Nannobacterial alteration of pyroxenes in martian meteorite Allan Hills 84001

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(Received 2002 January 16; accepted in revised form 2002 May 2)

Abstract—In martian meteorite Allan Hills (ALH) 84001, this scanning electron microscope study was focused on the ferromagnesian minerals, which are extensively covered with nanometer-size bodies mainly 30–100 nm in diameter. These bodies range from spheres to ooids to caterpillar shapes and resemble, both in size and shape, nannobacteria that attack weathered rocks on Earth and that can be cultured. Dense colonies alternate with clean, smooth cleavage surfaces, possibly formed later. Statistical study shows that the distribution of presumed nannobacteria is very clustered. In addition to the small bodies, there are a few occurrences of ellipsoidal 200–400 nm objects, that are within the lower size range of "normal" earthly bacteria. We conclude that the nanobodies so abundant in ALH 84001 are indeed nannobacteria, confirming the initial assertion of McKay et al. (1996). However, whether these bodies originated on Mars or are Antarctic contamination remains a valid question.

INTRODUCTION

Martian meteorite Allan Hills (ALH) 84001, found lying in the Antarctic ice by NASA scientists in 1984, became the object of intense scientific interest when McKay et al. (1996) announced the existence of possible martian life. The most dramatic criterion for life was the presence of minute sausage-shaped "nannobacteria", which resembled recently discovered organisms just like terrestrial bacteria except for the fact that, with diameters of 0.05–0.25 μm, the martian "fossils" were only about 1/1000th the volume (Folk, 1993; McBride et al., 1994; Sillitoe et al., 1996; see Romanek, 1997, for an interesting account of how the discovery came about). This conclusion led to a firestorm of objections by the biological/paleontological community that these objects were far too small to be living organisms, as the lower limit of life was supposed to be around 0.2–0.25 μm (see Knoll and Osborne, 1999, for a recent emphatic restatement). This NASA discovery, the best potential key we have yet to the existence of extraterrestrial life, has led to a multitude of conferences, papers and books, and dozens of scientific squabbles (e.g., Hoover, 1997; Folk and Lynch, 1997a, 1998, 1999; Benoit and Taunton, 1997; Goldsmith, 1997; McSween, 1997; Parker, 1998; Gibson et al., 1998; Thomas-Keprta et al., 1998, 2000; Sears and Kral, 1998; McKay et al., 1999; Taylor, 1999; Treiman, 1999; Schopf, 1999; Folk and Taylor, 2000; Gillet et al., 2000; Folk et al., 2001b).

We will only address, to a limited extent, the two principal arguments against the martian ooids and worms being fossilized microorganisms, then proceed to our own study on the several grams of ALH 84001 obtained by L. A. T. from NASA. We fully realize that morphology alone cannot establish without a doubt the existence of ancient life, especially in forms so bland and minute, moreover coming from outer space and perhaps billions of years old. But morphology is a start.

Negative argument (1) was that the photographs published by NASA in 1996 (and many later photos published by other authors since) showed merely artifacts of the gold-coating process (such as gold-decorated cleavages) and did not represent real objects in the specimen (Bradley et al., 1997; Kerr, 1997; Sears and Kral, 1998; Bradley, 1999). They were right in one respect: excess gold coating of 1 min or more, indeed, can produce nannobacteria-like artifact beads (see Folk and Lynch, 1997b and McKay et al., 1997b, for a discussion of the artifact problem). However, on the Denton machine at University of Texas, Austin, a gold coat of 30 s provides excellent imaging with no artifacts visible at 100 000×, sharp crystal edges (e.g., Fig. 1) and clearly defined "real" objects as small as 20–30 nm. The gold-coating argument is invalid if proper procedure is used, but each laboratory must run experiments with its own sputter-coater.

To further investigate this problem, R. L. F. was invited by Dr. Kenneth Nealson to NASA Jet Propulsion Laboratory (JPL) in February 2001, so that a joint examination could be made of a sample from the hot springs of Viterbo, Italy, the discovery site for nannobacteria. First, a non-coated sample was placed in the environmental scanning electron microscope (SEM). Abundant 30–70 nm spheres and ooids were found in the center of aragonite-needle spherulites. Second, a similar Viterbo
nannobacteria demonstrate that they can reproduce on their own without having to invade larger cells. Scanty genetic data by other laboratories on modern, similarly minute analogues, allies them most closely with the proteobacteria. On those grounds, we continue to designate them as fossilized "nannobacteria" as opposed to viruses or blobs of non-living organic chemicals. Indeed, if these are organisms approximately 3 or 4 Ga old, it is not likely that many diagnostic organic chemicals or bits of DNA strands will survive to further identify them.

Most of NASA's published work has centered on the disc-shaped, zoned-carbonate concretions (mostly calcite) found in fractures in ALH 84001 (McKay et al., 1996; Benoit and Taunton, 1997). Studies of the mother igneous rock include that of McKay et al. (1997a) and Westall et al. (1998), who found possible biofilms on pyroxene surfaces, and Thomas-Kepka et al. (1998), who studied martian forms on igneous minerals compared with bacteria cultured from subsurface basalts on Earth.

Meteorite ALH 84001 is a piece of the original martian crust, 4.5–4.6 Ga old, that dates virtually to the beginning of the solar system. It is an orthopyroxenite, consisting of ~90% orthopyroxene (hypersthene), with 10% olivine, chromite, and other accessories (Mittlefehldt, 1994; Treiman, 1995; Shearer, 1999). It underwent an early period of shattering and heating, probably by meteorite impact. At one time, running water was common on Mars (Baker, 1982; Carr, 1996), and at some stage, these fractures were infiltrated by water, and the zoned disc-shaped plaques of Ca (with some Fe and Mg) carbonates were precipitated within them. These carbonate precipitates are dated as 3.9–4.1 Ga (Borg et al., 1999). A later period of intense shattering occurred, probably caused by the huge impact that sent the martian rock careening into space ~16 Ma ago. Thus, the rock is pervasively riddled by fractures and crush zones (Mittlefehldt, 1994).

If at one time early in its history, Mars had surface water, there surely was also subsurface water; if the surface was strongly impacted by incoming asteroids or meteorites, there must have been an almost infinite number of fractures in the subsurface rocks, ranging from meters to nanometers wide; and, if the rocks consisted of iron-rich minerals such as hypersthene or olivine, then the conditions were ideal for nannobacterial life to develop. In the presumed warmth of subsurface Mars, this seems almost to be an inescapable conclusion.

RESULTS OF THE SCANNING ELECTRON MICROSCOPE STUDY

Several bits of the meteorite were obtained by L. A. T. from Planetary Materials Curation at Johnson Space Center before the rock became notorious. The pieces of ALH 84001 reported on here contain no evidence of carbonate veins, and all the possible bioforms we report occur on minerals that test out with energy dispersive x-ray spectrometry (EDS) as silicates.
rich in Fe and Mg, or as chromite crystals. The fragments have a pale-grayish olive-green color (5GY 5/1). Chips were mounted with Duco cement on an Al stub and gold coated for 30 s only.

We compare here the putative bioforms found on the meteorite fragment with very similar appearing objects found on volcanics as a result of weathering; an Italian tuff, a limburgite peridotite (Pilot Knob, Travis Co., Texas, USA), and a submarine-weathered basalt off Kilauea (collected by K. L. Milliken). A preliminary comparison of the martian photos previously published by NASA with similar images of nannobacteria from Sicilian clays was published by Folk and Lynch (1997a).

In our sample, we have looked at surfaces of Fe-Mg silicates (pyroxene vs. olivine not distinguished) and at one chromite crystal. The chromite is heavily covered with nanobodies (to adopt a purely descriptive term), while the adjacent pyroxenes show a smaller population.

Pyroxene surfaces range from nanobody-free, vacant areas showing sharp cleavage planes, to surfaces with scattered single nanobodies, to those with discretely defined colonies, to surfaces completely covered with nanobody balls or caterpillar-shaped bodies.

Smooth, non-colonized surfaces look crisp, break with well-defined cleavage, and possess no nanobodies when viewed at 20,000×. However, when the magnification is increased to 50,000×, a curious curdled or mud-crackled appearance is revealed, at a scale of 50–100 nm (Fig. 1). This may be an artifact of SEM preparation or examination, but we do not find it on all rocks. We do find it on weathered samples of igneous rocks (e.g., see Fig. 21 in Folk and Lynch, 1997a), and the same feature was illustrated by McKay's group on Mars ALH 84001 (Gibbs and Powell, 1996), but not mentioned in the discussion. We suspect it may have been a mucus-like coating (biopolymer) on the incipiently weathered minerals. The smooth cleavage surfaces that are not covered with nanobodies may have been late fractures generated by the impact that blasted the meteorite into space, or produced when it was freshly broken in sampling.

We now discuss the more interesting modified surfaces. Isolated 20–60 nm balls scattered over a surface are shown in Figs. 2 and 3. Distinct colonies of uniformly sized nanobodies, with adjacent smooth, deserted areas, are shown in Fig. 4. Nanobodies here are uniform in size at 50 nm. The presence of deserted areas is important because it belies the criticism that the little balls are the result of gold-coating artifacts during SEM preparation (see Folk and Lynch, 1997b, for discussion of this problem).

**Fig. 2.** Sparse, isolated clumps and chains of 20–30 nm balls on a slightly naturally etched mineral surface.

**Fig. 3.** Thinly scattered 40–60 nm nannobacteria. Some chains and worm-like forms are visible.

**Fig. 4.** Distinctly defined colony of nannobacteria in contrast to an adjacent smooth deserted area. The bodies here are 40–50 nm wide, and most are slightly elliptical, a good plus for "biology".
More densely crowded accumulations of nanobodies are shown in Fig. 5 (40–110 nm) and Fig. 6 (20–50 nm). In Figs. 7 and 8, nanobodies of 30–50 nm merge into a quasi-uniform sheet, losing their identity and forming a continuous film. Figure 9 illustrates a naturally etched martian pyroxene covered with 25 nm balls that again may represent some form of mucus-like biofilm (see Westall et al., 1998) rather than being fossilized organisms per se.

Nanobodies in any one field of view are relatively uniform in size, about as alike as canned peas, but some samples have balls of widely ranging sizes (e.g., Figs. 3 and 8) where they range from 25 to 75 nm. See later section for a quantitative discussion.

Rare surfaces are covered with a swarm of caterpillar-shaped bodies 30 nm wide and 100–150 nm long (Fig. 10), as also depicted by the famous NASA images (photo by McKay et al. at NASA; published by Treiman, 1996; Gibbs and Powell, 1996; Jakosky, 1997). At the limit of resolution, one can see that they are, at least in some examples, made up of strings of minute equant 30 nm beads. Even though there is an undeniable main trend of orientation, there is a great deal of deviation from this trend, and individual bodies often show sinusuous curves and "crawl" over each other, so that the criticism that this feature represents excess gold-coat artifacts on exposed cleavage surfaces (Bradley et al., 1997) is not valid (note: compare the clean, sharp cleavages in Fig. 1). McKay et al. (1997a,b) also illustrated caterpillar-like forms on flake-edges. Westall et al. (1998) illustrate a plant to web-like possible biofilm on the pyroxene. An alternate interpretation of their Fig. 2c infers irregular chains of 30–40 nm spheroids that appear to be similar to nanobacteria. Strikingly similar nanobacterial

**FIG. 5.** More densely scattered nanobacteria, mostly 50–80 nm wide; many are ovoids. Measurement data on size and shape are shown in Fig. 19.

**FIG. 6.** Pyroxene surface completely covered with tightly-packed 20–50 nm balls. These may be incipient nannobacterially generated clays, advancing in shingled sheets of balls.

**FIG. 7.** (a) Another tightly packed layer of balls, merging at right into an almost-solid sheet, where balls can barely be made out. (b) An enlarged view shows the 30–40 nm balls in a more loosely packed area; measurement data in Fig. 19.
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"caterpillars" have been cultured on feldspars by Spark et al. (2000).

McKay's team at NASA (e.g., McKay et al., 1999) found larger bacteriform objects (spheroids of 0.3 μm, some in chains; and a large ellipsoid ~2 × 0.8 μm). We have also found occasional groups of larger bacteriform objects, smaller than "normal" bacteria (which typically are 0.5 × 1 to 2 μm), but larger than the 50–200 nm nannobacteria on Earth (Fig. 11). These are bacillus-shaped bodies, with a rather uniform width of ~150 nm and length of 300–500 nm (see measurements below). The rounded ends and slightly curving shapes indicate a life form rather than a mineral crystal. Had these been seen in a modern sediment, no biologist would have hesitated in proclaiming them to be a small variety of bacteria. Two are even seen in close conjunction (Fig. 11d, perhaps a rare example of fossilized reproduction), and some bacillus-like bodies have collapsed centers (Fig. 12), a characteristic of living objects with tough cell walls and easily decomposed interiors.

The features we have seen on these small pieces of martian meteorite ALH 84001 can be duplicated precisely by terrestrial examples, and here, we show only a few (see Folk and Lynch, 1997a, for other examples). Terrestrial analogues include

Fig. 8. Balls and ovoids of a wide size range, 20–70 nm.

Fig. 9. Naturally etched martian pyroxene surface. The etched surfaces are covered with a uniform coat of 20 nm balls. This is probably some feature of biologic etching, but the specific origin is not known; it may have been a biofilm reacting with the mineral in some way. It is analogous to similar features on terrestrial pyroxenes (Fig. 15).

Fig. 10. (a) Most nannobacteria are spheres to stubby ovoids, but one sharply defined field of worm-like forms was found (measurements in Fig. 19). The bodies are lying on a flat cleavage plane of the pyroxene. There is a general mineralogically controlled trend, but a great deal of randomness as well. (b) At the limit of resolution some "worms" appear to be made of chains of beads.
Fig. 11. Groups of larger bacilliform bodies, some almost large enough to qualify as "normal size" (300–500 nm long). Scale the same for all photos. The two lower fields show possible examples of reproductive pairs. The surface upon which these putative martian bacteria lie is covered with minute irregularities on the 10–20 nm scale, perhaps representing the effect of a biofilm modifying the mineral surface (analogous to those shown in Fig. 9).
distinct colonies (Fig. 13) and entire carpets of little balls on altered basic igneous rocks (Figs. 14 and 15), as well as worm-like forms (Fig. 16). In the laboratory we have succeeded in growing, in culture experiments, minute nannobacteria of similar size and shape to the martian bodies (Fig. 17, a range from tiny 40 nm ovoids to worm-like forms, and Fig. 18, analogous to Fig. 5 from Mars). Figure 19 compares the sizes and shapes of these cultured organisms to those found on the martian meteorite; the dimensional similarity between putative extraterrestrial organisms over 3 Ga old, and living cultures on Earth is remarkable.

Quantitative Study of Abundances, Sizes, and Shapes

How abundant are nannobacteria on the pyroxenes of our piece of the martian meteorite ALH 84001? Are we "cheating" by showing photographs of especially-dense fields? Does it require intense searching to find a few good examples, or are bodies spread throughout? To address these questions, we conducted a population study by choosing random fields following the protocol in Folk and Chafetz (2000).

(1) At a magnification of only 1000×, choose a field at random. Select an area that is relatively smooth and not tilted, and avoid grain contacts or large pores. At 1000×, one cannot resolve nannoflora, so this is an impartial method.

(2) Increase magnification up to 20 000×, and put on the small exposure (EXP) screen for best resolution. The area of the screen is now about 2 × 2 μm, and the magnification is high enough to resolve most genuine nannoflora.

(3) It is not feasible to count every one of the nanobodies in the counting area, so a logarithmic abundance scale of nanobodies/area is used: 0, 1–3, 4–10, 11–31, 32–100, over 100. Tabulate 50 such random fields.

When this was done for our samples of ALH 84001, about one-third of the 2 × 2 μm fields are devoid of nanobodies; and about half the fields contain 4–31 bodies per unit area, with a mode of about 10–15 (Table 1). A few counting fields have a hundred or more bodies. Such clustered distributions are typical for biologic populations; where food is abundant or "colonists" land, reproduction occurs, and the population spurs at that locality.
Fig. 14. Heavily weathered surface on pyroxene, covered with 30–50 nm ovoid nanobacteria. Pilot Knob basalt, Travis Co., Texas, USA ~1 mm from the outer weathered surface. Compare with Mars (Fig. 6).

Fig. 15. Weathered and etched pyroxene, covered with 20 nm balls, perhaps a biofilm; Pilot Knob, Texas, USA. Compare with etched martian pyroxene, Fig. 9.

Fig. 16. Weathered submarine basalt off Kilauea, Hawaii, USA (collected by K. L. Milliken). "Worms" are ~45 nm thick. Compare with martian "worms", Fig. 10.

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<tr>
<th>Number of bodies in area</th>
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<tr>
<td>0</td>
<td>34</td>
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<tr>
<td>1–3</td>
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<td>32–100</td>
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Shapes and Sizes of Putative Nannobacteria in Allan Hills 84001

It is obvious that some SEM fields of view contain swarms of uniformly minute bodies, other fields show mainly larger bodies, and some fields show a mixture of sizes. Do most nannobacteria have spherical, ovoid, or worm shapes? To address this question, a quantitative study of sizes and shapes was done on four different SEM fields, deliberately selected for their ranges of sizes and shapes. However, specific individuals measured were chosen by a random-grid system. Dimensions were measured with a $3\sqrt{2}$ scale of graded circles (ratio 1.26). The results are shown in Fig. 19.

Field (1), obtained from Fig. 7a, consists of densely crowded, uniformly scattered objects. Field (2), from Fig. 5, has larger and more widely scattered bodies, and is typical of most areas examined on this piece of Mars. Field (3), from Fig. 10b, is a restricted colony of worm-shaped nannobacteria, and group (4) is a compilation of larger bodies from several different SEM fields. Common to all bodies is the fact that they have rounded ends, which are not characteristic of minerals; in all examples, width tends to be constant as length increases, so that larger ones are also more elongate.

Field (1) is crowded with small, tightly packed bodies that, in fact, merge together in part of Fig. 7b. The average length is 40 nm (two-thirds of the bodies range between 30 and 50 nm); the coefficient of variation (CV, $\sigma$/mean) is 25%, so these bodies are as well sorted as a typical beach or dune sand. The average width is near 30 nm, so that these particles are somewhat ovoid, especially the larger ones (which average length/width (L/W) = 1.5:1).

Field (2), from Fig. 5, consists of well-defined individuals scattered uniformly over a pyroxene surface. These are larger and also have a much wider size range; the average length is 95 nm (two-thirds range 60–130 nm, with a CV of 35%). Widths are more constant, averaging 60 nm (two-thirds range 45–80 nm), and the average L/W ratio is 1.5:1, so they are clearly ovoid; again, larger ones are more elongate (2:1).

Fields (1) and (2) appear to grade into each other on the graph, so we suggest that if the bodies are closely packed, they cannot grow much more; the more loosely scattered nannobacteria—perhaps with better access to nourishment—
FIG. 19. Length vs. width plots for martian nannobacterial bodies. (a) Field (1), the dwarfs, shown in triangles; field (2) shown as filled dots, for which width remains fairly constant as the length increases. Field (3) shown by “v” is clearly distinct from field (2), in the worm-like shapes with widths constant at ~30 nm. The smaller individuals of the “giant” bacteria are shown by “X”. Ellipsoids, in the upper left of the field, show accurately plotted dimensions of the range of body sizes and shapes in the three fields. (b) Similar to (a) but condensed to show accurately the size of the “giant” martian bacteria (hexagons) in comparison to the shaded fields which are based on the points in (a). The arrowed, curved line “H” refers to dimensions of modern cultured nannobacteria from the work of Hiebert (1994); and the short, arrowed line “B” refers to cultured nannobacteria from Barton Springs water. The emphasis here is that modern, culturable nannobacteria have the same sizes and shapes as the probable fossilized martian nannobacteria that are billions of years older and from another planet. The upper curved, dashed line showing a volume of 4 x 10^6 nm^3 for the bodies is the “lower limit of life” as proposed by most biologists (e.g., Knoll and Osborne, 1999), representing a sphere 200 nm in diameter. The lower curved, dashed line shows a value of 500 000 nm^3 for the approximate volume of the larger nannobacteria in ALH 84001. Clearly, both the modern culturable nannobacteria and most martian analogues are much smaller than the “lower limit of life”, though the larger martian “giants” extend into the non-objectionable realm of “possible life”. 
can grow to considerably larger size, mainly by lengthening. The individuals in group (2) have \( \sim 10 \times \) the volume of those in group (1).

Field (3) is unique in the abundant worm-like shapes (Fig. 10). Lengths of the nannobacteria show a wide variation, averaging 100 nm (two-thirds range 70–140 nm); but the width is quite constant between 25 and 35 nm. The average L/W is 3:1, but they range up to 5:1. At the limit of resolution (100 000×), some appear to be made up of a single string of 30 nm beads (the same size as those in field (1)). The nannobacteria are often curved and writhe over each other like pulling maggots, clearly not mineral characteristics or "cleavage outcrops". For smaller "worms", field (3) appears to grade into field (1) as the width stays the same.

Group (4) is a compilation from various SEM fields, and represents "giants" with a huge size range. Of the 19 bodies measured, two-thirds of them range from 200 to 400 nm long and 100–200 nm wide; the average body is 300 × 160 nm. As in groups previously noted, the larger ones show greater elongation as the width remains relatively constant. They average \( \sim 20 \times \) the volume of their most closely related group (i.e., group (2)); with a volume of \( 4 \times 10^{6} \) nm³, they are large enough to be considered real "bacteria" by microbiologists, though pressing their lower size range.

Are these groups gradational populations, differentiated by age, nutrition, or something else? Or are they different "species"? At this point, one can only wonder, until significant biological work can be done on terrestrial nannobacteria. In Fig. 19b, two-dimensional shape plots of living, cultured nannobacteria are superimposed on the supposed nannobacteria in this martian rock. The culture from Barton Springs (Austin, Texas, USA) has elongate bodies ranging 50 to 200 nm long and falls between martian fields (2) and (3). The Hiebert (1994) starvation culture shows bodies ranging from the small objects in field (1) up into the martian "giants" of about 200–400 nm, hewing close to the 2:1 elongation line. Thus, both cultured examples fall right in with the dimensions of the nannobacteria on this piece of Mars.

**CONCLUSIONS**

We have studied and reported here on the pyroxenes/olivines of the mother rock of the martian meteorite ALH 84001, not the vein-filling carbonate disc or globules in which NASA scientists first discovered "nannobacteria" (McKay et al., 1996). The pyroxenite mass is completely pervaded by nanobodies, mainly in the 30–120 nm range. These are clearly not "gold-coat artifacts" or "cleavage outcrops". These minute forms do not have crystal faces; instead, they are spheroids, ovoids, and worm- or caterpillar-shapes with rounded ends. Their shapes are definitive of microbiology, not mineralogy, and match those found on weathered basic rocks on Earth. Had they been \( 10 \times \) larger, no biologist would have objected to their being identified as fossil bacteria. A quantitative study of their occurrence shows that they are abundant throughout the meteorite fragment; though absent in about a third of the 2 × 2 \( \mu \)m fields censused, they range up to over 100 per field of view, with a mode of about 10–15 bodies per field. Precise measurement of their lengths and widths shows several groups, predominately of elliptical shape, with a most common aspect ratio of 1.5:1 to 2:1. Similar measurements of nannobacteria cultured on Earth reveal a remarkable dimensional similarity. On the basis of these identities, we conclude that the nanobodies so abundant in ALH 84001, indeed, are fossil nannobacteria, confirming the initial assertion of McKay et al. (1996).

Whether these nanofossils are terrestrial contamination, as is the case with the outer edge of martian meteorite Dhofar 019 (Folk et al., 2001b), or are remains of martian organisms, perhaps billions of years old, is a matter for much further study. L. A. T. prefers the former conclusion, while R. L. F. favors the latter. To solve this question, a quantitative traverse must be performed from the rim to the center of the large piece of ALH 84001, using the census protocol herein and examining the silicates of the mother rock. Furthermore, a similar census must be made of basic igneous rocks outcropping in Antarctica, or occurring within moraines, in order to show the abundance of nanofoms from rim to center of terrestrial rock samples, and the degree of penetration along fractures.

This will result in one of two alternatives: (1) nannobacteria are abundant throughout ALH 84001, with no concentration toward the modern weathered rim; and, basic igneous rocks known to be of Antarctic provenance and subjected to Holocene weathering show no nannobacteria or they are present only on the weathered rim. In this case, the conclusion is that the nannobacteria, indeed, do represent extraterrestrial life forms, and they should now be represented by remnants of highly matured organic chemicals. (2) Nannobacteria are found concentrated on the rim of ALH 84001 with few or none in the center; and basic rocks from Antarctica also show nannobacterial alteration near the rim. In this case, the alteration by nannobacteria is clearly terrestrial contamination, and should be easily identified by chemical tests revealing immature organic compounds, or by \(^{14}C\) dating.

If case (2) prevails, there is a hugely important process of nannobacterial alteration going on in the relatively sterile environment of Antarctica, a process totally unknown to biologists, who have not yet examined rocks using magnifications we use here. Then, the implications for calculating Earth biomass are enormous, and it behooves microbiologists to make a serious effort at investigating them.

**Acknowledgements** – We thank Anne Marie Christian for typing, Joe Jaworski for preparation of the plates, F. Leo Lynch for assistance with the SEM work on the Italian clays, and Ina Pavlova for growing the cultures. In addition, Frances Westall did an evaluation of the manuscript for which we are grateful. Francis Chapelle and an anonymous critic did a great job of finding mistakes and casting out hyperbole, as did the careful review and editing of Scott Sandford. The Geology Foundation of the University of Texas supported the SEM study. A portion of this research was also supported by NASA grant S-10414 to L. A. T.
Although the views expressed in this paper are not all as strongly held by both authors, minor disension is healthy. The reader is left to draw his/her own judgement about who wrote what and its significance. In particular, L. A. T. wishes to thank his long-time Tennessee friend, Jack Daniels, for providing the encouragement for him to participate in the noble venture of this study.

Editorial handling: S. A. Sandford

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