Life on Mars: Evidence from Martian Meteorites

David S. McKay[1] Kathie L. Thomas-Keprta[2] Simon J. Clemett[2]
Everett K. Gibson[1], Jr., Lauren Spencer,[1] and Susan J. Wentworth[2]. [1]NASA Johnson Space Center, 2101 NASA Parkway, Houston TX USA; [2]Jacobs Technology, NASA Johnson Space Center, 2101 NASA Parkway, Houston TX USA 77058

ABSTRACT

New data on martian meteorite 84001 as well as new experimental studies show that thermal or shock decomposition of carbonate, the leading alternative non-biologic explanation for the unusual nanophase magnetite found in this meteorite, cannot explain the chemistry of the actual martian magnetites. This leaves the biogenic explanation as the only remaining viable hypothesis for the origin of these unique magnetites. Additional data from two other martian meteorites show a suite of biomorphs which are nearly identical between meteorites recovered from two widely different terrestrial environments (Egyptian Nile bottomlands and Antarctic ice sheets). This similarity argues against terrestrial processes as the cause of these biomorphs and supports an origin on Mars for these features.

Keywords: Mars meteorites, ALH84001, Nakhla, Y000593, Life on Mars

INTRODUCTION

Martian meteorite ALH84001

Our original publication on this subject presented a suite of characteristics closely related in space and time within martian meteorite ALH84001, all of which could be best explained by a hypothesis that they were formed by microbes early in martian history.[1] These observations included the presence of chemically zoned carbonates precipitated from water in cracks openings in the meteorite, morphological forms similar to known terrestrial fossils, polycyclic aromatic hydrocarbons (PAHs) associated with the carbonates, and nanophase magnetites embedded within the carbonates. A single hypothesis that all of these features were formed or assisted by early martian microbes was proposed by us. Initially, this hypothesis was challenged on the basis that some of these features were terrestrial contamination, and that the carbonates formed at high temperature.[2; 3] Detailed published studies by our group[4] and others[4-6]successfully refuted each of these objections. One alternative hypothesis, that the carbonates formed by inorganic precipitation[7; 8] was also shown to be incapable of explaining the chemistry and the morphology of the actual martian carbonates. [4]Additionally, it was proposed that the nanophase magnetites were formed by thermal and shock heating of the iron-rich carbonate present in ALH84001 during its early martian history or during the impact that ejected it from Mars.[9; 10]

To summarize the current situation, most of the scientific community now accepts that nearly every ALH84001 feature that we discussed in the original *Science* paper actually formed on Mars including the carbonates and the magnetites. Formation of the carbonates by precipitation from water at moderate temperatures is also now generally accepted[4]. The Recent detailed analysis and thermodynamic treatment has now definitively ruled out the hypothesis that the nanophase magnetite within ALH84001 formed by thermal or shock decomposition of any of the associated carbonate[11]. ALH84001 Background

McKay et al[1] characterized a number of closely associated features in ALH84001 and suggested that this suite of features, taken together, could best be explained by a biogenic hypothesis in which early Martian microbes were directly or indirectly involved in producing the features. These features include:

Carbonate globules or pancakes found in cracks and veins which we suggested were formed at relatively low temperatures and involved water--formation possibly assisted by microbial action

Possible microfossils are present (biomorphs)

Polycyclic Aromatic Hydrocarbons (PAHs) are present and closely associated with carbonates

Nanophase magnetite (Fe_3O_4) similar to magnetite produced by magnetotactic bacteria is present embedded in the carbonates

This suite of features taken together provided the possible evidence for the biogenic hypothesis. Note that no single feature was either definitive for biology, or conversely, that showing that no single feature was definitely produced by non-biogenic processes would invalidate the hypothesis, although it would clearly weaken it.

A number of early objections to our hypothesis were made at meetings and in publications:

The carbonate globules formed at high temperature by volcanic or impact processes on Mars

The meteorite was contaminated in Antarctica

Carbonates grew in Antarctica

PAHs were deposited from Antarctic melt water

Magnetites were from terrestrial sources such as wind-blown dust

Magnetotactic bacteria would not develop on Mars because Mars had no magnetic field

The "microfossils" were coating artifacts added during preparation for SEM studies

The microfossils were too tiny to be real

We addressed most of these objections in published rebuttals and papers. In addition, some of the earliest criticisms were essentially retracted by more careful analysis of the available data. Some[3; 12] proposed that the carbonates formed at high temperatures. If true, this would rule out microbial involvement and seriously weaken our hypothesis. These papers were given wide play in the media and in some scientific meetings. The consensus began to develop that we had been discredited. However, Treiman and RomanekWarren 1998, and McSween and Harvey ,2000 [5] published papers supporting a low temperature aqueous precipitation hypothesis for the carbonates. Note that McSween and Harvey did a complete reversal from their earlier interpretation of the carbonates.[5] The majority of scientific papers published in the past 10 years now accept that carbonates formed on Mars at low temperature by precipitation from water.

Terrestial contamination was another issue. However, detailed isotope studies proved that the carbonates formed on Mars, not in Antarctica. Careful search for PAHs in Antarctica melt waters near the collection site failed to find detectable PAHs casting doubt on whether the ALH84001 PAHs resulted from contamination[13]. Laboratory results showed that PAHs are relatively insoluable in water and would not be concentrated in carbonates. It is now generally accepted that the PAHs in this meteorite are Martian in origin.

Similarly, if the carbonates are Martian, the embedded magnetites must also be Martian. No mechanism has been proposed to embed terrestrial magnetite in the Martian carbonates. One objection to the hypothesis that the Martian magnetites were produced by Martian magnetotactic bacteria is that Mars did not have a global magnetic field, thought to be a requirement for bacteria to develop magnetic inclusions within their cells. However, after the original paper was published, mapping of the Martian surface by orbiting spacecraft revealed that early crustal rocks did have strong remnant magnetism which could only be explained if Mars had an early strong magnetic field, now gone.

While some researchers [14]have supported our biogenic hypothesis for the origin of many of the magnetites, a number (Golden et. al, Treiman, Brearly, and others) [2; 8; 15; 16]have proposed an alternative hypothesis that the magnetite was formed totally nonbiologically by thermal decomposition of the iron-rich carbonate during or following an impact shock event.[7; 8; 15] This alternative non-biologic hypothesis has been used for the past decade as the primary argument against our hypothesis. In a recent paper, we have now addressed this alternative hypothesis in detail and have shown that it cannot explain the pure chemistry of the most of the magnetites and their lack of other cations such as Mn and Mg considering that surrounding carbonate is mostly a mixed carbonate containing Mg, Mn, and Ca as well as Fe virtually all laboratory studies have shown that thermal decomposition of a mixed carbonate produce a mixed composition spinel (magnetite), not the pure Fe magnetite common in the carbonates[11]. We conclude that the nanophase magnetites could not have been made by thermal or shock decomposition of the carbonate and therefore these magnetites had a separate origin not directly related to the carbonates. Our original hypothesis that they were produced by martian magnetotactic bacteria and introduced and trapped in the precipitating carbonate pancakes remains a viable explanation. The unique properties of these magnetites (elongated along the c-axis, single domain grain size, extremely pure Fe oxide, tightly sorted grain size distribution) remains a suite of properties absolutely unique to magnetotactic magnetites on Earth[17]. This suite of properties has been used for decades as certain biosignatures when found in terrestrial sediments or water. Application of this biosignature concept to these martian magnetites remains a viable and credible approach.

BIOMORPHS IN ALH84001

Biomorphs are physical features and textures that resemble features known to be biogenic from terrestrial environments. Biomorphs are not proof of a biological origin, but can serve as pointers for further investigation such as chemistry, isotopic characterization, and mineralogy. Additional biomorphs have been found within ALH84001. **Figure 1** shows a series of molds within the carbonate pancakes of this meteorite. These molds are lined with a lower Z lining. The uniform ~1 micrometer diameter of these molds is characteristic of molds of many kinds of coccoid bacteria cells where the impression of the cell is left in the matrix after the cell has decayed away. **Figure 2** is a filament from ALH84001. Filaments and filament fragments of this size are common in modern microbial biofilms and are a product of microbes much larger than the filament.

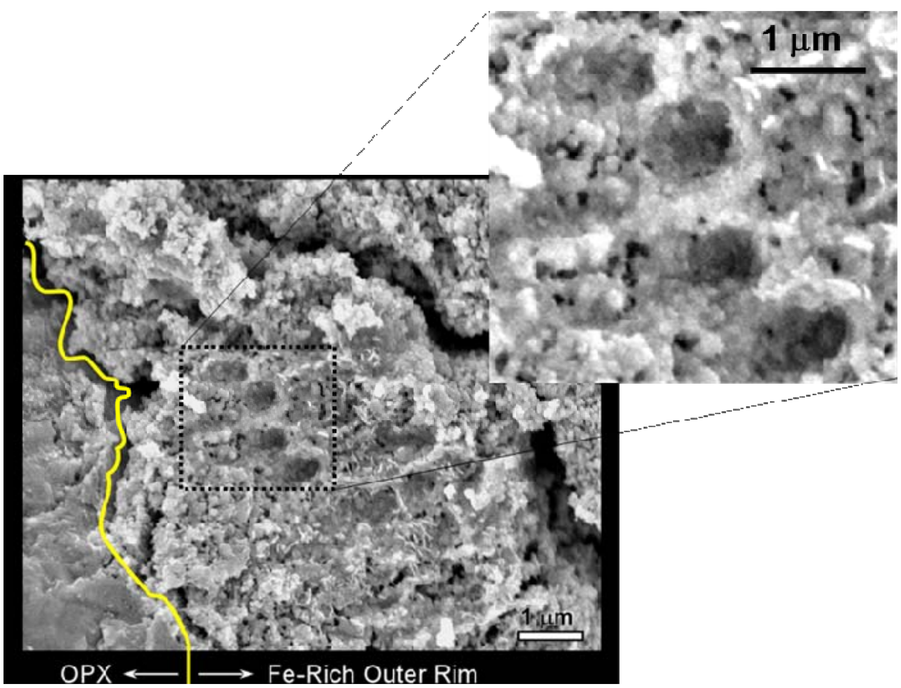

Figure 1. SEM view of carbonate pancake near the border with the host Orthopyroxene in ALH84001. These depressions are biomorphs suggestive of cavities left after embedded coccoid bacteria have partially or completely

decayed away. The uniform ~1μm size of these depressions is typical of a biological origin.

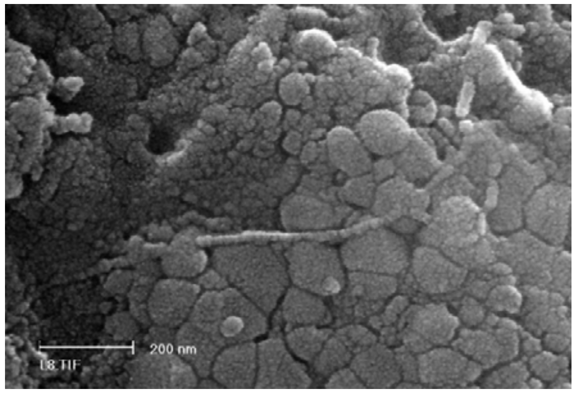

Figure 2. A filament from ALH84001. Filaments and filament fragments of this size are common in modern microbial biofilms and are a product of microbes much larger than the filament. This filament is clearly intergrown with the matrix and is unlikely to be random microbial contamination.

NAKHLITE METEORITES

A number of martian meteorites in museum collections all have similar mineralogy, chemistry and ages One group is named after the meteorite Nakhlite and this and similar meteorites are termed Nakhlites which are all about 1.3Gy old. Nakhla was seen to fall in Egypt June 28, 1911 and Yamato 000593 recovered recently by the Japanese Polar Expedition in Antarctica . Most of the Nakhlites that we have examined have biomorphic features, resembling known terrestrial microfossils. Many of these biomorphs appear to be integrally embedded in the iddingsite crack filling material of these meteorites. Iddingsite is a mixed phase including smectites and oxide minerals. In Nakhlites, iddingsite has a distinctive texture and distinctive chemical compositions. It is commonly accepted to be a low temperature martian aqueous alteration feature.[18]

All Nakhlites examined in detail show low-temperature aqueous secondary mineral alteration which occurred on Mars. Furthermore, all Nahlites examined in detail contain carbonates formed on Mars, usually closely associated with the iddingsite.. Furthermore, all Nakhlites examined closely by us and by other also show biomorph features.

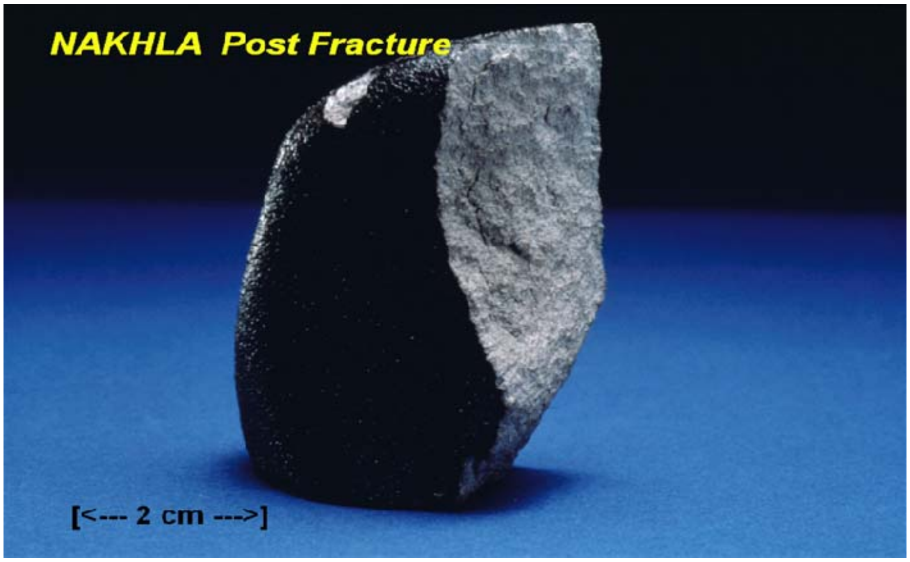

Figure 3. A fragment of Nakhla. This original piece had a nearly complete and continuous fusion crust. The light gray area, mostly pyroxene with lesser olivine, was revealed only after the original piece was cracked open.

BIOMORPHS AND RECENT BIOLOGICAL CONTAMINATION

The possibility that meteorites may become contaminated with microbial features such algae, mold, fungi, bacteria, or even detectable viruses must always be considered[19; 20]. We have been particularly alert for such terrestrial contamination in both meteorite falls and meteorite finds. The next figures present biomorphs that we considered to be terrestrial contamination from three separate martian meteorites. They all have in common the presence of abundant low Z composition, high C, the lack of typical elements from natural rocks and minerals, and the tendency to charge up in the electron beam. In addition they have diagnostic textural features that are different from the biomorphs that we describe later in this paper which we consider to be genuine indigenous features. The terrestrial contaminants are always found covering or partly covering the substrate without any indication that they are intergrown or embedded with the substrate. Clear contamination may consist of filaments that extend through existing cracks and may disappear into holes or cracks, but in no case are they intergrown with indigenous matrix, mineral crack filling, or mineral coatings. Particularly critical is textural evidence that a biomorph is intergrown or embedded with matrix material such as iddingsite which is known to be indigenous based on independent evidence such as non-terrestrial isotopes. So specific criteria to determine terrestrial contamination includes both composition and texture of the biomorph. The most reliable evidence for indigenous biomorphs is the textural evidence showing that it is embedded and completely intergrown in a mutually reactive manner with a matrix such as iddingsite which can be firmly documented as nonterrestrial. The chemical evidence of high organic composition and the lack of rock-forming chemistry is added support for contamination. From a practical approach, features that have obvious low Z, are electron transparent, and show abnormal charging properties are likely contamination. If we have any question about any of these characteristics we do not include the features in our category of possible Martian biomorphs.

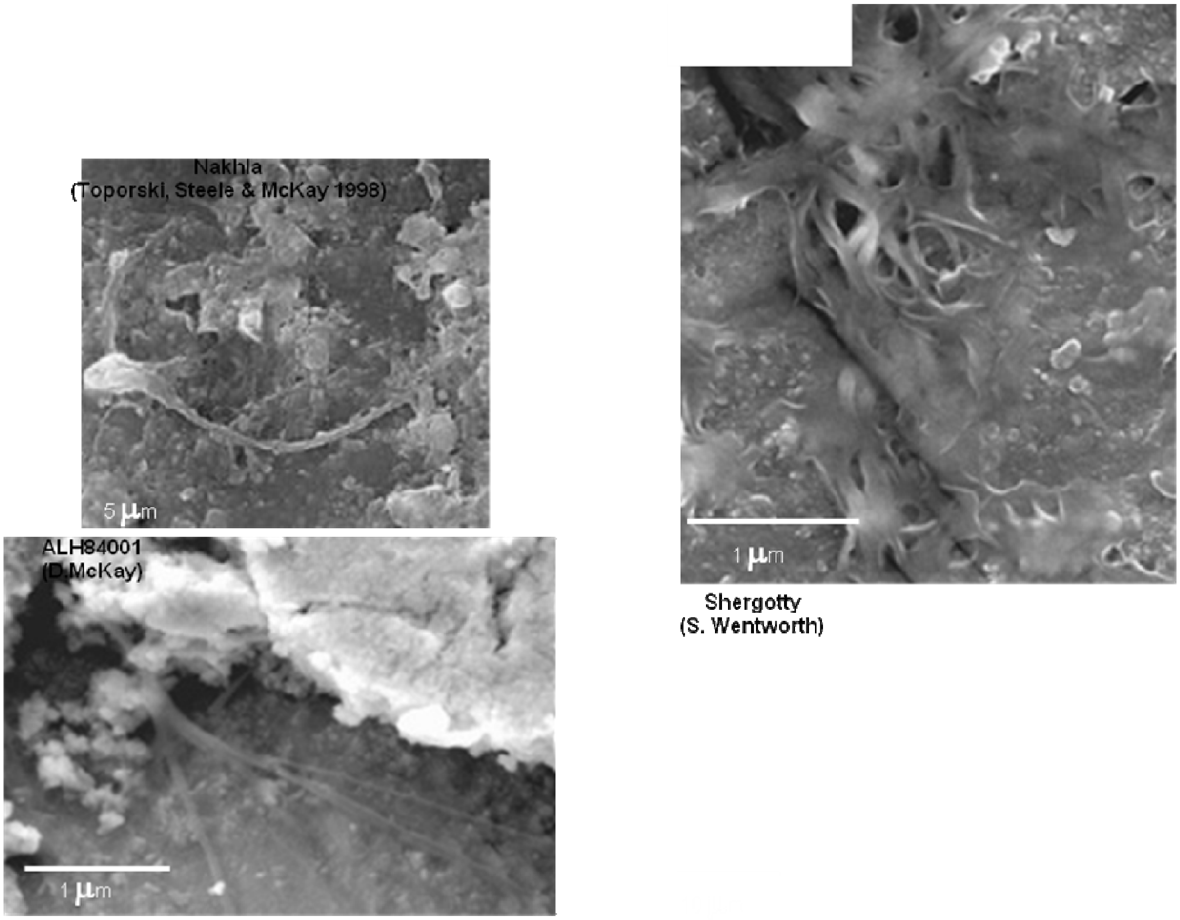

Figure 4. Likely microbial terrestrial contamination found in three separate martian meteorites. These feature consist of filaments and biofilm-like coatings on martian mineral grains in Nakhla (A), in Shergotty (B), and in ALH84001 (C)..

NAKHLITE BIOMORPHS

When Nakhla is broken, the chips sometimes part along existing fractures and reveal surfaces with iddingsite. Attached to these surfaces or partly embedded in the iddingsite are a number of features which can be correctly called biomorphs because of their close resemblance to features known to be created by biology in the form of microbial bodies, casts of microbes, molds of microbes, or remnants of biofilms or debris from microbial colonies. Most of these features are associated with iddingsite Iddingsite is a common crack and void filling in Martian meteorites, particularly Nakhlites. The iddingsite in Nakhla has been roughly dated at about 700my[21; 22] **The** measured D/H ratios is +500 to +800 per mil for minerals associated with the iddingsite[23]. This isotopic composition is much to heavy to be the result of terrestrial water and its presence shows that the iddingsite was formed on Mars.[23]

All of these biomorph features are common in recent geologic samples of material known to be rich in biology, and some of these features are found in ancient rocks where they have been specifically identified as microfossils or trace fossils. All of these features fail the test for terrestrial contamination as discussed previously.

The following figures are examples of biomorphs in Nakhla and the Nakhlite Yamato000593.

Figure 4 is an example of biomorphs in Nakhla. These forms resemble closely many coccoid fossils. SEM/EDX chemical analysis of these features reveals that they are dominated by iron and oxygen and the substrate is iddingsite.

Figure 5 shows several coccoid biomorph forms partially wrapped in a layer of iddingsite. Clearly, these forms were present during the interval when the iddingsite precipitated. They are contemporaneous with the formation of the iddingsite Biomorphs may resemble typical bacteria but may show weathering, alteration, and partial replacement.

Figures 6-8 show some of the complex iddingsite texture and presents the concept of microstratigraphy of the iddingsite which can be used to provide relative time information on the biomorphs.

Figure 9 is a rod-shaped biomorph that displays a basic iron oxide chemistry but also shows a significant carbon peak in the EDX spectrum. This biomorph is not completely embedded in the adjacent iddingsite substrate, but is firmly attached to it.

Figures 10-11 show biomorphs from the Columbia River Basalt.   Such biomorphs from known biologic regions within rocks provide examples and standards for comparison with the martian biomorphs.

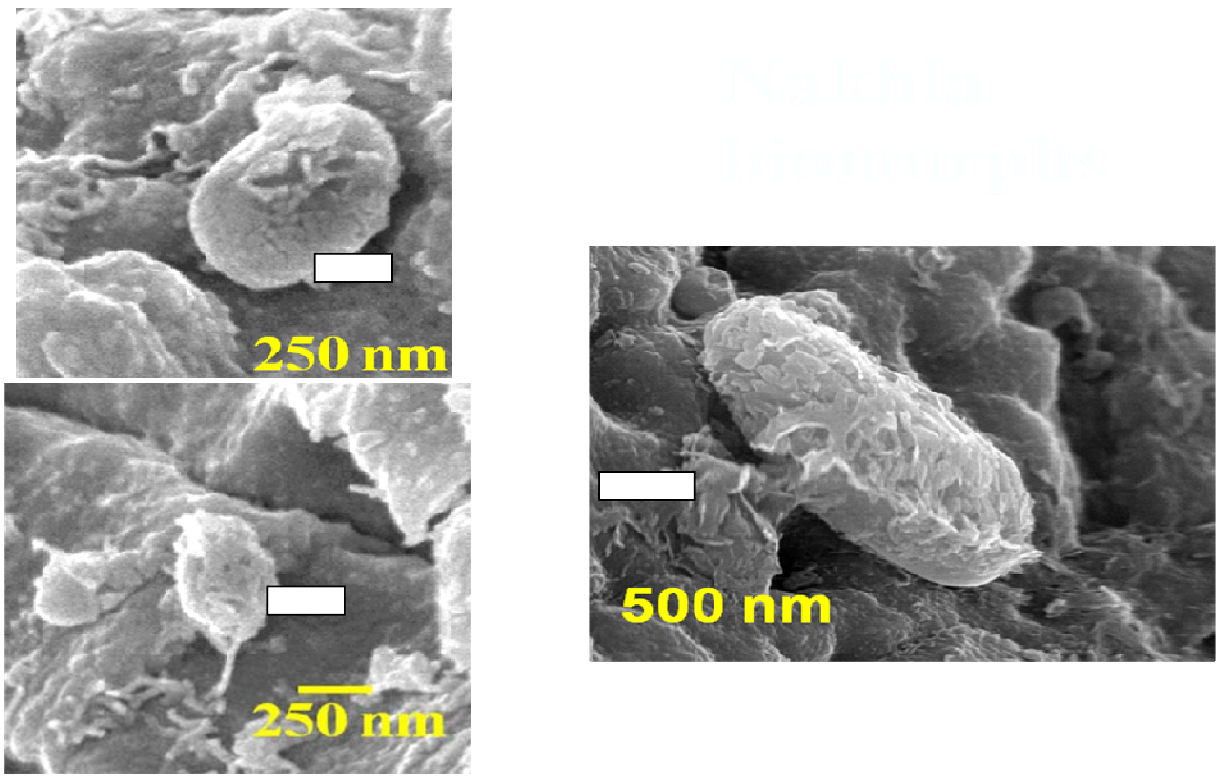

Figure 4**.** Biomorphs in Nakhla attached to a substrate of iddingsite. The composition of these objects is mainly iron oxide.

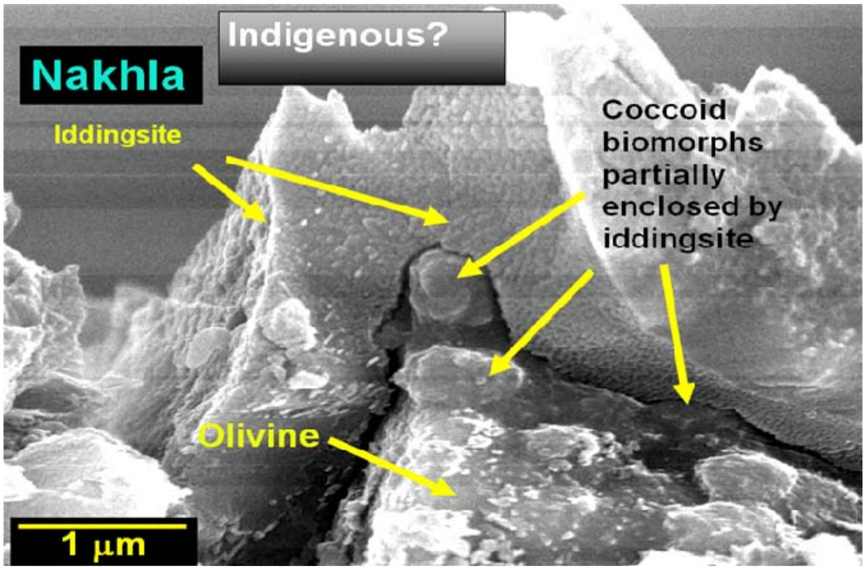

Figure 5.Coccoid biomorphs partially wrapped by iddingsite supporting the interpretation that they are indigenous and contemporaneous with the precipitation of the iddingsite.

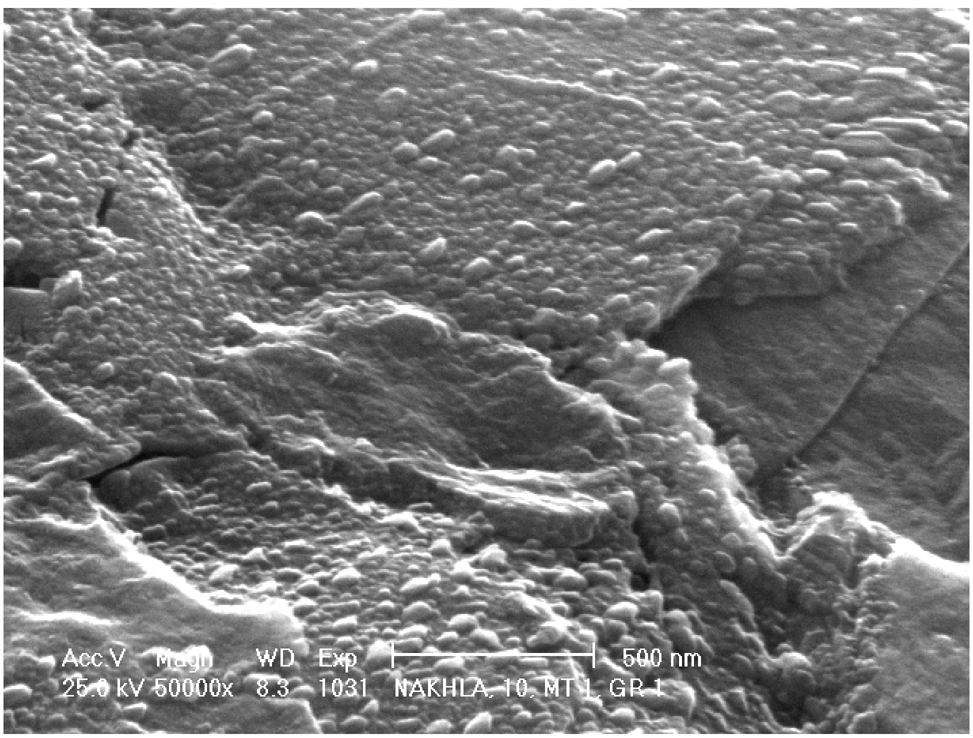

Figure 6. Multiple layers (at least four) of iddingsite in Nakhla showing the complexity of this crack filling sequence. A biomorph similar to a collapsed cell is present in the center of the image and is partly imbedded in

the layer of iddingsite.

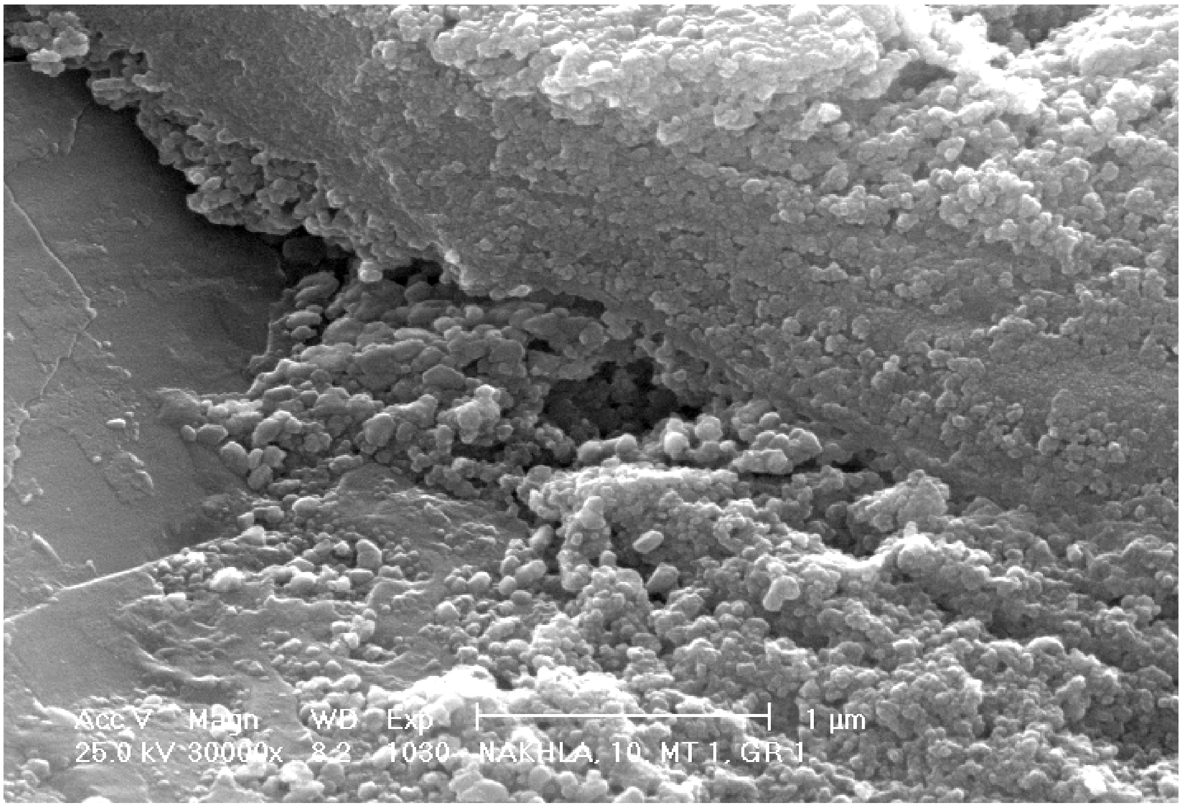

Figure 7. Another region of multiple iddingsite showing several thin layers (bottom), a fragmental layer, and a massive partly stratified layer, and another fragmental layer.

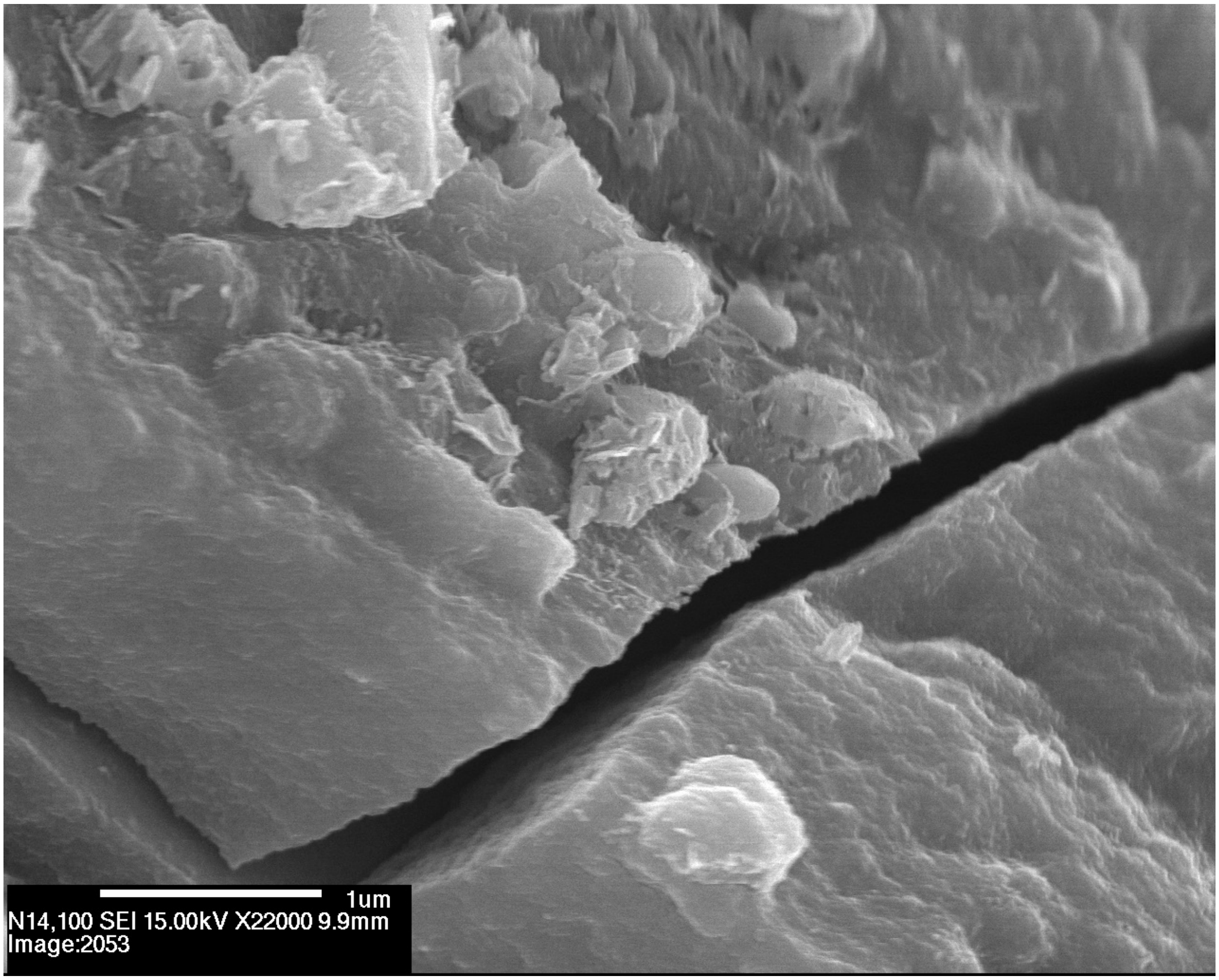

Figure 8. Nakhla biomorphs consisting of coccoidal and rod-shaped forms partly embedded in iddingsite,

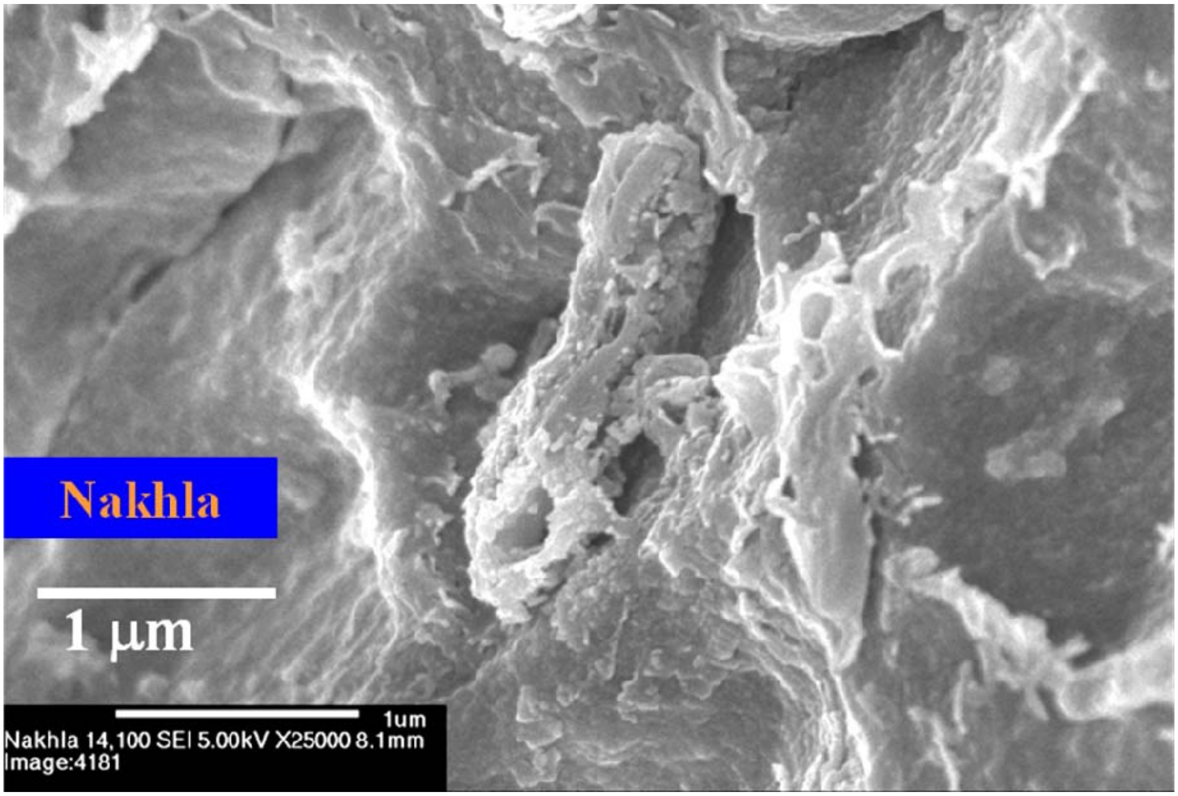

Figure 9. A rod-shaped biomorph, partly weathered and altered. The primary chemistry is iron, oxygen, and carbon.

As part of our attempt to understand biomorphs, we have also examined a series of terrestrial samples in which microbial colonies grew on weathering basaltic rocks from the Columbia River basalts in the state of Washington[24].

Figure 9 is a several biomorphs in which the original cellular structure has been mostly replaced by iron oxide minerals. The overall cellular shape is preserved, but the composition is now almost entirely iron oxide. Previous work had identified these iron oxide as ferrihydrite.

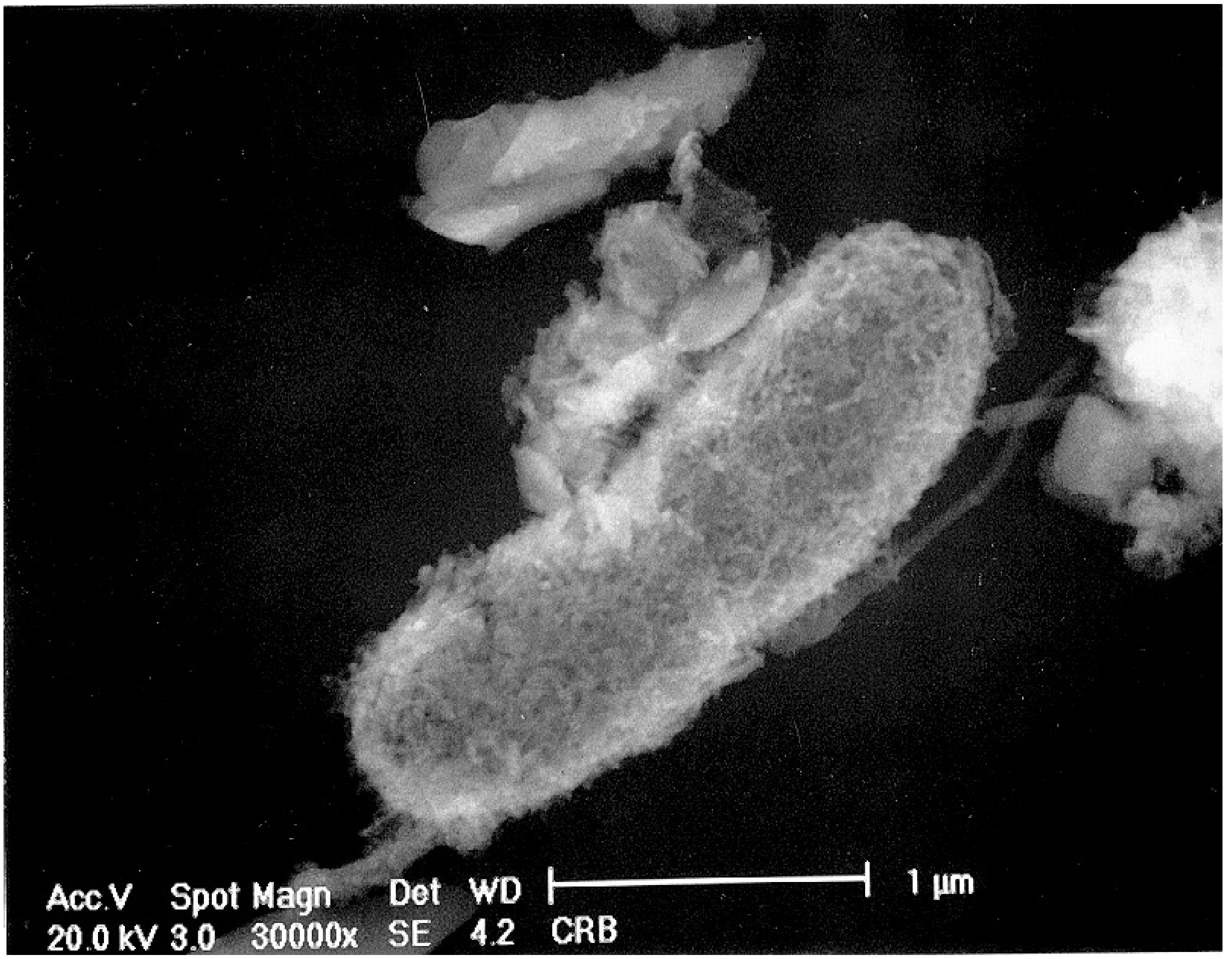

Figure 10. Two elongated cells joined together along with several filaments and possibly some smaller cells. These biomorphs are from samples of the Columbia River Basalt in Washington State[24]. Here, the original organic cell walls have been mostly replaced with iron oxide, probably ferrihydrite. Similar cells in these samples are sometimes hollow, having only iron oxide grains defining the original cell shape. The progression from organic cells to iron oxide biomorphs as cells weather and decay may be fairly typical of weathering in basaltic terrain. It is the major mode of diagenesis in the Columbia River Basalt samples that we have studied.

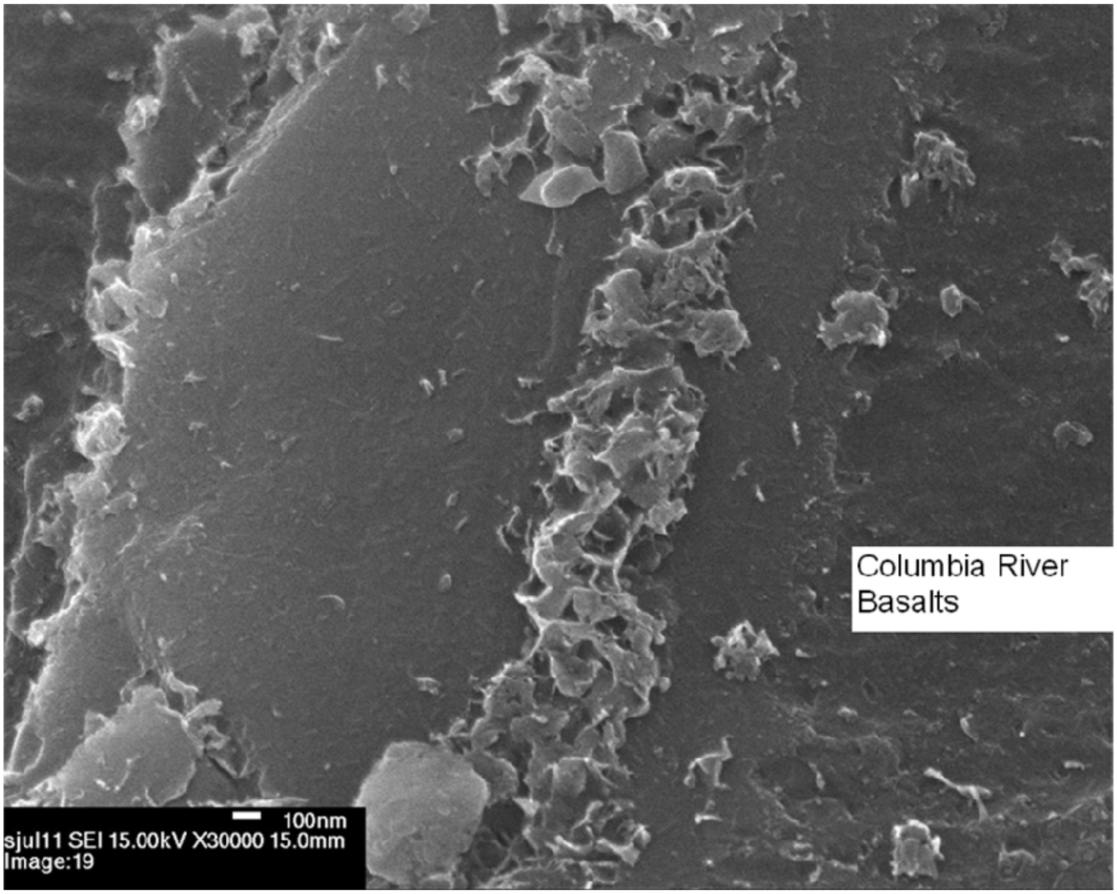

Figure 11. Another Columbia River Basalt biomorph. This elongated biomorph interpreted as the remains of a rod-shaped bacterium. These remains are primarily iron oxide in composition.

Figures 12 A and B provide examples of elongate filament-like biomorphs which may be heavily altered, but which still resemble clear biologic structures form altered terrestrial rock samples (Figure 11).

Figure 13 shows extremely old coccoidal fossils from a terrestrial site (Australian Archea). It provides part of the reference morphology for similar features in Nakhla and Yamato000893.

Figures 14-18 provide examples of biomorphs filling depressions in mineral surfaces or in iddingsite. In most cases, the depressions are partly or completely filled with material different from the matrix and possibly carbon-containing.

Figure 19-20 provide striking biomorphs that resemble closely terrestrial examples. However, these biomorphs both pass our contamination test criteria (composition and texture)and appear to be genuinely indigenous to the martian meteorites in which they are found.

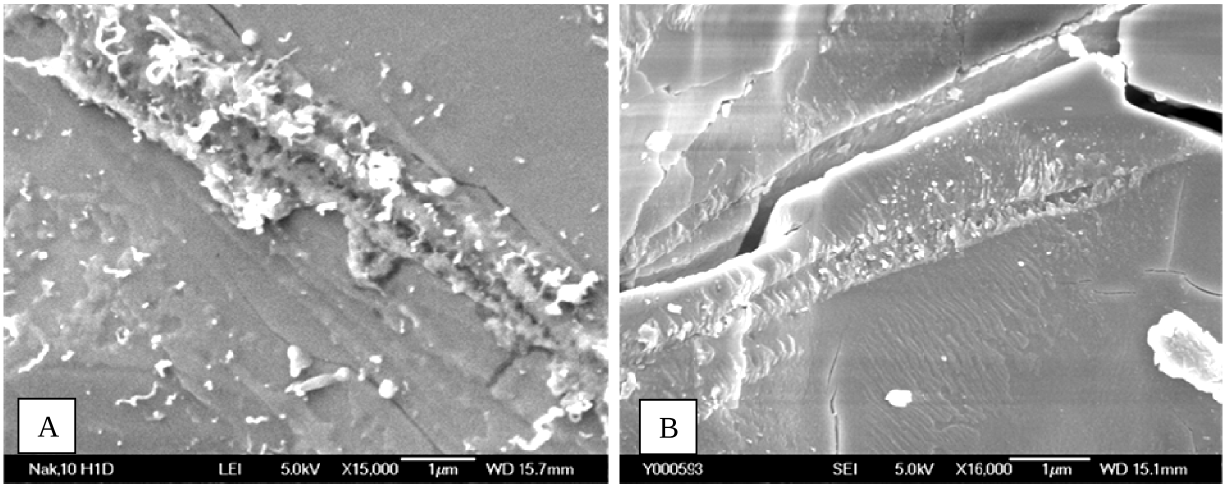

Figure 12. A is a biomorph from Nakhla. This biomorph is very similar to the microfossil from the Columbia River Basalt in Figure 10. B is a biomorph from the Nakhlite Yamato 000593 recovered from Antarctica.

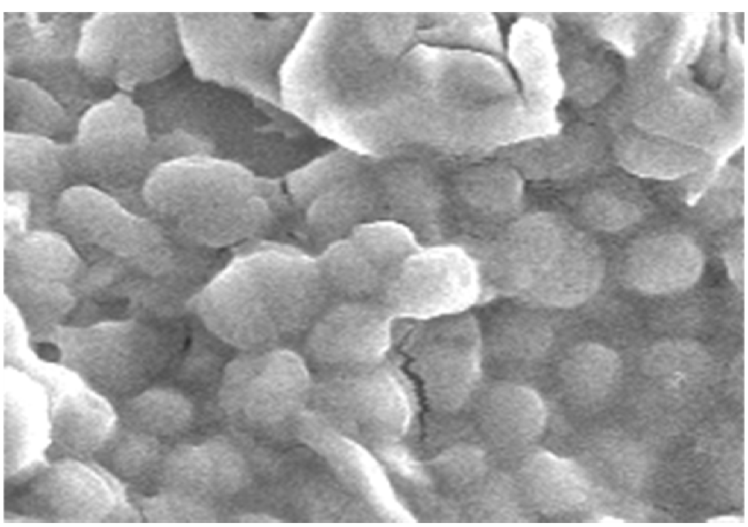

Figure 13. Coccoidal microfossils from the Archean of Australia)[25]. Width of field is ~10 micrometers.

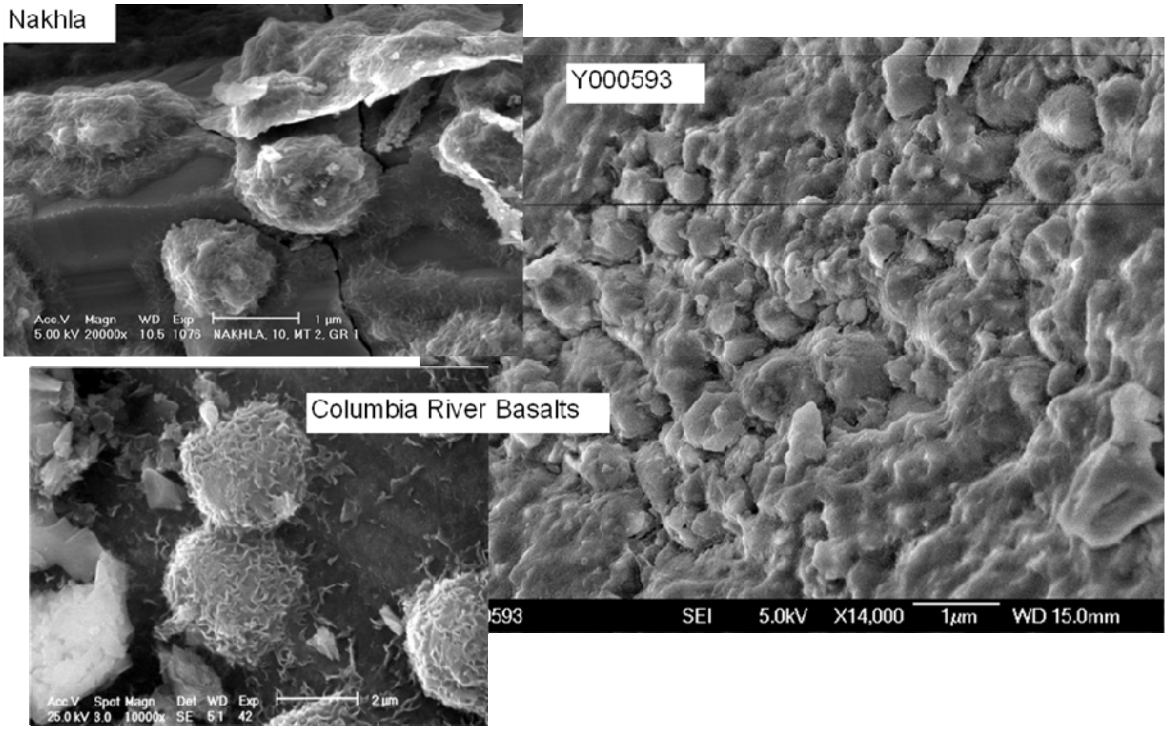

Figure 14. Coccoidal biomorphs from Nakhla, Y000593, and Columbia River Basalt.

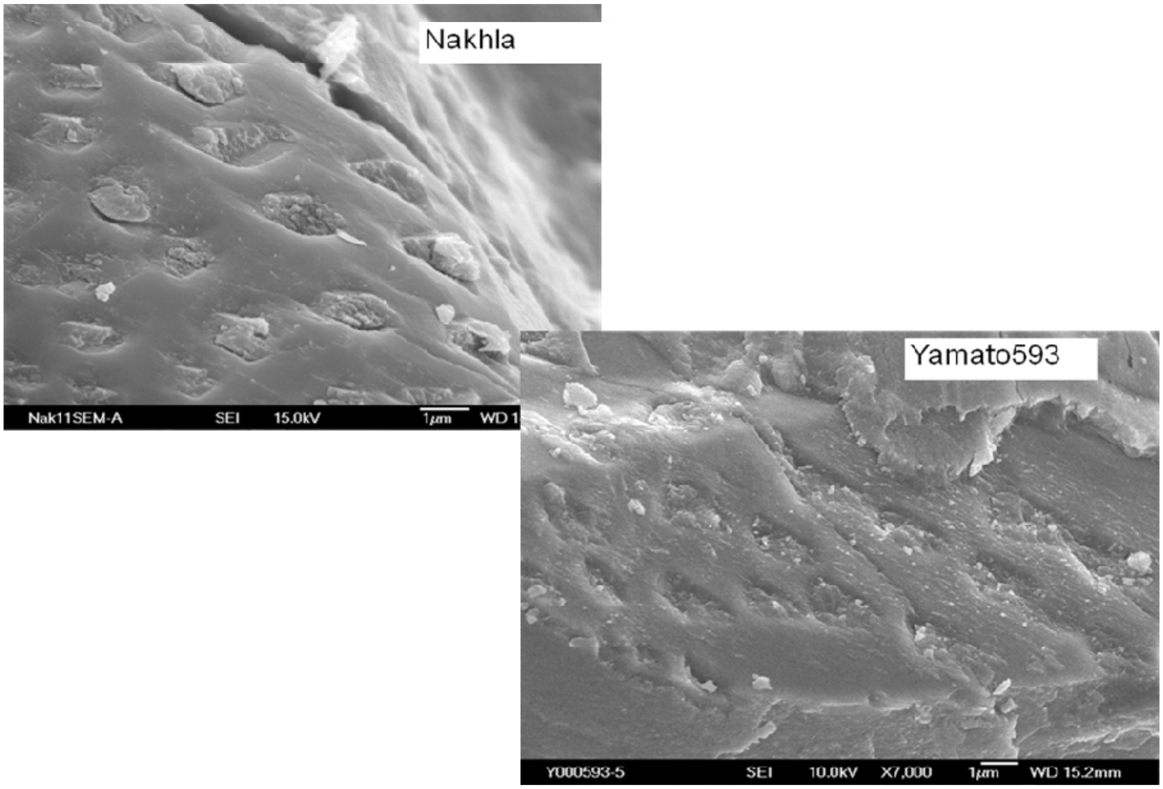

Figure 15. Depressed areas in minerals and iddingsite in two Nakhlites. In each case these shallow depressions are partly filled with other material which EDX indicates in richer in C than the surrounding matrix. These depressed areas are interpreted as biomorph in which the organic acid from the original cell etched a small pit in which the cell resided. After cell death, some of the cell material remained in the pit. The close correspondence of these two features in samples collected in Egypt and Antarctica supports the hypothesis that both features were made on Mars.

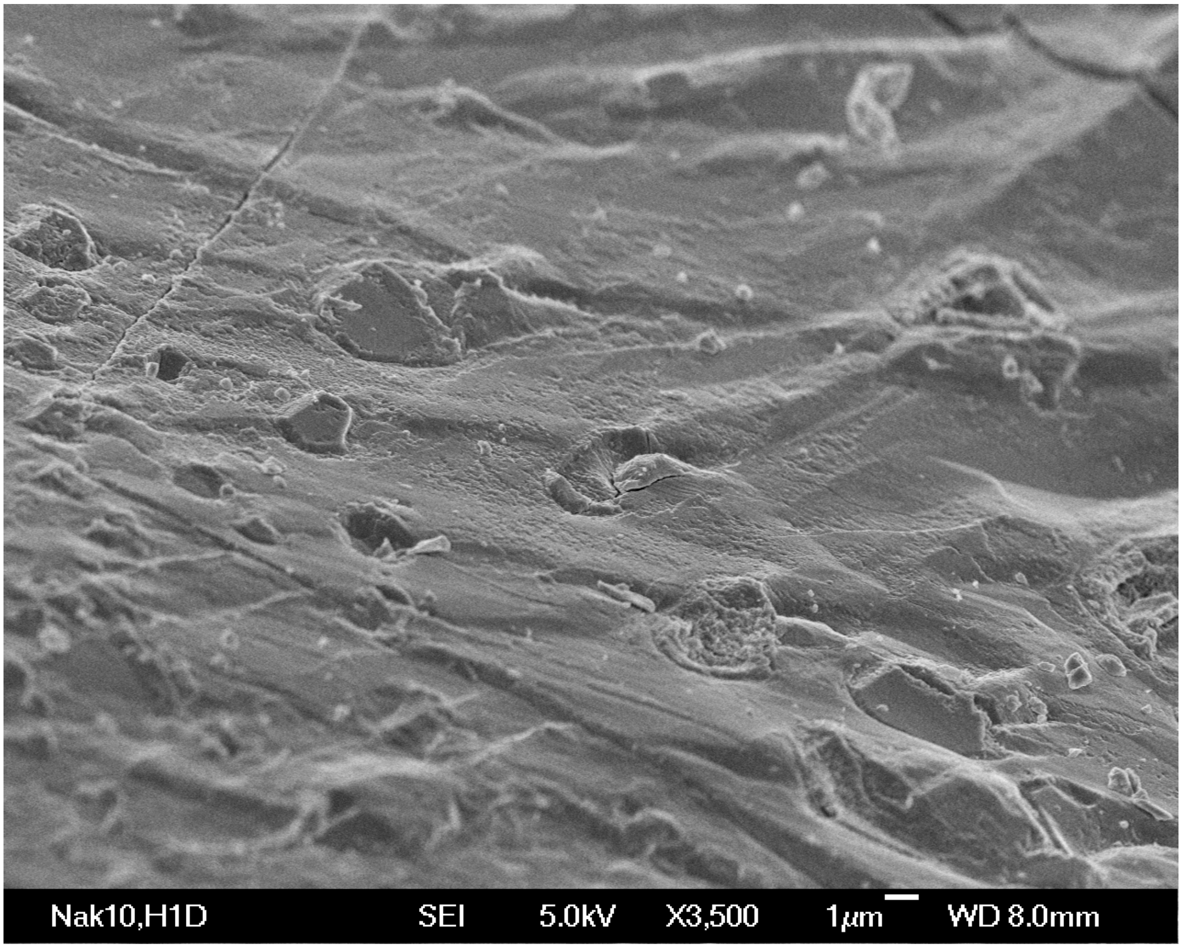

Figure 16. Another area in Nakhla showing biomorphs firmly embedded in an irregular iddingsite layer.

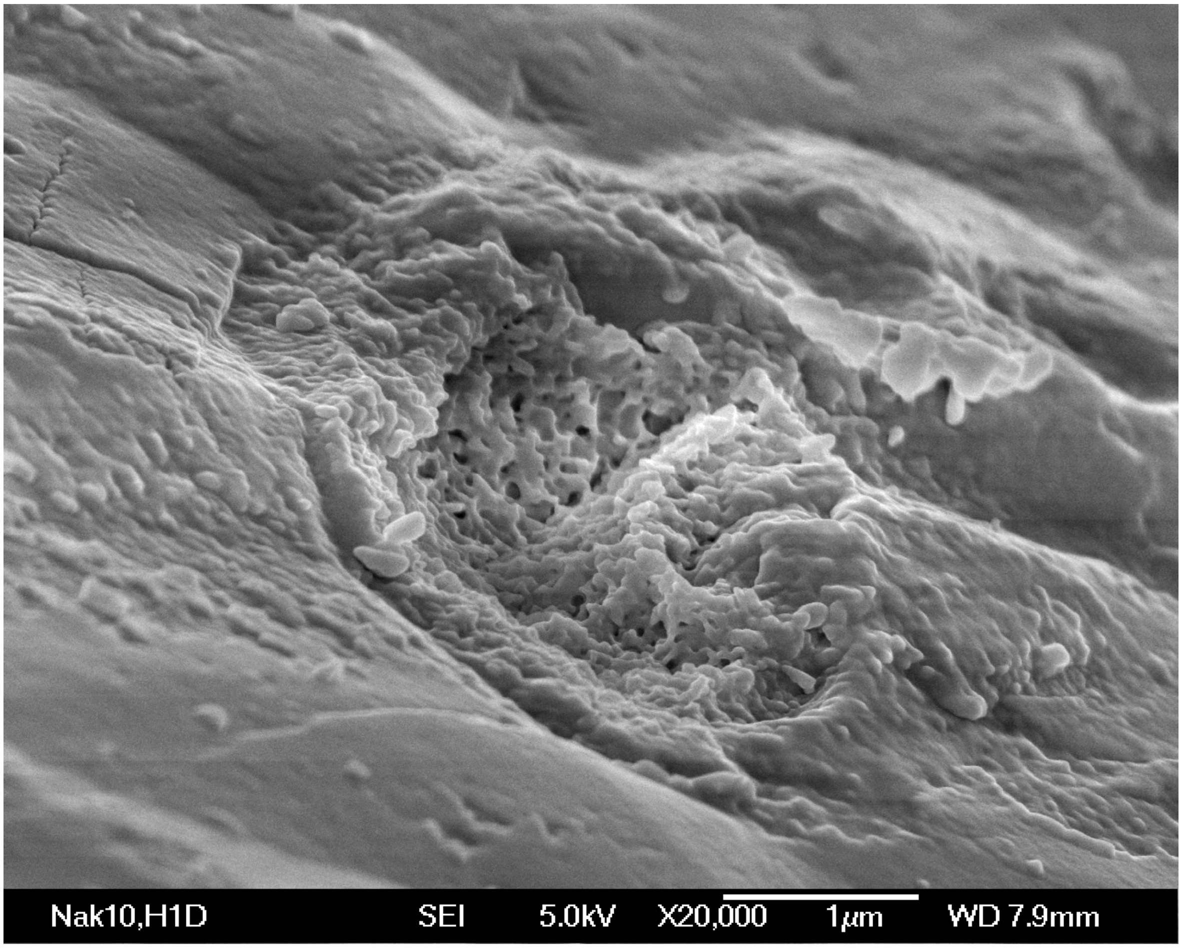

Figure 17. Closeup view of a Nakhla biomorph partially embedded in an iddingsite matrix.

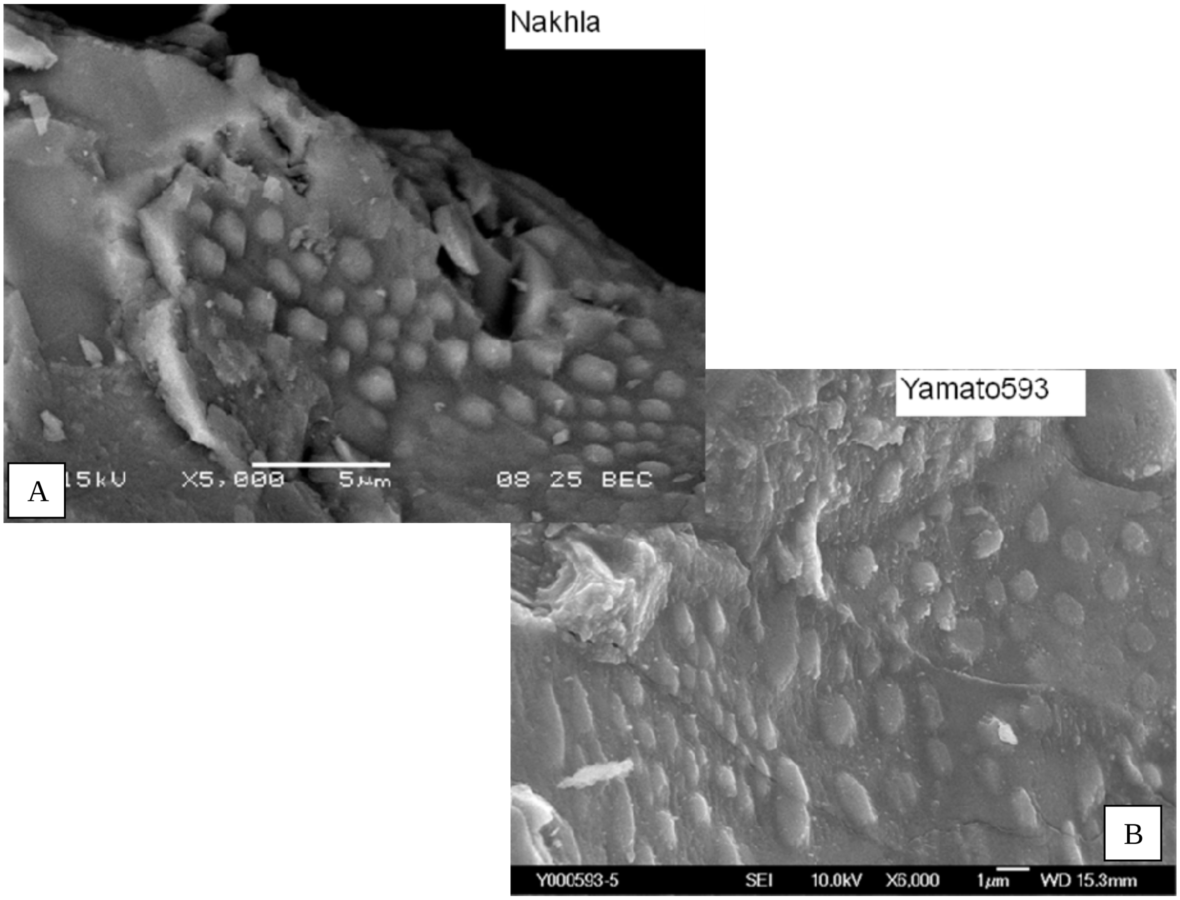

Figure 17. Bumps partly embedded in a matrix of iddingsite in Nakhlite (**A) and Yamato 00593 (B).** These bumps have a significant C peak in EDX which is not present in the matrix. The y are interpreted as biomorphs based on their shape, size, and presence of C.

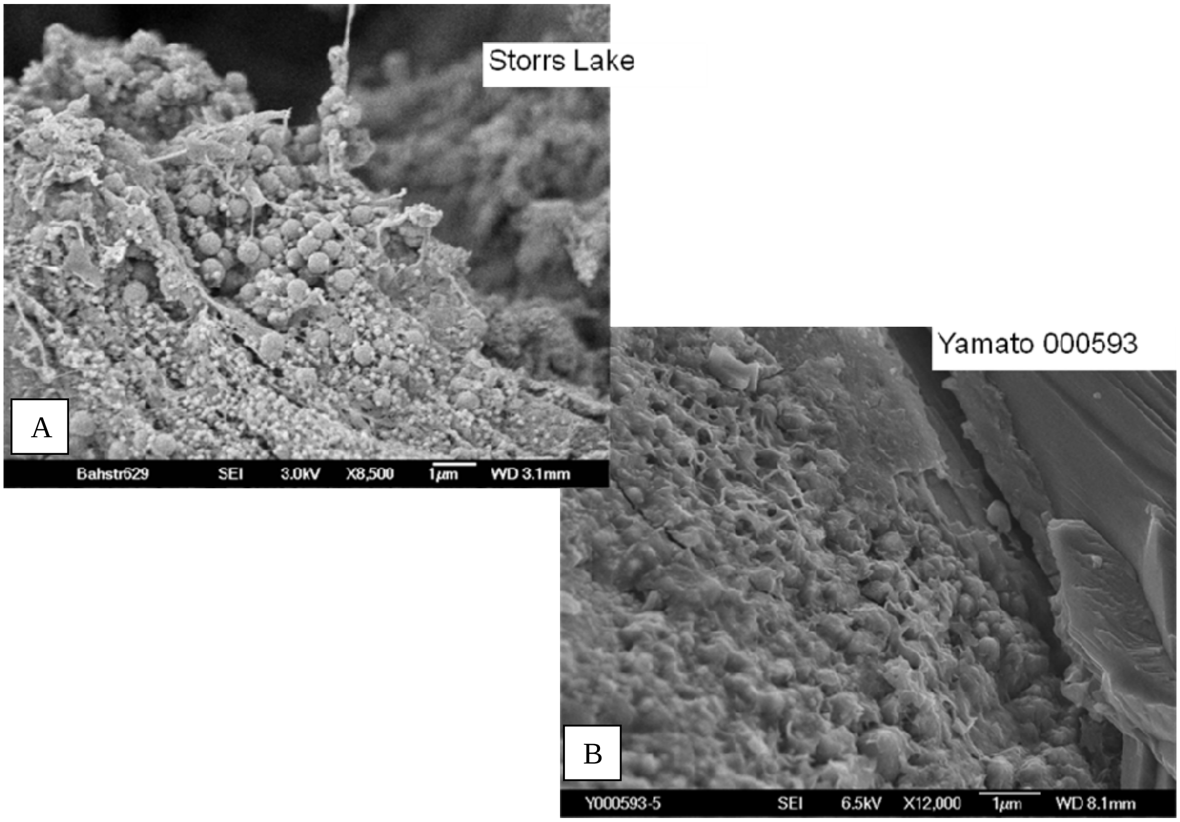

Figure 19. A. Image of collection of modern-day coccoidal bacteria from Storrs Lake, Bahamas (Image by Monica Grady). B. Image of coccoidal biomorphs in Yamato 000593 collected from the Antarctic ice fields. It is difficult choose two terrestrial environments so different. Yet the biomorph features are very similar. Both have remnants of biofilms-like material in addition to the coccoid forms.

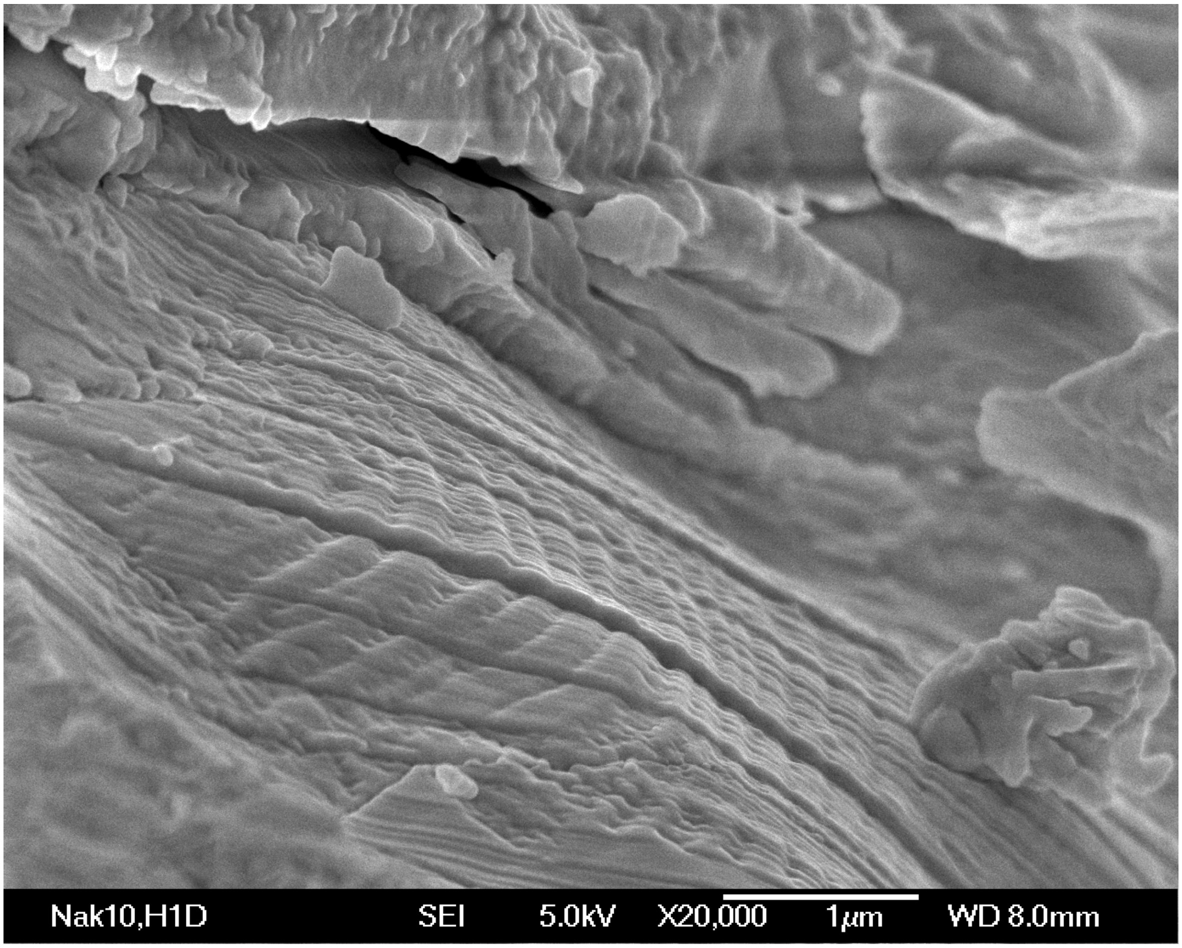

Figure 20. This corrugated or ropy texture is a biomorph in Nakhla. It resembles the texture of some cyanobacteria sheaths, but it is clearly incorporated in and partly covered by an iddingsite layer.

SUMMARY

Martian meteorites from widely different terrestrial environments contain features similar to each other and to known biogenic features from other terrestrial environments.

We term many of these features biomorphs and use them as pointers for more exhaustive analysis by SEM EDX, TEM, and nanoscale elemental and isotopic analysis by ionmicroprobe (NanoSims Such analysis will include biogenic elements N, C, P, etc., three dimensional mapping, of oxygen isotopes, and determination of deuterium/hydrogen ratios Focussed ion beam sample preparation of selected features is also underway.

Biomorphs found in martian meteorites must also pass our tests for terrestrial contamination in order to be considered genuine evidence for possible microbial life on Mars.

Overall Conclusions:

None of the original features supporting our hypothesis for ALH84001 has either been discredited or has been positively ascribed to non-biologic explanations.

The most controversial feature, the presence of distinctive nanophase magnetite (always accepted as a certain biosignature when found in Earth environments), despite repeated attempts, has never been accurately produced in the laboratory in verified reproducible experiments.

Multiple studies by European and US investigators have shown that pure Fe-magnetite cannot be produced by thermal decomposition of mixed composition carbonate: Mixed composition spinels are always the product.

There is no evidence that Alh84001 ever contained any pure Fe-carbonate (siderite); it is impossible to produce the pure Fe-magnetite in this meteorite by the thermal decomposition of any carbonates in the meteorite,

Other Martian meteorites from quite different terrestrial environments contain nearly identical biomorphs suggestive of fossilized bacteria from Mars.

The martian biomorphs are intimately associated and interlaced with iddingsite vein fillings which are now universally accepted as martian in origin.

These martian biomorphs are very similar to terrestrial biomorphs from modern microbial complexes as well as biomorphs from Archean rocks interpreted as microbial fossils.

In summary, the original hypothesis that features in ALH84001 may be the result of early microbial life on Mars remains robust and is further strengthened by the presence of abundant biomorphs in other martian meteorites. These biomorphs, while not completely definitive for microbial life, are clearly associated with martian aqueous alteration (iddingsite) and are nearly identical to terrestrial biomorphs known to be formed by microbial activity. New martian data since our original paper have significantly supported the habitability of Mars and the possibility of life there. These data include the presence of an early magnetic dynamo detected by by the discovery of strongly magnetized crustal rocks, the presence of abundant early surface water and recent near-surface water, the presence of early clay minerals and carbonates, and the presence of methane plumes in the atmosphere which may have a biological origin.

"The possibility of life on Mars is too thrilling for mankind to ignore." *The Economist*, Jan 22, 2009.

REFERENCES

[1] McKay, D. S., J. E. K. Gibson, K. L. Thomas-Keprta, H. Vali, C. S. Romanek, S. J. Clemett, X. D. F. Chiller, C. R. Maechling, and R. N. Zare, "Search for past life on Mars: Possible relic biogenic activity in Martian meteorite ALH84001", Science, 273, 924-930, (1996).

[2] Bradley, J. P., R. P. Harvey, and J. H. Y. McSween, "Magnetite whiskers and platelets in the ALH84001 Martian meteorite: Evidence of vapor phase growth", Geochimica et Cosmochimica Acta, 60(24), 5149-5155, (1996).

[3] Harvey, R. P., and J. H. Y. McSween, "A possible high-temperature origin for the carbonates in the Martian meteorite ALH84001", Nature, 382(6586), 49-51, (1996).

[4] Valley, J. W., J. M. Eiler, C. M. Graham, J. E. K. Gibson, C. S. Romanek, and E. M. Stolper, "Low-temperature cabonate concretions in the Martian meteorite ALH84001: evidence from stable isotopes and mineralogy", Science, 275(5306), 1633-1638, (1997).

[5] McSween, J. H. Y., and R. P. Harvey, "An evaporation model for formation of carbonates in the ALH84001 Martian meteorite", International Geology Review, 40, 774-782, (1998).

[6] Kent, A. J. R., I. D. Hutcheon, F. J. Ryerson, and D. L. Phinney, "The temperature of formation of carbonate in Martian meteorite ALH84001: Constraints from cation diffusion", Geochimica et Cosmochimica Acta, 65, 311-321, (2001).

[7] Golden, D. C., D. W. Ming, C. S. Schwandt, R. V. Morris, S. V. Yang, and G. E. Lofgren, "An experimental study on kinetically-driven precipitation of calcium-magnesium-iron carbonates from solution: Implications for the low-temperature formation of carbonates in Martian meteorite Allan Hills 84001", Meteoritics and Planetary Science, 35, 457-466, (2000).

[8] Golden, D. C., D. W. Ming, C. S. Schwandt, H. V. J. Lauer, R. A. Socki, R. V. Morris, G. Lofgren, and G. A. McKay, "A simple inorganic process for formation of carbonates, magnetite, and sulfides in Martian meteorite ALH84001", American Mineralogist, 86, 370-375, (2001).

[9] Barber, D. J., and E. R. D. Scott, "Origin of supposedly biogenic magnetite in the Martian meteorite Allan Hills 84001", Proceedings of the National Academy of Sciences of the United States of America, 99, 6556-6561, (2002).

[10] Barber, D. J., and E. R. D. Scott, "Shock and thermal history of Martian meteorite Allan Hills 84001 from transmission electron microscopy", Meteoritics and Planetary Science, 41(4), 643-662, (2006).

[11] K. L. Thomas-Keprta, S. J. C., D. S. McKay, E. K. Gibson, S. J. Wentworth, "Origins of magnetite nanocrystals in Martian meteorite ALH84001", Geochimica et Cosmochimica Acta, In press, (2009).

[12] Scott, E. R. D., A. N. Krot, and A. Yamaguchi, "Formation of carbonates in Martian meteorite ALH84001 from shock melts", Meteoritics and Planetary Science, 32(4, Supplement), A117-118, (1997).

[13] Clemett, S. J., M. T. Dulay, J. S. Gillette, X. D. F. Chillier, T. B. Mahajan, and R. N. Zare, "Evidence for the extraterrestrial origin of polycyclic aromatic hydrocarbons (PAHs) in the Martian meteorite ALH84001", Proc. Royal Soc. (?), (1998).

[14] Kirschvink, J. L., A. T. Maine, and H. Vali, "Paleomagnetic evidence of a low-temperature origin of carbonate in the Martian meteorite ALH84001", Science, 275, 1629-1633, (1997).

[17] Kirschvink, J. L., "Seventh Criterion for the Identification of Bacterial Magnetofossils", EOS. Transactions AGU, Spring Meeting, 82(2), #GP41A-07 (abstr.), (2001).

[18] Treiman, A. H., R. A. Barrett, and J. L. Gooding, "Preterrestrial aqueous alteration of the Lafayette (SNC) meteorite", Meteoritics, 28, 86-97, (1993).

[20] Steele, A., Goddard, D. T., Stapleton, D., Toporski, J.K.W., Sharples, G., Wynn-Williams, D.D., McKay, D.S., "Imaging of an Unknown Organism of ALH84001", Lunar and Planetary Science, XXX: Abst #1326(Lunary and Planetary Institute, Houston, TX (CD-ROM)), (1999b).

[21] Swindle, T. D., Grier, J. A., Li, B., Olson, E., Lindstrom, D. J., and Treiman, A. H., "Kr-Ar Ages of Lafayette Weathering Products: Evidence for Near-Surface Liquid Water on Mars in the Last Few Hundred Million Years", Lunar and Planetary Science, XXVIII, 1403-1404, (1997).

[22] Swindle, T. D., A. H. Treiman, D. J. Lindstrom, M. K. Burkland, B. A. Cohen, J. A. Grier, B. Li, and E. K. Olsen, "Noble gases in iddingsite from the Lafayette meteorite: Evidence for liquid water on Mars in the last few hundred million years", Meteoritics and Planetary Science, 35, 107-115, (2000).

[25] Westall, F., [Fossil bacteria in terrestrial and extraterrestrial rocks].