Further Evidence of Microfossils in Carbonaceous Chondrites

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ABSTRACT

Scanning electron microscopy investigations carried out independently in the United States and Russia have yielded further evidence of microfossils in meteorites. Numerous complex biomorphic microstructures representing possible microfossils have been found in interior surfaces of freshly broken samples of the Murchison, Orgueil, and Efremovka carbonaceous chondrites. Similar biomorphic forms were not encountered during comparable investigations of the Nikolskoye meteorite. Energy Dispersive Spectroscopy (EDS) and Link microprobe analysis provides elemental distributions indicating many of the microstructures have a carbon enhancement that is superimposed upon composition of the meteoritic matrix. The *in-situ* mineralized biomorphic microstructures found embedded in freshly fractured meteoritic surfaces are not considered to be recent surface contaminants.

Environmental Scanning Electron Microscope (ESEM) in the US and SEM studies in Russia on different samples of carbonaceous chondrites revealed many spherical bodies (some with spikes) similar in size and shape to the forms of uncertain biogenicity designated "organized elements" by prior workers. These studies also revealed the presence of far more complex bodies in carbonaceous chondrites. Numerous biomorphic microstructures were found which exhibit morphology, size, distribution and chemical composition that is consistent with the lithified remains of microorganisms (i.e. microfossils). We have observed characteristics indicative of biology, including evidence for colonial distribution, cell-walls, and close associations of forms exhibiting diverse aspects, known from living and fossil microbes, representing motile, reproductive, and life cycle developmental stages. Many of the meteoritic microstructures are very similar to microfossils of cyanobacteria, such as we have found in Cambrian phosphate-rich rocks (phosphorites) of Khubsugul, Northern Mongolia and high carbon Phanerozoic and Precambrian rocks (oil shales and black shales) of the Siberian and Russian Platforms. We have interpreted these complex microstructures in carbonaceous chondrites to represent the lithified remains of prokaryotic microorganisms including coccoidal and filiform cyanobacteria. We present images of these possible microfossils found in the Murchison, Efremovka, and Orgueil meteorites and compare these forms with known microorganisms and microfossils.

Keywords: Astrobiology, cyanobacteria, microfossils, Murchison, Orgueil, Efremovka, meteorites, phosphorites

1.0 INTRODUCTION

The detection by McKay et al.[1] of chemical biomarkers and possible microfossils in an ancient meteorite from Mars (ALH84001) has stimulated research of great importance to the newly emerging field of Astrobiology. The

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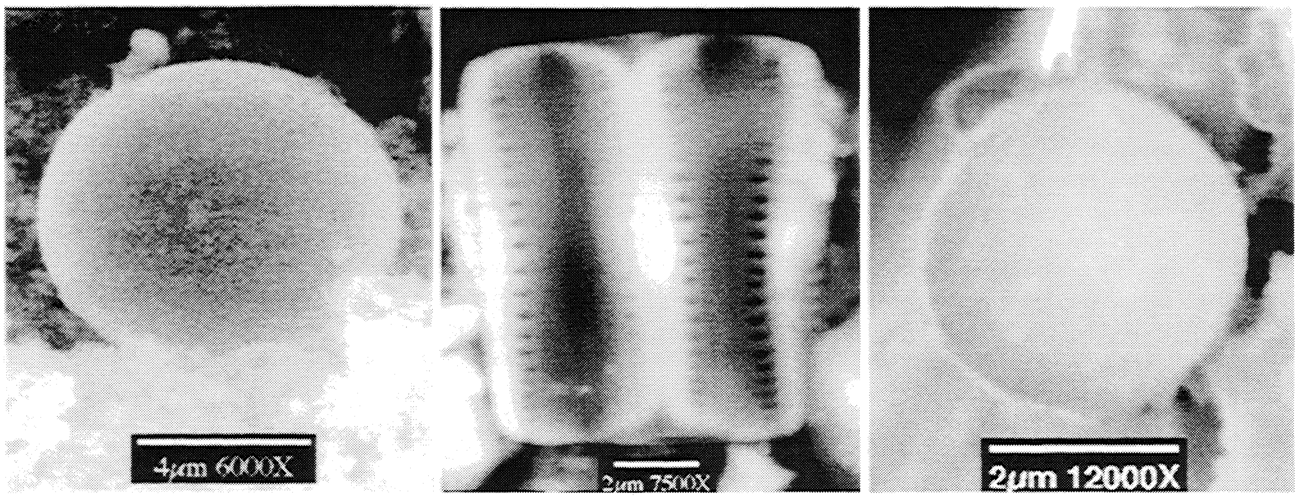
resulting scientific debate has helped delineate many important areas of research that must be addressed to facilitate the detection and recognition of biosignatures, microfossils, and living or dormant microorganisms in ancient terrestrial rocks, astromaterials, comets, satellites, planets or other bodies of the solar system. The minute size of the putative microfossils in ALH84001 revealed that the limits of size of terrestrial microbial life was not well understood. This has stimulated research into dwarf bacteria[2], nanofossils, and nanobacteria.[3-7] Recent studies indicate that autonomous (culturable) microorganisms as small as 100 nm diameter live on Earth. The ultimate limit to cellular life is not yet established. However, many of the ALH84001 forms interpreted as microfossils can not be dismissed on size alone. Knowledge of microbial life on the nanometric scale has been greatly enhanced, and theoretical and experimental studies to establish the limitations of cellular life is of great importance to Astrobiology.

The ALH84001 investigations also demonstrated the importance of identifying those biomarkers that may be interpreted as clear indications of biogenic activity in astromaterials. Biomarkers are also of tremendous importance to the exploration of the Earth's earliest biosphere and establishing the first appearance of life on our planet. Mojzsis et al. [8] concluded, based upon the interpretation of biomarkers in ancient terrestrial rocks, that life has existed on Earth for more than 3.8 billion years. Work is now underway at several institutions to evaluate the relative significance of various biomarkers encountered in SNC meteorites, carbonaceous chondrites, and ancient terrestrial rocks. Important biomarkers may include biologically significant elements and compounds, biochemicals and biominerals, magnetites and magnetosomes, stable isotope ratios, and Polycyclic Aromatic Hydrocarbons (PAH's). The first investigations of possible microfossils in carbonaceous chondrites were conducted in 1961 after a study of the biogenic hydrocarbons[9] in carbonaceous chondrites indicated that organic chemicals indigenous to the Orgueil meteorite were much more similar to those encountered in ancient rocks and petroleum geochemistry than to those found in recent sediments. Nagy[10] has provided an extensive review of the organic chemistry of carbonaceous meteorites as well as petroleum geochemistry. Over the past several years, careful researchers obtained evidence that many of the complex organics typically associated with life processes are encountered in carbonaceous meteorites. These include kerogens[11], heterocyclics[12], polymers[13], PAH's[14], aromatic and aliphatic hydrocarbons[15-17], nucleic acid bases, purines, pyrimidines, and triazines[18], isomeric alkanes and isoprenoids[19], extraterrestrial[20] and non-protein[21] amino acids with unusual stable isotope ratios [22], chiral amino acids with enantiomeric excess[23-26], and porphyrins[27,28], microvessicles and organic nanoparticles[29-31], and possible microfossils[1,32-37]. These diverse observations constitute independent data sets consistent with the hypothesis that microbial life may have existed on the parent bodies of the carbonaceous chondrites and SNC meteorites. The detection of similar biomarkers would undoubtedly be considered important signatures of ancient biology if encountered in ancient sediments or rocks from Earth. A primary objection to this interpretation seemed to reside with the assumed difficulty of life evolving on the parent body of the meteorites. However, it is becoming clear that liquid water was abundant on ancient Mars. Therefore processes similar to those that resulted in the origin of microbial life on Earth might also have resulted in the appearance of life on early Mars. If biomarkers are to have relevance to Astrobiology, they must be interpreted rationally and consistently.

It is now widely accepted that ALH84001 and the other SNC meteorites are rocks from Mars[38-40] that were ejected from the crust of that planet and transported to Earth as a result of meteorite impact ejection phenomena[41-45]. The presence of large impact craters on Earth and the moon indicate that many deep impact events have occurred throughout the history of our planet as well. Recent microbiological research has revealed the presence of indigenous microorganisms in deep aquifers[46], and granitic and basalt groundwaters.[47-50] Samples collected by Onstott et al.[51] in deep gold mines of Witwatersrand, South Africa were found to contain high concentrations ($\sim 10^5$ to 10^8 cells/g) of viable microbes, such as *Desulfobacter sp.* and the thermophilic facultative Fe(III) reducing bacteria *Thermus sp.* Surprisingly, phylogenetic analysis indicates that one of the microorganisms (designated CL-A) from the deep rocks has close affinity to the cyanobacteria.[51] Strong evidence now exists that the deep hot biosphere proposed by Gold[52] does exist on our planet and that rocks at great depths (>3 km) within the crust teem with living chemolithotrophic microorganisms. The deep hot biosphere may be the most important biome on Earth.[53,54] It is now understood that thermophilic and hyperthermophilic prokaryotic microorganisms (such as bacteria and archaea) flourish in hot volcanic springs, deep sea hydrothermal vents, geysers, hot springs, and deep igneous rocks.[55] Figure 1a is an Environmental Scanning Electron Microscope (ESEM) image of a coccoidal thermophilic microorganism (probably bacterial) from the hot (66°C) Obsidian Pool of Yellowstone National Park. It is also known that microorganisms and microfossils exist in permafrost and the polar ice sheets. Abyzov[56] has shown that ice cores from deep (~3 km) within the Central Antarctic ice sheet at Vostok, Antarctica contain microorganisms, including eukaryotic forms such as diatoms (Figure 1b.). Some (~3-20%) of the deep ice microorganisms have remained viable and can be cultured after long term (50,000-400,000 yr.) storage in a state of deep anabiosis. [57] It has also been recently shown that biomineralization processes, such as phosphatization, can occur rapidly and result in excellent three-dimensional preservation of ancient bacteria, algae, and animal embryos.[96-97] The existence in ancient rocks of well preserved microfossils of bacteria, cyanobacteria, fungi , algae and other prokaryotic and eukaryotic microbes and the ability to investigate these microfossils and their living analogs with advanced electron microscopy (SEM, ESEM, and TEM) instruments has given rise to a rapidly developing field designated "bacterial paleontology." [98] Microorganisms are far more widely distributed and their well preserved microfossils more extensively distributed than previously thought possible. They are not restricted to sedimentary rocks, as was the prevailing scientific paradigm in the 1960's when the initial debate raged over possible microfossils and "organized elements" in carbonaceous meteorites (Figure 1c).



a. b. c.

Figure 1(a) Thermophile from Obsidian Pool, Yellowstone; (b) pennate diatoms from 2827M deep in ice core at Vostok, Antarctica; (c) "organized element" spheroid in Murchison meteorite.

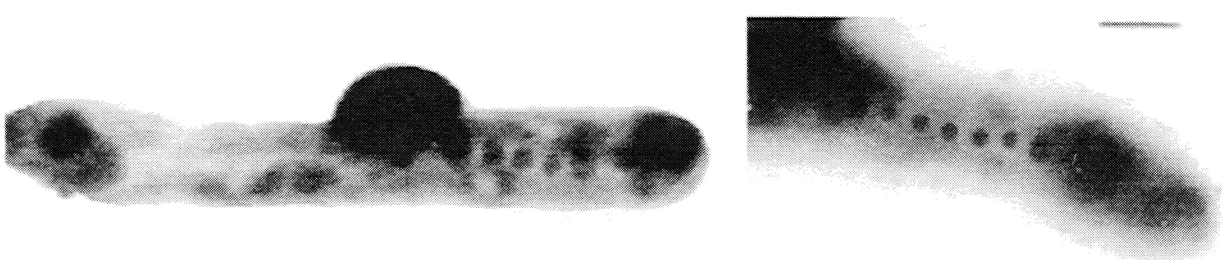
Planet Earth does not represent a closed ecosystem. Several researchers have explored the role of impact shocks on the synthesis of organic molecules[58] and the possible significance of organic chemicals brought to early Earth by comets and meteorites.[59-62] Chemolithotrophic extremophiles, such as presently thrive in deep hydrothermal vents and igneous rocks deep within the crust, may represent the most ancient life forms on Earth. Viable ancient microorganisms (Archaea, Bacteria, and Eukarya) can be found frozen (in deep anabiosis) in permafrost[63,64] and polar ice sheets.[56,57] It has been shown that indigenous volatile organics in meteorites survive atmospheric heating and impact effects. It is not yet known if planetary microbiological cross-contamination via transfer of genetic material or living microbes contained within deep rocks or ice ejected by deep impacts of comets and asteroids is feasible. However, the possibility that biochemicals, genetic materials and perhaps even viable microorganisms might be transferred from one solar system body to another by impact ejection/spallation processes is clearly an important question worthy of serious scientific investigation. Detailed investigations of biochemicals and biomarkers in meteorites (including possible microfossils) may provide important clues to help resolve this question.

2.0 REVIEW OF PRIOR RESEARCH ON METEORITES

The detection of biogenic chemicals and possible microfossils in ALH84001 stimulated research on SNC meteorites carbonaceous chondrites. The investigation of biogenic hydrocarbons as biomarkers[65] and the study of "organized elements"[66-69] in carbonaceous meteorites was pioneered in the early 1960's by Bartholomew Nagy, George Claus and their co-workers. Their results triggered controversy and were strongly criticized, primarily by E. Anders and F. Fitch[70-75] who argued that the biogenic hydrocarbons were due to contamination by terrestrial organics and that the "organized elements" were neither indigenous nor fossilized, but instead were recent contaminants, primarily pollen. They also reported one case of intentional contamination[76] of Orgueil which they suggested might have occurred a century ago. The attack by critics stifled serious scientific research concerning the possibility that biomorphic microstructures encountered in meteorites might be indigenous biogenic bodies. The ESA Exobiology Science Team report reveals the unhealthy atmosphere that existed for scientific research in this area: "It should not be considered unscientific to indulge in detailed characterization of the organic matter in carbonaceous chondrites from the point of view of Exobiology (Nagy et al, 1961) but as already stated this is almost a taboo area."[77]

It is now widely believed that the "organized elements" (spheroidal or ovoid bodies, many with spikes) found by Claus and Nagy and other early workers in carbonaceous chondrites were nothing more than recent terrestrial pollen contaminants.[78] However, that interpretation is not supported by contemporaneous peer-reviewed scientific literature. Furthermore, our independent research on different specimens of several carbonaceous chondrites using the Scanning Electron Microscope (SEM) in Russia and the Environmental Scanning Electron Microscopy (ESEM) in the United States reveals that simple (spheroid and ovoid bodies with or without spikes) "organized element" type microstructures do exist and are relatively abundant in carbonaceous chondrites (Fig. 1c). From morphology alone it is not possible to conclude with any degree of certainty that these simple microstructures are biogenic. However, the size distribution and chemical composition of these forms and their frequent appearance in clusters (possible colonial associations) are certainly consistent with biology. By way of example, we provide an ESEM image of a living thermophile (Fig. 1a) from the Obsidian Pool (66 C) of Yellowstone National Park with similar characteristics to those of many such forms encountered in several different carbonaceous chondrites.

In 1966, the Nobel Laureate, Harold C. Urey[79] provided an extensive review of the scientific evidence for biological materials in meteorites. He observed that the organic substances encountered in meteorites resemble those in ancient terrestrial rocks but not recent contaminants. According to Urey: *"If found in terrestrial objects, some substances in meteorites would be regarded as indisputably biological."* However, a serious problem was that meteoritic minerals were igneous, and igneous rocks were not consistent with microfossils or microbial activity in the prevailing worldview of 1966. *"Those of us who had been working on meteorites for some years were certain that there could not be the residue of living things in them. Had the meteorites had the composition of sedimentary rocks on the Earth, no great surprise would have been expressed."*[79] Microfossils and chemolithotrophic microorganisms in volcanic hydrothermal vents and deep igneous rocks were unknown. The explanation of "organized elements" as pollen was conclusively dismissed by investigations of Orgueil carried out by the palynologist, Martine Rossignol-Strick, and the Archaean microfossil pioneer, Elso S. Barghoorn. Using standard palynological techniques with a clean interior Orgueil sample, they found numerous hollow organic spheres (i.e., "organized elements"). These forms were determined to be indigenous to the meteorite and not pollen. Many of the forms were similar in size, shape and appearance to Precambrian microfossils (e.g. *Eosphaera tyleri, Melasmatosphaera sp., and Huroniospora sp.*). They emphasized that these acid resistant "organized element" bodies *"reacted negatively to the palynological stain safranin and could not be confused with pollen grains, fungus spores, and textile fibers"* [80]. They noted that: "the abundance of the organic objects in Orgueil might be interpreted as evidence of biogenicity. The chances of fossilization for an individual organism are low for a small living population and increase with the size of the population, eventually resulting only in a few fossils but these originating from many living individuals." However, the meteorite did not exhibit sedimentary layers, which were considered an "extrinsic criteria for biogenicity, related to the environment." Hence, Rossignol-Strick and Barghoorn interpreted these meteoritic bodies to be abiogenic, although *"indigenous to the Orgueil meteorite and of extraterrestrial origin."* [80]



(a.) (b).

Figure 2.(a.) Electron dense bodies in Orgueil filament; (b.) Magnetosomes in *Rhodopseudomonas rutilis*
Photo Courtesy Sam L.. VanLandingham *Photo Courtesy Mikhail Vainshtein*

Other researchers had also encountered acid resistant filamentary microstructures in carbonaceous meteorites that were obviously not related to pollen. Some of the most interesting Orgueil microstructures (Figure 2a) are the filaments containing "electron dense" solid bodies discovered by Tan and Van Landingham.[30,90] M. Vainshtein[81] noted that the Orgueil filaments with electron dense spherical bodies in longitudinal chains are similar to purple photosynthetic bacteria that contain linearly distributed non-crystal mineral particles of magnetite or griegite surrounded by tri-layer membranes known as magnetosomes. Figure 2b shows a Transmission Electron Microscope image of a single cell of type strain ATCC17001 of the purple photosynthetic bacteria *Rhodopseudomonas rutilis.* This form is capable of oxidizing and reducing iron.[81-83] In 1966, when Tan and VanLandingham obtained images of possible biological microstructures in Orgueil magnetotactic bacteria and magnetosomes were unknown to science.

3.0 INSTRUMENTATION AND METHODOLOGY

The investigations described herein were initially carried out independently at the Paleontological Institute of the Russian Academy of Sciences in Moscow, Russia, and the Marshall Space Flight Center (MSFC) in Huntsville, Alabama, USA. Subsequently, collaborative studies were carried out at MSFC. These investigations were directed toward the search for indigenous microfossils *in-situ* in freshly broken surfaces of carbonaceous chondrites. At the Paleontological Institute, freshly broken samples and thin sections, coated with gold, were examined using a Cambridge CamScan Scanning Electron Microscope (SEM) equipped with a Link 860 microprobe system.

Investigations at MSFC employed the ElectroScan Corp. Environmental Scanning Electron Microscope (ESEM). The ESEM uses partial pressure of water vapor (10 Torr vacuum) to allow imaging of living biological specimens and nonconductive materials. The operating voltage is 10-30 kV and magnifications up to 100,000X are possible. We have also employed a Hitachi Field Emission Scanning Electron Microscope, which uses a field emission electron source allowing reduced accelerating voltage. Operating within the 0.5 to 30 kV regime, this instrument is capable of imaging uncoated non-conductive materials over a magnification range of 30X-250,000X. Some critics of the ALH84001 results argued that some of the possible nanofossils were artifacts resulting from the gold coating process. The use of uncoated samples eliminates all possibility of coating artifacts as well as sample contamination by oil or foreign materials that might be encountered during the coating process.

3.1 CONTAMINATION OF METEORITIC MATERIALS

Contamination is an extremely serious problem to investigations of possible microbiological components in meteoritic materials. In their research, Claus and Nagy[10,65] encountered in Orgueil a number of possible contaminants, including pollen, soil microorganisms, and a few diatoms, which they identified and discounted. Several decades ago, Imshenetsky and Abyzov[84] conducted exhaustive investigations to evaluate the magnitude of the problem of contamination of meteorites by soil microorganisms. They found that meteorites buried in wet soil near Moscow could become contaminated with known viable, soil microorganisms within a few hours. However, when they carried out studies at the Russian meteorological stations in the Kara-Kum desert of Turkmenistan and Dixon Island in the Arctic they obtained remarkably different results. They found that meteorites buried in dry desert sand or frozen in Arctic ice for periods as long as 8 months did not become contaminated with viable terrestrial microorganisms. These results indicate that to minimize contamination effects, meteoritic materials should be collected as soon as possible and maintained in dry (or preferably dry and frozen) conditions at all times possible.

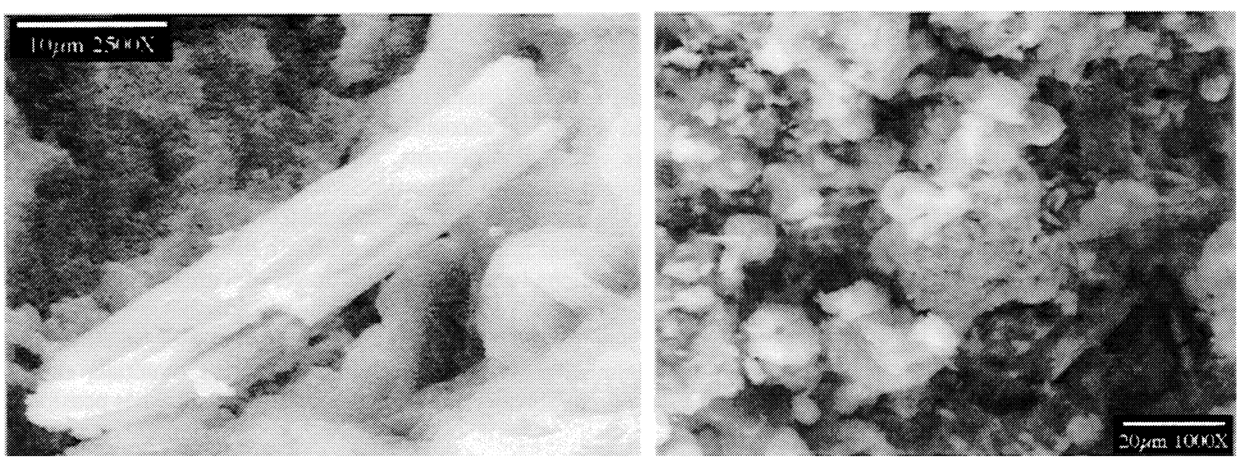
Murchison remains one of the most pristine carbonaceous chondrites known. However, we have detected filamentous microorganisms, probably actinomycetes or mycelial fungi, on the exterior surface of the fusion crust and in surface cracks of one sample of Murchison meteorite provided by the Field Museum of Natural History. These forms were obviously not microfossils, and we have interpreted them as recent terrestrial contaminants. We are presently attempting to culture these forms for phylogenetic analysis and to facilitate precise identification. These contamination effects warrant careful investigation. Similar microorganisms have not been found in freshly fractured interior portions of this sample of Murchison; nor have they been found in several other Murchison samples obtained from diverse sources. The study of freshly broken interior surfaces of meteoritic materials minimizes, but does not totally eliminate, the possibility of recent microbial contamination.

Great care must also be exercised to avoid contaminating the meteoritic materials during storage, handling, and sample preparation. At MSFC, samples are kept in sterile vials, purged with filtered dry nitrogen and stored in a freezer at -80°C. During sample handling, fracturing and mounting, new chisels and electron microscopy tweezers were used only once with each meteorite sample. The work surfaces of these implements were flame sterilized immediately before use by heating them to a white glow with a propane torch. For fracturing, the meteorite material was placed in flame sterilized, disposable aluminum pans. The broken samples were then mounted on flame sterilized boron nitride discs using Electron Microscopy silver cement extracted with a sterile pipette. The prepared specimen is immediately inserted into the ESEM sample chamber and pumped down. The fresh fracture surface of the sample was not cleaned, coated, or allowed to contact liquids. Since many microfossils are destroyed by acids, treatment to extract acid resistant microfossils as used by prior investigators were not used in these studies.

4.0 INVESTIGATIONS OF THE ORGUEIL METEORITE

The Orgueil meteorite is a CI carbonaceous chondrite. It was observed to fall on May 14, 1864, near the villages of Nohic and Orgueil, France.[87] This meteorite is comprised of a soft, black, friable material, with ammonium salts, humic substances, magnetite, silicic acid, and 8 to 10% indigenous water of hydration. The Orgueil minerals are similar to clays and lath-like minerals with a texture that resembles pyroclastic sediments similar to the terrestrial ash flows formed by volcanic ash settling in water, although its chemical composition is quite different.

A 1.0 gm sample of the Orgueil CI carbonaceous chondrite (No. 219) was provided by Museum National d'Histoire Naturelle in Paris. ESEM investigations revealed numerous coccoidal forms similar in size and morphology to the bodies designated "organized elements" by prior workers. These forms are relatively abundant and frequently encountered in clusters suggestive of bacterial colonies (Figure 3.a.). The Orgueil meteorite also contains other interesting microstructures with morphological similarities (including branching and splitting of regular cylindrical fibers) to fibrous kerites from middle Proterozoic pegmatites in Volyn, Ukraine.[85] These non-biogenic structures have high amino acids and hydrocarbon abundance similar protein. Yushkin suggests they may provide a model for protobiological organisms.[86] We also do not interpret these kerite-like forms in Orgueil as biogenic. Their morphology is not easily confused with known microorganisms. However, the Orgueil mineral bodies are interesting, and further research may reveal if these microstructures have any affinities with fibrous kerites.



a. b.

Figure 3(a.) Kerite-like microstructure in Orgueil with coccoidal cluster and (b.) coccoidal and toroidal forms

The Orgueil and Murchison meteorites also contain many toroidal forms (Figure 3.b.), some of which have small rounded tips that appear to protruding through the center of the toroid. These interesting lithified bodies encountered in both the Orgueil and Murchison meteorites are morphologically similar to toroidal coils or spirals observed in developmental stages[99,100] of certain microbes such as some of the hormogonia of Nostocacean cyanobacteria. Phycologists have used the term "hormogonia" to designate short, motile, vegetative trichomes that may be liberated from immotile, ensheathed, parental trichomes.[101] The hormogonia represent a transient cell form associated with developmental or reproductive stages of several species of cyanobacteria.

5.0 INVESTIGATIONS OF THE MURCHISON CARBONACEOUS CHONDRITE

The Murchison meteorite is a CM2 carbonaceous chondrite that was observed to fall in a 1 by 10 mile scatter ellipse around the town of Murchison, Australia at 11:00 A.M. on September 28, 1969. The parent body of the Murchison meteorite is not known, but it was certainly not the Earth or the Moon, nor is Murchison a SNC meteorite from Mars. Asteroids are considered to be the most probable parent bodies for the CI and the CM meteorites, but extinct cometary cores or protocometary bodies are also possibilities. [88] We initially conducted independent electron microscopy investigations of the Murchison meteorite in Russia [89] and in the United States. [90] The studies we carried out in Russia employed the Cambridge CamScan SEM using freshly broken samples and thin sections coated with gold. Figure 4a shows an intricately organized microstructure in the mineral matrix that we have concluded can be interpreted with a rather high degree of probability to be the lithified remains of a macrocolony of coccoid bacteria. These mineralized microstructures are very similar to the type of present day cyanobacteria belonging to the genus *Gloecapsa*. Morphologically similar coccoidal microorganisms produced a bubble mat that served as the source of organic matter for the oil shales—the shungites[91] of the Karelian lower Proterozoic and the kuckersites[92] of the Baltic Ordovician. Figure 4b shows lithified remnants of microbial-like forms embedded in the Murchison mineral matrix. These microstructures are interpreted as being similar to present day cyanobacteria *Enthophysalis granulosa* from the Gavish Sabhka mat. Flattened mineralized sheaths[89] have also been found in both the Murchison and Efremovka meteorites that correspond in size and morphology to those of the filiform cyanobacterium *Microcoleus*.

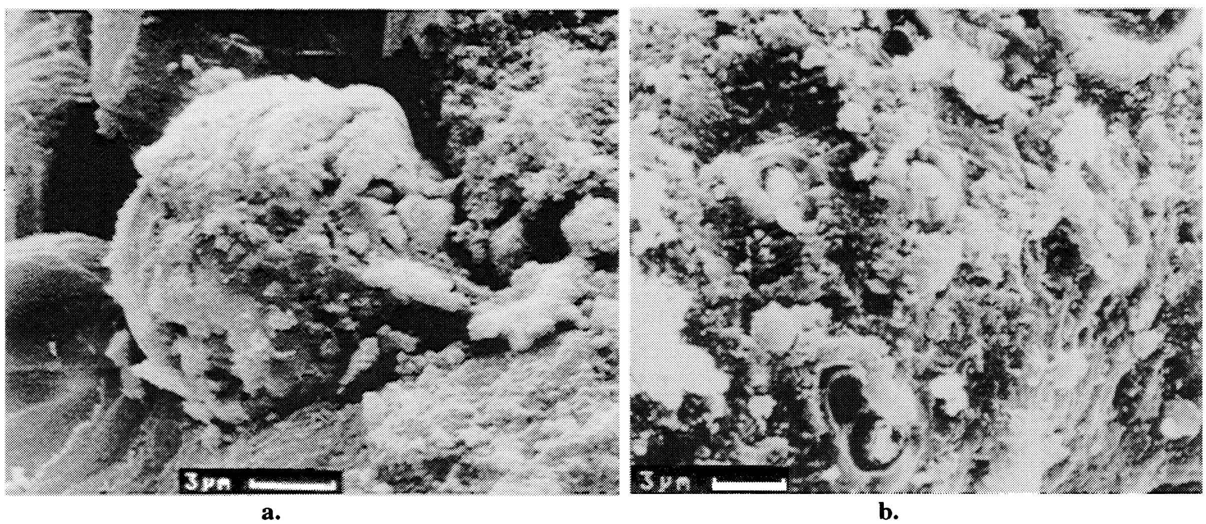


Figure 4. Possible microfossils in Murchison mineral matrix - (a.) lithified remnants similar to macrocolony of cyanobacteria *Gloecapsa sp.;* (b.) embedded, lithified forms similar to cyanobacteria *Enthophysalis granulosa*.

We have also encountered in Murchison several large, complex microstructures embedded within the matrix of Murchison. Figure 5a is an image of a black colored (as seen with optical microscope) carbon rich microstructure, possibly made of kerogen. This body is in close proximity to a number of filaments of size and morphology similar to forms we have observed in fossil cyanobacteria. We had initially interpreted the form to be a myxomycete. However, we also now recognize that this form strongly resembles the morphological characteristics exhibited by clusters of trichomes of the cyanobacteria *Microcoleus* within a common sheath (See Gerasimenko *et al., Fig. 2.b.*). A broken portion of another form with similar morphology and composition (EDS analysis) is shown in Figure 5b in close proximity to a number of coccoidal "organized element" bodies and spherical indentations in the meteorite matrix where similar bodies resided before the specimen was fractured. The images provide convincing evidence that these lithified bodies are indigenous to the meteorite and not the result of recent contamination effects.

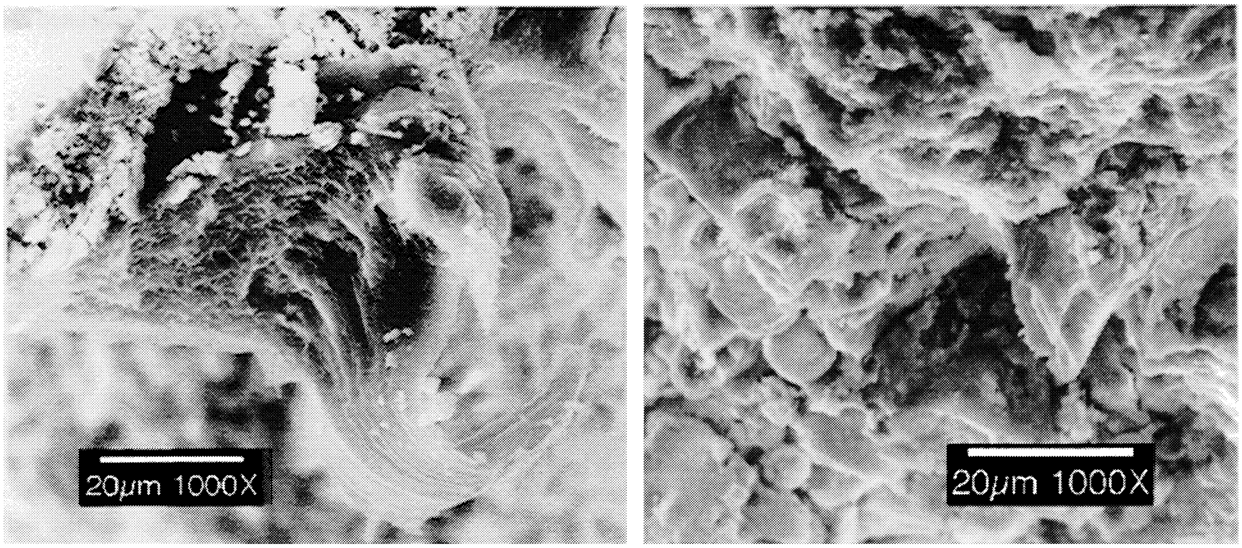


Figure 5. Murchison microfossils (a.) possible cluster of cyanobacterial trichomes in common sheath or myxomycete and (b.) embedded portion of similar microstructure with cluster of coccoidal forms in matrix

Figure 6 provides an ESEM image of a long branched filament embedded within the meteorite matrix. This interesting body exhibits a number of characteristics of cyanobacteria, including attached hormogonial development, trichome, hollow tube, and flattened bumpy sheath in close proximity to numerous toroidal, hormogonia-like coils and round celled spore-like forms. This close association of a number of life-like characteristics of cyanobacteria provides compelling evidence that these lithified microstructures found *in-situ* in freshly broken surfaces of the Murchison carbonaceous chondrite are biogenic in nature, and we consider them to represent microfossils.

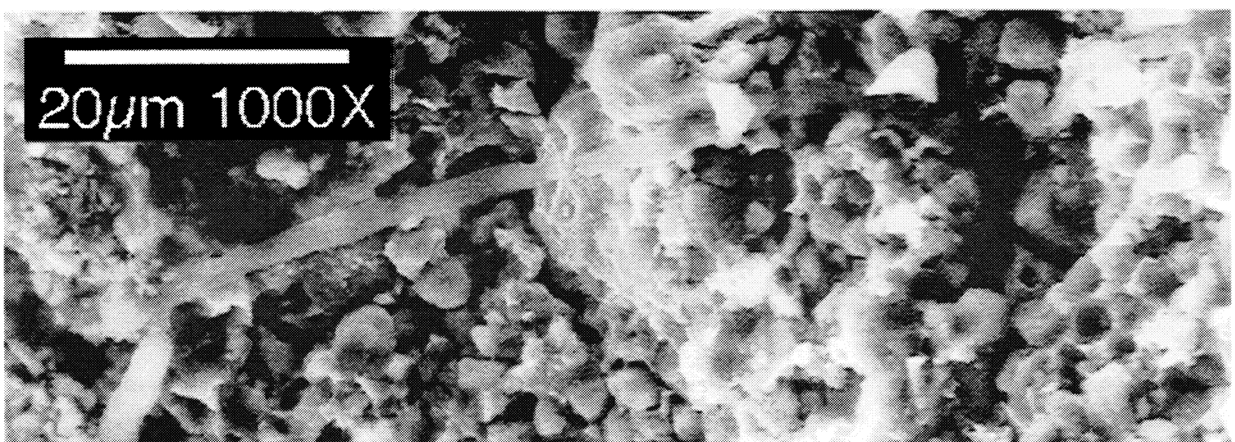
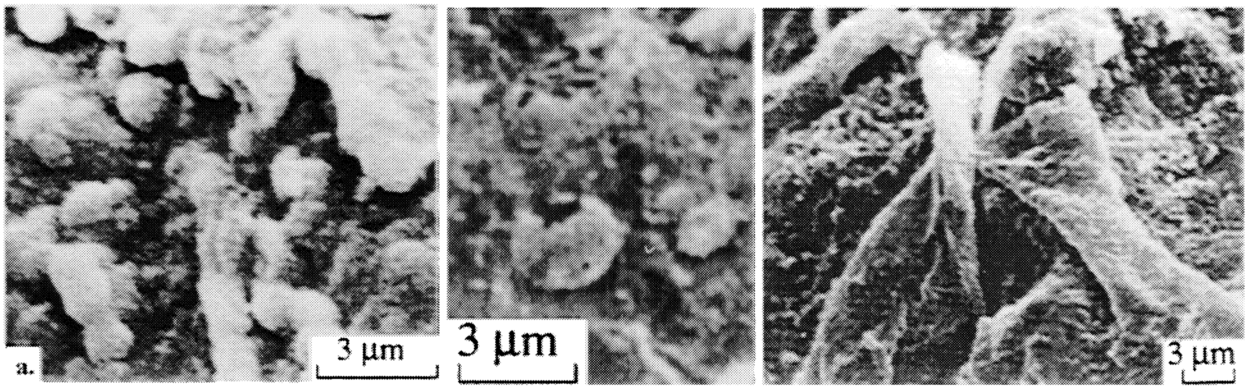


Figure 6. Murchison filament with many characteristics of cyanobacteria-trichome, hollow tube, and flattened bumpy sheath in close proximity to toroidal, hormogonia-like coils and round celled, "spore-like" bodies.

6.0 INVESTIGATIONS OF EFREMOVKA AND NIKOLSKOYE METEORITES

Efremovka is a CO type carbonaceous chondrite that was found in 1962 in Kazakhstan. Investigations of this meteorite revealed the presence of coccoidal and filiform microstructures embedded in the mineral matrix. The coccoidal forms have morphological similarities to the small unicellular cyanobacteria of the genus *Aphonotheceae.*

There exist short chains of the small coccoid forms, that sometimes appear to be in stages of cell division (i.e. diplococci) (Figure 7a). They have also been encountered as hollow spheres (Figure 7b), and we interpret these forms as the remnants of cells and their capsules. We have also found in Efremovka filiform microstructures that resemble the sheaths and trichomes of cyanobacteria similar to *Microcoleus* (Figure 7c). This cyanobacteria was involved in the formation of oil shales of the Baltic Ordovician[93] and the Kuonamka shales of the Cambrian in the Siberian Platform[94]. Other branched filiform microstructures found may belong to mycelial fungi or actinomycetes. We have not found similar biomorphic microstructures in the Nikolskoye meteorite.



a. b. c.

Figure 8. Lithified remnants of possible microorganisms in Efremovka: (a.) cocci, diplococci, and short chains resembling unicellular cyanobacteria *Aphonotheceae;* (b.) hollow spheres; (c.) filiform microstructures interpreted as remnants of sheaths and trichomes of cyanobacteria like *Microcoleus*.

7.0 INTERPRETATION

Some of the criteria that were described by Schopf and Watts[95] for establishing the authenticity of archean microfossils are relevant to the interpretation of possible microfossils in meteorites. The criterion concerning geologic age is crucial to determining if terrestrial fossils are genuinely Archaean, but of little value to this research, since the possible microfossils could represent microorganisms that existed at many different times during the history of the parent body. For the possible microfossils to be legitimately associated with the meteorites it is only necessary that they represent microbial life that existed on the parent body prior to arrival of the meteorite on Earth.

The criterion concerning the indigenous aspect of the possible microfossils is of paramount importance. To address this matter, we have confined our investigations to the interior surfaces of freshly broken meteorite. These studies, carried out independently in Russia and the United States have resulted in the detection of a large number of *in-situ* bodies that we consider to be physically embedded in the meteoritic rock matrix. Energy Dispersive Spectroscopy and Link microprobe analyses indicate that these forms frequently exhibit enhanced carbon, but with the distinct overprint of the meteorite elemental distribution, and we have interpreted these forms as indigenous.

The criterion concerning biogenicity is also crucial. The biogenicity guidelines we employed include the condition that the proposed microfossils must be relatively abundant, which has certainly been well satisfied for the possible microfossils in Murchison, Orgueil, and Efremovka. The bodies considered possible microfossils are numerous. In addition, biogenic structures and characteristics have been detected (e.g. cell walls, diplococci, colonies, and other motile, developmental, and reproductive stages, trichomes, hormogonia, and spores-like forms). These meteoritic microstructures have been analyzed with EDS and Link microprobe systems, and many have been found to have enhanced carbonaceous composition. We interpret the close association of the *in-situ* lithified remains consistent with the size and morphology of known microbes and exhibiting various life developmental cycle stages of morphologically similar modern and fossilized microorganisms to provide extremely strong evidence of biogenicity.

The criterion that the possible microfossils must occur in geologically plausible context (e.g. relatively unmetamorphosed sedimentary rocks) is not satisfied for these meteorites. However, in view of the fact that there are many terrestrial microorganisms and microfossils in deep igneous rocks, rocks associated with volcanic springs and deep sea hydrothermal vents, and microfossils deep within the polar ice caps of our planet, we do not consider this criterion to be determinant to the possible existence of microfossils in either terrestrial rocks, ice or astromaterials.

8.0 CONCLUSIONS

High resolution SEM and ESEM investigations carried out independently in Russia and the United States have revealed the presence of numerous possible biogenic microstructures in the Murchison and Efremovka carbonaceous chondrites. Careful *in-situ* examinations of freshly fractured meteorite surfaces have revealed these microstructures to be embedded within the meteoritic mineral matrix. We have found numerous coccoidal and ellipsoidal bodies (some with spikes) in the Murchison, Efremovka, and Orgueil meteorites that are similar to forms of uncertain biogenicity that were designated "organized elements" by prior researchers. This has led us to conclude that these "organized elements" do exist in carbonaceous chondrites, and the hypothesis that the "organized elements" comprised nothing more than recent "tree pollen" contaminants is not supported. These bodies may represent microfossils, but their simple nature makes it difficult to ascribe biogenicity with any degree of certainty. We have also found the Orgueil meteorite to contain microstructures similar in morphology to fibrous kerites. Possible affinity with the kerite crystals has not yet been established, but it is considered worthy of future investigations.

We have also found far more complex biomorphic forms embedded within the mineral matrix of the meteorites. These forms occur in relative abundance in the Murchison, Efremovka, and Orgueil carbonaceous chondrites, but we have not found any "organized element" type forms or more complex biomorphic microstructures in the Nikolskoye L5 stony meteorite. We have observed many characteristics consistent with biology in these complex microstructures, including features we interpret as cell walls, colonial associations, diplococci, filaments and multiple filaments in sheath, and motile, developmental, and reproductive stages including trichomes, hormogonia, and spores. EDS and Link microprobe analyses of these bodies reveals carbonaceous enhancement as well as elemental distribution characteristics of the matrix. These mineralized microstructures have been found embedded in the matrix, and we are unable to dismiss them as recent terrestrial contaminants. We interpret the close association of the *in-situ* lithified remains of microbial-like forms to provide further evidence of microfossils in carbonaceous chondrites. Many of the meteoritic forms detected exhibit size, distribution, morphology, cell walls and other biogenic features. The microstructures encountered in the carbonaceous chondrites exhibit size, morphology, associations and other characteristics consistent with the size, morphology, reproductive, motile and developmental life cycle characteristics known in living cyanobacteria from mats and microfossils of bacteria, fungi, and cyanobacteria encountered in ancient Cambrian phosphate-rich rocks (phosphorites) of Khubsugul, Northern Mongolia and Dictyonema oil shales of the Baltic Ordovician and Kuonamka shales of the Cambrian and Siberian Platform.

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