. In some cases, colonized rocks show a “bleached” zone beneath the surface presumably caused by the mobilization of metal compounds such as iron oxides.

5.3 Microbiology

Preliminary results show a number of filamentous as well as coccoid cyanobacteria in the cryptoendolithic environment. Filamentous cyanobacteria include *Pseudanabaena* sp. and *Nostoc* sp.; non-filamentous forms include *Chroococcidiopsis* sp. as well as a red-pigmented *Gloeocapsa* sp., both forming spherical to sub-spherical colonies in culture.

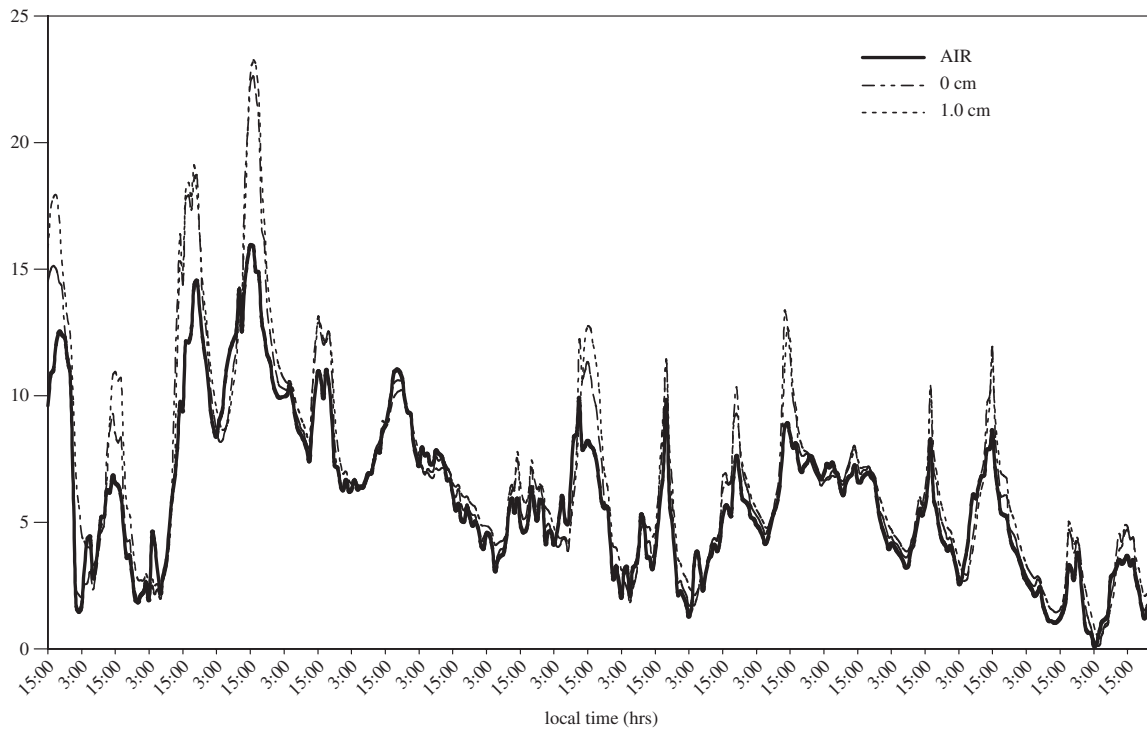


Figure 4. Air and rock temperatures of a sandstone outcrop containing cryptoendoliths, July 15–31, Eureka, Nunavut.

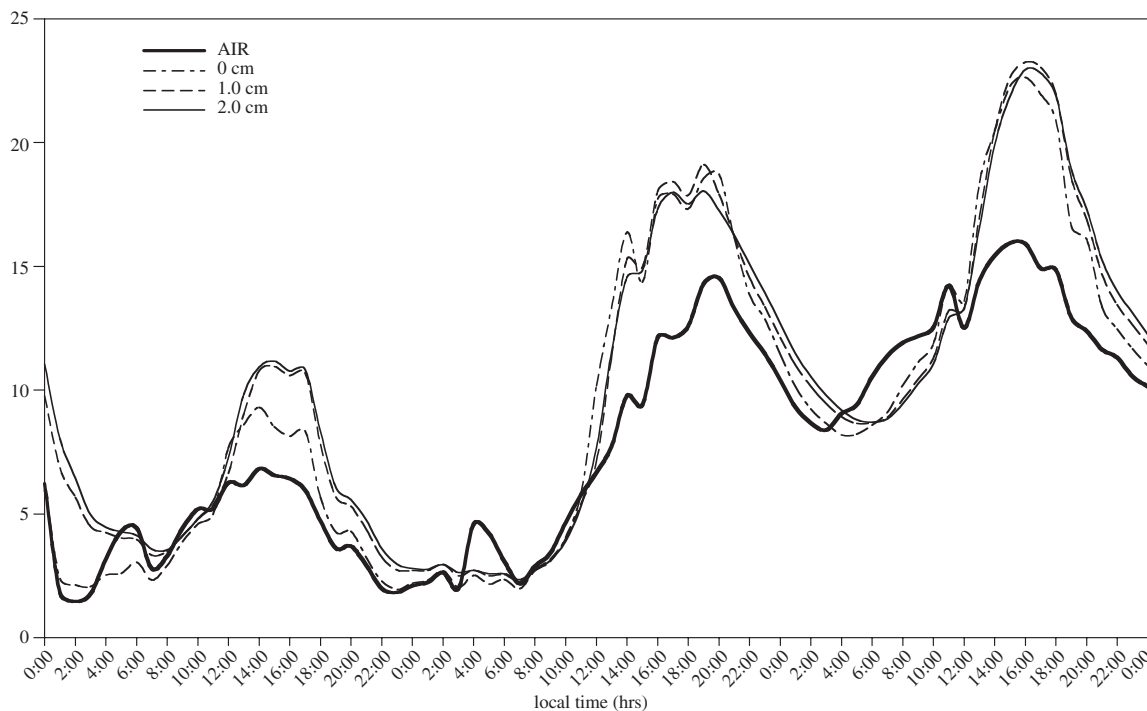


Figure 5. 72-hour period taken from Figure 4. Note large rock temperature amplitude due to heating of mineral grains as well as relatively small temperature difference with increasing depth.

6 DISCUSSION

6.1 Temperature

As shown previously (McKay & Friedmann 1985), microbial communities are commonly observed in the

subsurface zone of lithic environments that generally experience warmer temperatures during insolation over ambient air and surface temperatures. This preferential heating is due to the thermal characteristics of the rock substrate, leading to both higher absolute temperatures and longer perpetuation of these warmer conditions.

Similar conditions appear in the high Arctic environment (Fig. 4) and although differences in temperature with increasing depth are relatively small (Fig. 5), the overall warming of the subsurface creates a more hospitable environment for microorganisms.

Lewkowicz (2001) monitored the overall temperature regime of a sandstone tor of similar geology approximately 40 kilometers southeast of the current study location. In addition to identifying important temperature trends (e.g. differences between the degree of annual temperature amplitude and when the largest temperature differences between air and rock occur), Lewkowicz (2001) reports 51 temperature cycles through 0°C (freeze/thaw) on a SSE-facing rock surface in a one-year period, which has implications for both mechanical weathering as well as biological stress.

6.2 *Moisture availability*

The limited distribution of water in polar regions is highly uneven due to the fact that for much of the year this water is unavailable in the form of snow and ice, and much of this is lost through sublimation. However, due to the fact that rock surface temperatures can be significantly higher than air temperatures when in direct sunlight, snowmelt can be a significant contributor of water (Friedmann 1978) and can effectively extend periods of biological activity to times when air temperatures are still below 0°C. In addition, water entering the subsurface is retained within the rock matrix, persisting for days after ambient relative humidity has returned to normal low levels (Friedmann et al. 1987).

The Eureka area receives relatively little precipitation but this does not appear to be a limiting factor in the sustainability of microbial endoliths. Total precipitation is higher than in the Antarctic Dry Valleys and can occur as rainfall during summer months. Similar to Antarctic endoliths, the porous nature of the sandstone host rock permits infiltration of water down to several centimeters beneath the surface where it is commonly retained for hours after the precipitation event has passed.

6.3 *Photosynthetically active radiation (PAR)*

Although pore space temperatures are generally higher than air temperatures, the maximum depth to which phototrophic microbes can successfully survive is limited by the amount of PAR extending into the subsurface environment. This change in PAR with depth has been observed in a variety of endolithic environments (Nienow et al. 1988), creating a vertical zonation of microbial communities and restricting their migration deeper into the rock. Measurements of this steep light gradient in Antarctic rock samples show that approximately 0.1% of the ambient light energy

reaches the top of the cryptoendolithic microbial community but diminishes rapidly to 0.01% of total light at the depth of the lowermost organisms (Nienow et al. 1988).

Temperature changes induced by insolation propagate down to depths of 30 cm in sandstone outcrops in the high Arctic (Lewkowicz 2001) but current work shows that microbial colonization is restricted to the upper centimetre, presumably due to rapidly decreasing light required for photosynthesis. It is clear that light attenuation is an important factor in the vertical distribution of microorganisms in high Arctic cryptoendolithic environments, and future work will provide more definitive conclusions.

6.4 *Metabolic activity*

Based on climate data from the High Arctic Weather Station at Eureka, a general comparison of metabolic activity between the Arctic cryptoendoliths presented here and their counterparts in the Dry Valleys of Antarctica (77°36'S, 161°05'E) is presented. Friedmann et al. (1987) provide estimates for both (1) the total active period for metabolic activity (defined as the time period during which pore space temperatures within the rock are higher than -10°C), and (2) the ideal active period for metabolic activity (restricted to time periods when measured temperatures are above 0°C). In both cases, Friedmann et al. (1987) define the period of metabolic activity as also having conditions of humidity within the pore spaces >75% and light (PAR) above 100 μM photons · m⁻² · s⁻¹. Although data for humidity and PAR are currently not available for the Arctic cryptoendolithic environment, it is assumed that humidity and PAR levels are never a limiting factor in sustaining metabolic activity. This argument is consistent with the fact that air (and rock) temperatures between March and September are controlled by insolation, and radiation levels adequate to heat air and rock are greater than observed minimum requirements for metabolic activity. Furthermore, humidity levels measured in the pore spaces of Antarctic endoliths were always above minimum stated levels when temperatures were above -10°C, and the Dry Valleys experience much lower levels of precipitation than the area around Eureka. Based upon these assumptions, temperature is defined as the main controlling factor in determining periods of metabolic activity. In addition, although air temperature is used as the determinative control for metabolically-active periods, this is probably an underestimation as rock temperatures are generally always warmer than air temperatures when there is insolation, and it is therefore expected that subsurface temperatures to be warmer for longer periods of time than air temperatures.

Friedmann et al. (1987, 1993) estimated total time available for metabolic activity (i.e. when temperatures were higher than -10°C) of Antarctic cryptoendoliths to be between ~ 750 and $\sim 1000 \text{ hr} \cdot \text{yr}^{-1}$ depending upon rock aspect. Their calculated estimated ideal active period is far shorter, between 50 and $550 \text{ h} \cdot \text{yr}^{-1}$. In comparison, monthly-averaged temperature data for Eureka suggests that air temperatures remain above 0°C for approximately $2000 \text{ hr} \cdot \text{yr}^{-1}$, and the total number of hours when air temperatures are $> -10^{\circ}\text{C}$ extend this period of metabolic to activity to $\sim 2880 \text{ hr} \cdot \text{yr}^{-1}$. This would suggest that microbial activity in the polar North is generally higher and, given the fact that these organisms are presumably psychrotolerant, that they are more abundant in Arctic endolith environments.

7 CONCLUSIONS

This initial work reveals that cryptoendolithic microbial communities are present in the Canadian high Arctic in sandstone outcrops. The subsurface provides warmer temperatures during periods of insolation and is sheltered from more rapid climatic fluctuations. Preliminary microscopic identification suggests that they are relatively simple ecosystems consisting of several species of cyanobacteria that find refuge in the protected lithic environment. Endolithic microorganisms in the high Arctic experience longer growing seasons than Antarctic endolithic microbes due to overall warmer temperatures and longer periods when temperatures are above 0°C . It is likely that this results in increased ecosystem diversity and sustainability.

REFERENCES

- Atmospheric Environment Service, 1984. *Eureka*. Principal Station Data No. 79. Atmospheric Environment Service, Environment Canada: Downsview, Ontario.
- Banerjee, M., Whitton, B.A., & Wynn-Williams, D.D. 2000. Phosphatase activities on endolithic communities in rocks of the Antarctic dry valleys. *Microbial Ecology* 39: 80–91.
- Friedmann, E.I. & Ocampo, R. 1976. Endolithic blue-green algae in the dry valleys: primary producers in the Antarctic desert ecosystem. *Science* 193: 1247–1249.
- Friedmann, E.I. 1978. Melting snow in the dry valleys is a source of water for endolithic microorganisms. *Antarctic Journal of the U.S.* 13(4): 162–163.
- Friedmann, R.I. 1982. Endolithic microorganisms in the Antarctic cold desert. *Science* 215: 1045–1053.
- Friedmann, E.I. & Weed, R. 1987. Microbial trace-fossil formation, biogenous, and abiotic weathering in the Antarctic cold desert. *Science* 236: 703–705.
- Friedmann, E.I., McKay, C.P., & Nienow, J.A. 1987. The cryptoendolithic microbial environment in the Ross Desert of Antarctica: satellite-transmitted continuous nanoclimate data, 1984–1986.
- Friedmann, E.I., Hua, M., & Ocampo-Friedmann, R. 1988. Cryptoendolithic lichen and cyanobacterial communities of the Ross Desert, Antarctica. *Polarforschung* 58: 251–259.
- Friedmann, E.I., Kappen, L., Meyer, M.A., & Nienow, J.A. 1993. Long-term productivity in the cryptoendolithic microbial community of the Ross Desert, Antarctica. *Microbial Ecology* 25: 51–69.
- Johnston, C.G. & Vestal, J.R. 1989. Distribution of inorganic species in two Antarctic cryptoendolithic microbial communities. *Geomicrobiology Journal* 7: 137–153.
- Johnston, C.G. & Vestal, J.R. 1991. Photosynthetic carbon incorporation and turnover in Antarctic cryptoendolithic microbial communities: are they the slowest-growing communities on Earth? *Applied and Environmental Microbiology* 57: 2308–2311.
- Johnston, C.G. & Vestal, J.R. 1993. Biogeochemistry of oxalate in the Antarctic cryptoendolithic lichen-dominated community. *Microbial Ecology* 25: 305–319.
- Lewkowicz, A.G. 2001. Temperature regime of a small sandstone tor, latitude 80°N , Ellesmere Island, Nunavut, Canada. *Permafrost and Periglacial Processes* 12: 351–366.
- McKay, C.P. & Friedmann, E.I. 1985. The cryptoendolithic microbial environment in the Antarctic cold desert: temperature variations in nature. *Polar Biology* 4: 19–25.
- Nienow, J.A., McKay, C.P., & Friedmann, E.I. 1988. The cryptoendolithic microbial environment in the Ross Desert of Antarctica: light in the photosynthetically active region. *Microbial Ecology* 16: 271–289.
- Rippka, R., Deruelles, J., Waterbury, J.B., Herdman, M., & Stanier, R.Y. 1979. Generic assignments, strain histories and properties of pure cultures of cyanobacteria. *Journal of General Microbiology* 111: 1–61.
- Siebert, J., Hirsch, P., Hoffman, B., Gliesche, C.G., Peissl, K., & Jendrach, M. 1996. Cryptoendolithic microorganisms from Antarctic sandstone of Linnaeus Terrace (Asgard Range): diversity, properties and interactions. *Biodiversity and Conservation* 5: 1337–1363.
- Sun, H.J. & Friedmann, E.I. 1999. Growth on geological time scales in the Antarctic cryptoendolithic microbial community. *Geomicrobiology Journal* 16: 193–202.
- Vestal, J.R. 1988a. Carbon metabolism of the cryptoendolithic microbiota from the Antarctic desert. *Applied and Environmental Microbiology* 54: 960–965.
- Vestal, J.R. 1988b. Primary production of the cryptoendolithic microbiota from the Antarctic desert. *Polarforschung* 58: 193–198.
- Wierzchos, J. & Ascaso, C. 2001. Life, decay and fossilization of endolithic microorganisms from the Ross Desert, Antarctica. *Polar Biology* 24: 863–868.
- Woo, M.-K., Heron, R., Marsh, P., & Steer, P. 1983. Comparison of weather station snowfall with winter snow accumulation in High Arctic basins. *Atmosphere-Ocean* 21: 312–325.
- Wynn-Williams, D.D., Edwards, H.G.M., & Garcia-Pichel, F. 1999. Functional biomolecules of Antarctic stromatolitic and endolithic cyanobacterial communities. *European Journal of Phycology* 34: 381–391.