

# Evidence of Microfossils in Carbonaceous Chondrites

Richard B. Hoover  
Space Sciences Laboratory, ES-82  
George C. Marshall Space Flight Center,  
Huntsville, AL 35812, USA

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372 757

Alexei Yu. Rozanov  
Paleontological Institute, Russian Academy of Sciences  
123 Profsoyuznaya str.  
117647 Moscow, Russia

S. I. Zhmur  
Institute of the Lithosphere, Russian Academy of Sciences  
Staromonetnyi per. 22,  
Moscow, Russia

V. M. Gorlenko  
Institute of Microbiology, Russian Academy of Sciences  
7,60-letiya Octobrya,  
117811 Moscow, Russia

## ABSTRACT

Investigations have been carried out on freshly broken, internal surfaces of the Murchison, Efremovka and Orgueil carbonaceous chondrites using Scanning Electron Microscopes (SEM) in Russia and the Environmental Scanning Electron Microscope (ESEM) in the United States. These independent studies on different samples of the meteorites have resulted in the detection of numerous spherical and ellipsoidal bodies (some with spikes) similar to the forms of uncertain biogenicity that were designated "organized elements" by prior researchers. We have also encountered numerous complex biomorphic microstructures in these carbonaceous chondrites. Many of these complex bodies exhibit diverse characteristics reminiscent of microfossils of cyanobacteria such as we have investigated in ancient phosphorites and high carbon rocks (e.g. oil shales). Energy Dispersive Spectroscopy (EDS) analysis and 2D elemental maps shows enhanced carbon content in the bodies superimposed upon the elemental distributions characteristic of the chondritic matrix. The size, distribution, composition, and indications of cell walls, reproductive and life cycle developmental stages of these bodies are strongly suggestive of biology. These bodies appear to be mineralized and embedded within the meteorite matrix, and can not be attributed to recent surface contamination effects. Consequently, we have interpreted these *in-situ* microstructures to represent the lithified remains of prokaryotes and filamentous cyanobacteria. We also detected in Orgueil microstructures morphologically similar to fibrous kerite crystals. We present images of many biomorphic microstructures and possible microfossils found in the Murchison, Efremovka, and Orgueil chondrites and compare these forms with known microfossils from the Cambrian phosphate-rich rocks (phosphorites) of Khubsugul, Northern Mongolia.

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

## 1.0 INTRODUCTION

The detection by McKay et al.<sup>1</sup> 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 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.

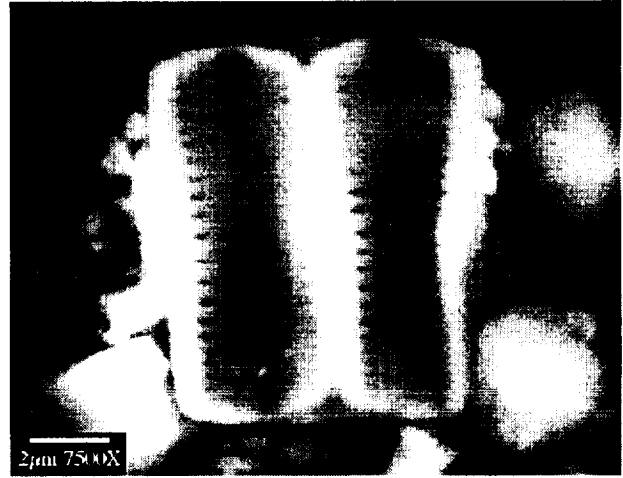
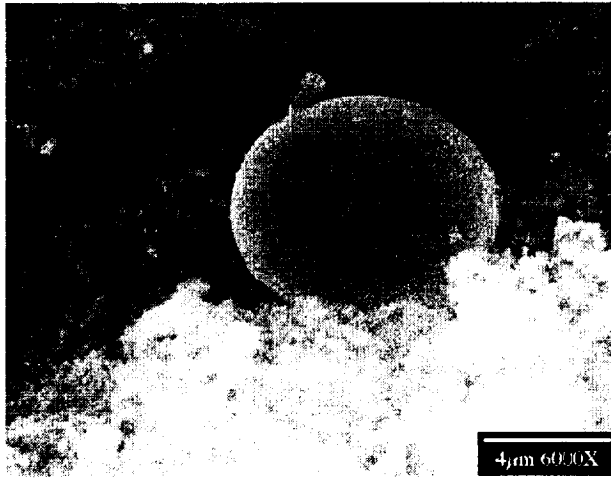
The minute size of the putative microfossils in ALH84001 revealed that the limits of size of terrestrial microbial life was not well understood. This has stimulated research into dwarf bacteria<sup>2</sup>, nanofossils, and nanobacteria.<sup>3-7</sup> Evidence has been obtained which shows that microfossils and living autonomous (culturable) microorganisms at least as small as 100 nm diameter are present on Earth. The ultimate limit to cellular life is not yet established, but it is now clear that many of the microstructures interpreted as possible microfossils in ALH84001 can not be dismissed strictly on the basis of their small size. It is now known there exists bacterial microorganisms and microfossils that are dramatically smaller than previously thought possible. The understanding of microbial life on the nanometric scale has been significantly enhanced, but additional research to ascertain by theoretical and experimental methods the limits of cellular life is obviously of great importance to Astrobiology.

The ALH84001 investigations have 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.<sup>8</sup> 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 that have been encountered in SNC meteorites, carbonaceous chondrites, and ancient terrestrial rocks. These 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<sup>9</sup> 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<sup>10</sup> has provided an extensive review of the organic chemistry of carbonaceous meteorites as well as petroleum geochemistry. Over the past several years, various careful researchers have demonstrated that a large number of complex organic that are typically associated with life processes are indigenous to carbonaceous meteorites. These include kerogens<sup>11</sup>, heterocyclics<sup>12</sup>, polymers<sup>13</sup>, PAHs<sup>14</sup>, aromatic and aliphatic hydrocarbons<sup>15-17</sup>, nucleic acid bases, purines, pyrimidines, and triazines<sup>18</sup>, isomeric alkanes and isoprenoids<sup>19</sup>, extraterrestrial<sup>20</sup> and non-protein<sup>21</sup> amino acids with unusual stable isotope ratios<sup>22</sup>, chiral amino acids with enantiomeric excess<sup>23-26</sup>, and porphyrins<sup>27, 28</sup>, microvessicles and organic nanoparticles<sup>29-31</sup>, and possible microfossils.<sup>1,32-37</sup> These would clearly be considered important signatures of ancient biology if encountered and ancient sediments or rocks from Earth. If biomarkers are to have relevance to Astrobiology, they must be interpreted rationally and with consistency. Consequently, it is logical to consider these diverse observations to 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 that have been found to contain numerous types of indigenous biomarkers. A primary objection to this concept seems to reside with the assumed difficulty of life evolving on the parent body of these meteorites. However, it is becoming increasingly clear that liquid water was abundant on ancient Mars. Therefore processes similar to those that resulted in the origin of microbial life on Earth may have also given rise to the appearance of life on early Mars.

It is now widely accepted that ALH84001 and the other SNC meteorites are rocks from Mars<sup>38-40</sup> that were ejected from the crust of that planet and transported to Earth as a result of meteorite impact ejection phenomena<sup>41-45</sup>. The presence of giant craters and astroblemes on the Earth and the moon clearly demonstrate that many deep impact events have occurred throughout the history of our planet as well. Recent microbiological research has shown the presence of indigenous microorganisms in deep aquifers<sup>46</sup>, and granitic and basalt groundwaters.<sup>47-50</sup> Samples collected

in deep gold mines of Witwatersrand, South Africa by Onstott et al.<sup>51</sup> were found to contain high concentrations ( $\sim 10^5$  to  $10^8$  cells/g) of a 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.<sup>51</sup> Strong evidence now exists that the deep hot biosphere proposed by Gold<sup>52</sup> does exist on planet Earth. Rocks at great depths (>3 km) within the Earth's crust teem with living chemolithotrophic microorganisms and may comprise the most important biome on our planet.<sup>53, 54</sup>



**Figure 1.a. Coccoidal thermophile from Yellowstone    1.b. Diatom from 2827 M deep ice of Vostok**

Living microorganisms and microfossils are also abundant in volcanic springs at Yellowstone National Park. **Figure 1.a.** is an ESEM image of an iron-rich coccoidal thermophile collected in the Obsidian Pool (66 C) at Yellowstone National Park. Prokaryotic microorganisms and microfossils are also present in great numbers in igneous rocks from terrestrial subsurface hydrothermal environments and deep sea volcanic hydrothermal vents.<sup>55</sup> The recognition that living microorganisms and microfossils exist in deep igneous rocks is in dramatic contrast to the prevailing scientific paradigm (that microorganisms and microfossils exist *only* in sedimentary rocks) of the 1960's when the early debate concerning possible microfossils and "organized elements" in carbonaceous chondrites was raging. Abov<sup>56</sup> has also demonstrated that ice cores collected from Vostok, Antarctica at depths  $\sim 3$  km contain abundant microfossils and frozen microorganisms including eukaryotic diatoms (**Fig. 1b.**). Some of the microorganisms ( $\sim 3$ -20%) from deep within the ice sheet of Central Antarctica are viable and have been cultured after long term storage in a state of deep anabiosis.<sup>57</sup>

It is now very evident that planet Earth does not represent a closed ecosystem. Several researchers have explored the role of impact shocks on the synthesis of organic molecules<sup>58</sup> and the possible significance of organic chemicals brought to early Earth by comets and meteorites.<sup>59-62</sup> It is now known that microfossils and living, chemolithotrophic, prokaryotic microorganisms (e.g. bacteria, archaea) thrive in deep hydrothermal vents and crustal igneous rocks. These extremophiles may well represent the most ancient forms of life on Earth. It is also known that microfossils and viable prokaryotic bacteria and eukaryotic microorganisms (e.g. yeasts, diatoms) can be found frozen (in deep anabiosis) in permafrost<sup>63,64</sup> and polar ice sheets.<sup>56,57</sup> 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 genetic material or living microbes contained within deep rocks or ice ejected by deep impacts of comets and asteroids is feasible. However, this is clearly an important question suitable for scientific investigation.

## 2.0 REVIEW OF PRIOR WORK

The detection of evidence of biogenic chemicals and possible microfossils in ALH84001 results has also resulted in extensive additional research on SNC meteorites and a renewed interest in the search for biomarkers and possible microfossils associated with carbonaceous chondrites. The investigation of biogenic hydrocarbons as biomarkers<sup>65</sup> and the study of "organized elements"<sup>66-69</sup> in carbonaceous meteorites is an area of research that was pioneered in the early

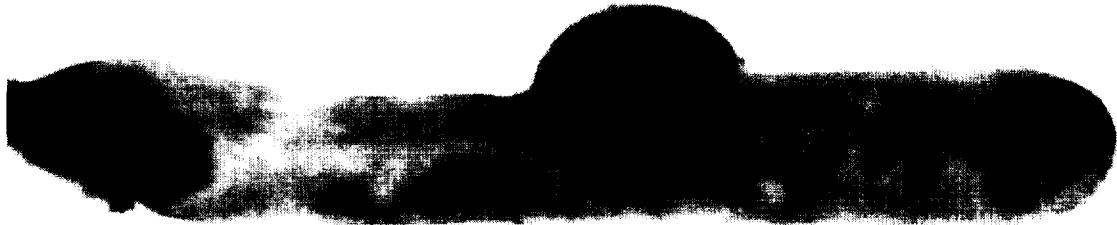
1960's by Bartholomew Nagy, George Claus and their co-workers. Their results were highly controversial and criticized extensively by their chief protagonists, E. Anders and F. Fitch.<sup>70-75</sup> It was argued that the biogenic hydrocarbons and "organized elements" were due to contamination with terrestrial organics and pollen. In one case it was argued that intentional contamination<sup>76</sup> was present, although this contamination was considered to have occurred sometime in the last century. This paper and the continuing efforts of the critics strongly impacted the serious scientific investigation of the interesting microstructures associated with carbonaceous chondrites. The ESA Exobiology Science Team Study report reveals how seriously poisoned was the atmosphere for scientific research into organic matter in these meteorites: "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."<sup>77</sup>

It has become a popular belief that the "organized elements" found in carbonaceous chondrites by the early researchers were nothing more than "tree pollen" grains contaminating the meteorite.<sup>78</sup> However, that interpretation is not supported by the peer-reviewed scientific literature. In 1966, the Nobel Laureate, Harold C. Urey<sup>79</sup> provided an extensive review of the scientific evidence for biological materials in meteorites. Noting that the organic substances encountered in meteorites resemble those in ancient terrestrial rocks but not recent contaminants, Urey remarked: "If found in terrestrial objects, some substances in meteorites would be regarded as indisputably biological." A serious problem was that meteoritic minerals were igneous, and in the prevailing world view of 1966, igneous rocks were not consistent with microfossils or microbial activity. "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."<sup>79</sup> Microfossils and chemolithotrophic microorganisms in volcanic hydrothermal vents and deep igneous rocks were inconceivable at that time.

The "pollen" contamination explanation for "organized elements" was conclusively dismissed by a study of Orgueil carried out by pollen expert, Martine Rossignol-Strick, and Archaean microfossil pioneer, Elso S. Barghoorn. They conclusively demonstrated that the hollow organic spheres of the Orgueil meteorite (called "organized elements" by Claus and Nagy) were indigenous to the meteorite and were not pollen grains. They used standard palynological techniques with a clean interior sample of the Orgueil carbonaceous chondrite. After demineralizing the meteoritic material with strong acids and found numerous hollow spheres, spheres with spikes, ovoids, and some membranes and "funnel" or "mushroom" shaped structures with rounded caps and tapering "stalks".<sup>80</sup> They discovered many forms similar in size, shape and appearance to microfossils (*Huroniospora sp.*) which occur in the Gunflint chert. The meteoritic forms were the same color, consistency, and chemical composition as the surrounding brown organic residue, and exhibited well delimited walls (similar to cell walls) and smooth inner surfaces and irregular outer surfaces. The walls were broken and exhibited elasticity. These abundant, acid resistant "organized element" type microstructures *reacted negatively to the palynological stain safranin and could not be confused with pollen grains, fungus spores, and textile fibers.* They observed: "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." The hollow spheres of Orgueil were similar (by morphological criteria) to the acid resistant 6-20µm hollow spheres found by Barghoorn in the Onverwacht (>3.2 Gy) sediments. Many meteoritic forms were similar in size, shape and appearance to a wide variety of Precambrian microfossils (e.g. *Eosphaera tyleri*, *Melasmatosphaera sp.*, *Huroniospora sp.*). However, they also noted that meteorite did not exhibit sedimentary structure. The presence of sedimentary layers were considered an "extrinsic criteria for biogenicity, related to the environment." Based upon this criterion, Rossignol-Strick and Barghoorn had no choice but to interpret these meteoritic bodies as abiogenic. They also concluded that organic, acid resistant microstructures found in the carbonaceous chondrite were "indigenous to the Orgueil meteorite and of extraterrestrial origin."<sup>80</sup>

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 (Fig. 2.a.) are the filaments containing "electron dense" solid bodies discovered by Tan and Van Landingham.<sup>30</sup> Vainshtein noted that the electron dense spherical bodies found in these filaments are similar to the linearly distributed non-crystal mineral particles of magnetite or grigite surrounded by tri-layer membranes known as magnetosomes. (Figure 2.b.) is an

electron microscope image of a single cell of the purple photosynthetic bacteria *Rhodospseudomonas rutilis*, type strain ATCC17001, which is capable of oxidizing and reducing iron.<sup>81-83</sup> It should be pointed out that when Tan and Van Landingham produced the electron micrograph of possible biological microstructures they found indigenous to the Orgueil carbonaceous chondrite, the existence of magnetotactic bacteria and magnetosomes was unknown to science.



**Figure 2.a.** Orgueil filament with chain of electron dense bodies (Courtesy Tan and Van Landingham)



**Fig. 2.b.** Magnetosomes in photosynthetic purple bacteria *Rhodospseudomonas rutilis*, type strain ATCC17001. (Courtesy M. Vainshtein)

### 3.0 INSTRUMENTATION AND METHODOLOGY

The investigations described herein were initially carried out independently at the the Paleontological Institute of the Russian Academy of Sciences in Moscow, Russia, and the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. Joint studies were also conducted 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, studies were carried out on gold coated samples using a Cambridge CamScan Scanning Electron Microscope (SEM) equipped with a Link 860 microprobe system.

The MSFC studies were primarily carried out using the ElectroScan Corp. Environmental Scanning Electron Microscope (ESEM). The ESEM uses partial pressure of water vapor (10 Torr vacuum) to permit the imaging of living biological specimens and nonconductive materials over an operating voltage of 10-30 kV with magnification of

up to 100,000X. Some initial studies employed the Field Emission Scanning Electron Microscope (FESEM), manufactured by Hitachi. This microscope employs a field emission electron source that allows the accelerating voltage to be reduced to within the 0.5 to 30 kV regime and is capable of producing high resolution images of uncoated non-conductive materials over the 30- 250,000X magnification range. Some critics of the ALH84001 results had argued that some of the possible nanofossils were artifacts that resulted from the gold coating applied to the specimen before the SEM images were obtained. The use of uncoated meteoritic materials eliminates all possibility that nanostructures can be confused with or result from coating artifacts. This also eliminates all possibility of sample contamination by oils or foreign materials during the coating process.

Contamination is an extremely serious problem to investigations of possible microbiological components in meteoritic materials. In their research, Claus and Nagy<sup>10,65</sup> encountered in Orgueil a number of possible contaminants, including pollen, soil microorganisms, and some diatoms. They carefully identified, tabulated, and discounted these contaminants. Several decades ago, Imshenetsky and Abyzov<sup>84</sup> conducted exhaustive investigations to evaluate the magnitude of the problem of contamination of meteorites by soil microorganisms. Their research revealed that meteorites exposed to wet soils could become contaminated with viable soil microorganisms within hours. However, their investigations carried out at Russian meteorological stations in the Kara-Kum desert of Turkmenistan and Dixon Island in the Arctic were particularly interesting. Their research also found that meteorites buried in dry desert sands or frozen Arctic ice for periods as long as 8 months remained uncontaminated by viable terrestrial microorganisms. These investigations indicate that in order to minimize contamination effects, meteoritic materials should be collected as soon as possible and maintained in dry (or both frozen and dry) conditions at all times.

Murchison is the most pristine carbonaceous chondrite known. However, we encountered grey-colored microbial forms on the fusion crust and in cracks adjacent to the fusion crust in a sample of Murchison provided by the Field Museum. These forms are 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 forms have not been encountered in interior portions of this sample of Murchison; nor have they ever been encountered in several other Murchison samples obtained from other sources. In order to minimize this type of surface contamination effects, we have been careful to explore freshly broken interior surfaces of the meteoritic materials.

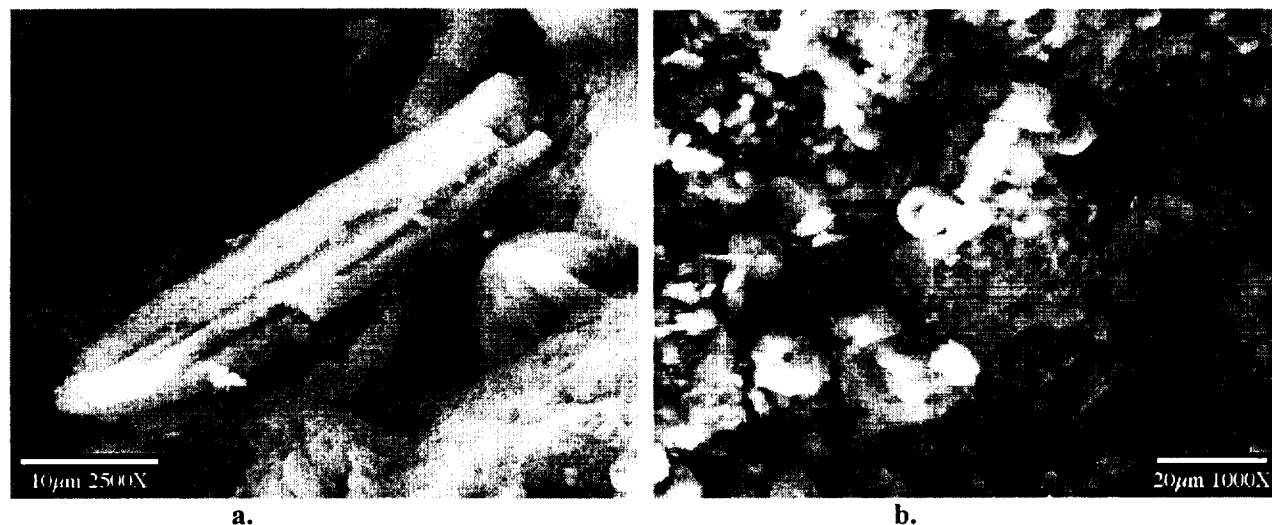
Great care has also been exercised to avoid contaminating the meteoritic materials during handling and sample preparation. All chisels and electron microscopy tweezers employed to handle and break samples of carbonaceous chondrites at MSFC were used only once with meteoritic materials. Prior to use, these implements were flame sterilized by heating the work surfaces to a white glow with a propane torch. The meteorite samples were then mounted (using Electron Microscopy Silver Cement extracted with a sterile disposable pipette) on flame sterilized Boron nitride discs. The prepared specimen was then immediately inserted into the ESEM sample chamber and pumped down. The fresh fracture surface of the sample was not cleaned or allowed to come into contact with any fluids, liquids, or stains. Since many microfossils can be destroyed by acids, etching treatment to extract acid resistant microfossils such as have previously been used by many researchers investigating carbonaceous chondrites have not been employed for these studies.

#### **4.0 INVESTIGATIONS OF THE ORGUEIL METEORITE**

The Orgueil meteorite is a CI carbonaceous chondrite that was observed to fall on May 14, 1864 near the villages of Nohic and Orgueil, France.<sup>87</sup> This meteorite is comprised of a soft, black, friable material, with ammonium salts, humic substances, magnetite, silicic acid, and 5.2 to 6.9% hygroscopic water and 8 to 10% indigenous water of hydration. The Orgueil stones disintegrate into a fine dust when in contact with liquid water. 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. (Volcanic ash usually has less magnesium and more silicon, aluminum and calcium oxides than found in meteorites.)

A sample of the Orgueil CI carbonaceous chondrite was provided by the Musee d'Histoire Naturel in Paris. ESEM investigations at MSFC revealed the presence of numerous coccoidal forms similar in size and morphology to the bodies designated "organized elements" by prior workers. These forms are relatively abundant and are frequently

encountered in clusters suggestive of bacterial colonies. (Fig. 3) The Orgueil meteorite also contains other interesting microstructures that exhibit morphological similarities (including branching and splitting or regular cylindrical fibres) to the fibrous kerite crystals from middle Proterozoic pegmatites in Volyn, Ukraine.<sup>85</sup> These fascinating non-biogenic structures have anomalously high amounts of amino acids and hydrocarbon abundances nearly identical to protein and have been interpreted by Yushkin as representing a model for protobiological organisms.<sup>86</sup> We do not interpret the meteoritic forms as biogenic since they do not exhibit strong similarity to any types of terrestrial microorganisms. However, they are very unusual, and additional work should be carried out to determine if these bodies might have any possible affinities with kerites.



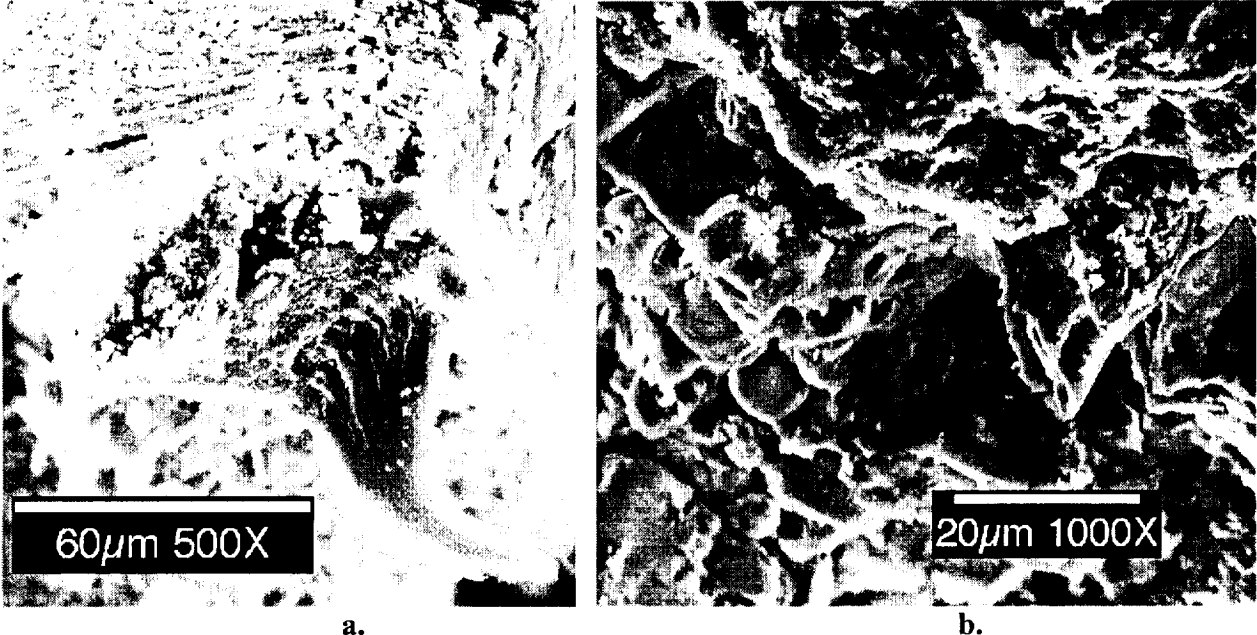
**Fig. 3.a. Coccoidal cluster on kerite-like crystals; 3.b. hormogonia-like toroidal bodies in Orgueil**

## 5.0 INVESTIGATIONS OF THE MURCHISON METEORITE

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.<sup>88</sup> We initially conducted independent electron microscopy investigations of the Murchison meteorite in Russia<sup>89</sup> and in the United States.<sup>90</sup> The studies we carried out in Russia employed the Cambridge CamScan SEM using freshly broken samples and thin sections coated with gold. **Figure 4.a.** 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 coccoid microorganisms produced a bubble mat that served as the source of organic matter for the oil shales—the shungites<sup>91</sup> of the Karelian lower Proterozoic and the kuckersites<sup>92</sup> of the Baltic Ordovician. Flattened mineralized sheaths<sup>89</sup> were also found in the Murchison meteorite that correspond in size and morphology to those of the filiform cyanobacterium *Microcoleus*. This cyanobacteria was involved in the formation of oil shales of the Baltic Ordovician<sup>93</sup> and the kuonamic shales of the Cambrian in the Siberian Platform<sup>94</sup>.

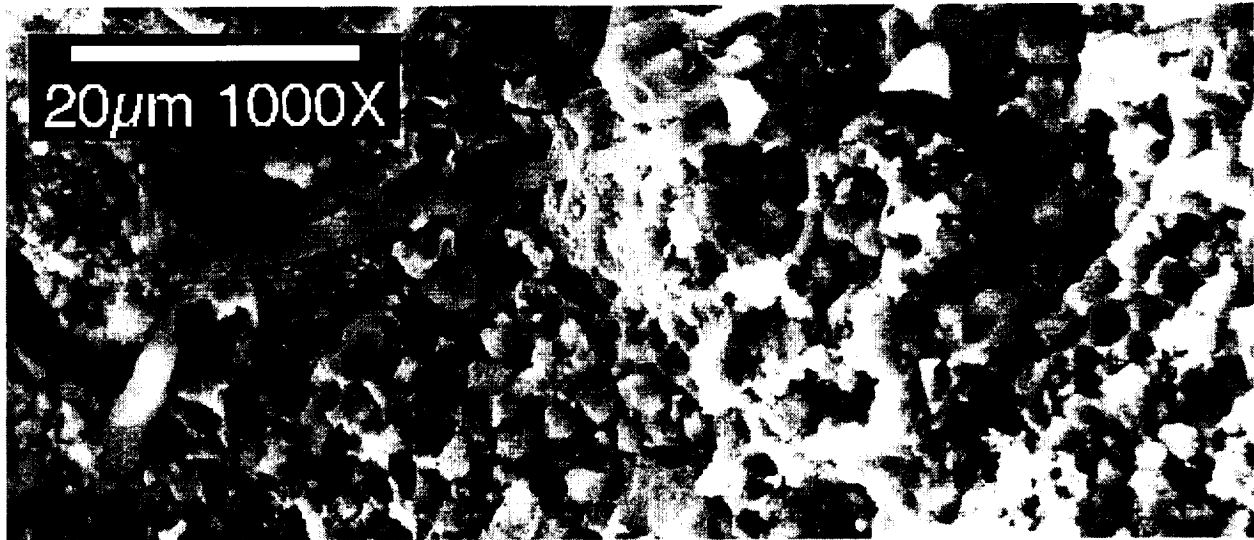


**Figure 4.a.** Microstructures in Murchison mineral matrix. (a.) complex structure similar to macrocolony of cyanobacteria *Gloecapsa sp.* and (b.) 3 micron diameter “organized element” type sphere with spike.



**Figure 5.a.** Murchison myxomycete type microstructure and (b.) similar fractured microstructure showing hollow cell wall in close proximity to colony of embedded spheres, and ovoids and matrix depressions.

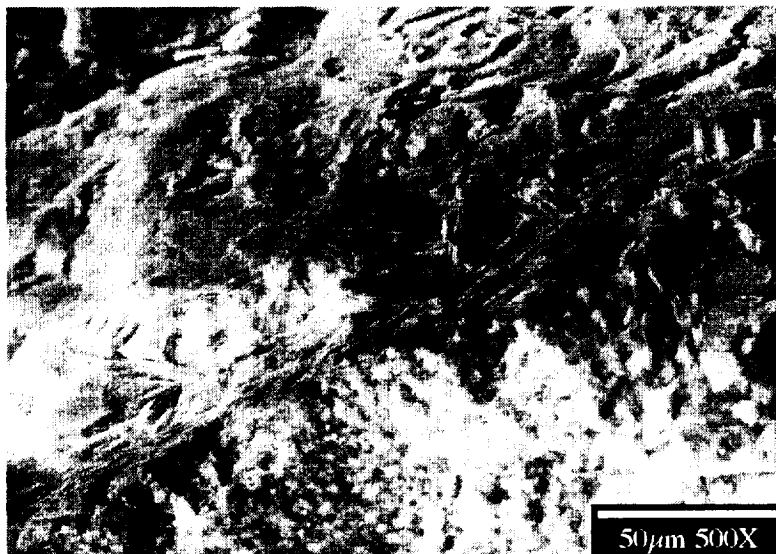




**Figure 5.** Long embedded cyanobacterial-like filament with trichome, hollow tube, and flattened sheath.

### 6.0 INVESTIGATIONS OF THE EFREMOVKA METEORITE

Efremovka is a CO type carbonaceous chondrite that was found in 1962 in Kazakhstan, USSR.



**Figure 5.a.** Microstructures in Efremovka reminiscent of cyanobacterial mat..

## 7.0 INTERPRETATION CRITERIA

Some of the criteria described by Schopf and Watts,<sup>95</sup> for establishing the authenticity of Archean microfossils are of relevance to the interpretation of possible microfossils in meteorites. Their criteria are considered below:

- I. **Geologic Age:** This is crucial to determining if terrestrial fossils are genuinely Archean, but it is not relevant to research concerning possible meteoritic microfossils. For the possible microfossils to be legitimately associated with the meteorites it is only necessary that they precede the meteorite's arrival on Earth.
- II. **Indigenoussness:** This is a critical criterion. ESEM study of freshly broken meteorite has yielded evidence that these *in-situ* bodies are physically embedded in the meteoritic rock matrix and EDS indicates similar chemical elements. The condition is considered satisfied.
- III. **Syngenicity:** Are possible microfossils contemporaneous? The EDS data reveals that the elemental composition of the proposed microfossils are consistent with the meteoritic rock matrix. And we consider this condition satisfied.
- IV. **Biogenicity:** The biogenicity guidelines include the condition that the proposed fossils must be relatively abundant. This criterion is certainly satisfied for many of the possible microfossils in Murchison and Efremovka. The bodies are numerous and colonies are often present.
  1. Be of carbonaceous composition.--- EDS data indicates many forms encountered satisfy this condition.
  2. Exhibit Biological Morphology---The size, morphology, variability of form, appearance of cell walls and possible cell division states and the presence of closely associated lithified remains representing various stages in life developmental cycles of morphologically similar modern and fossilized microorganisms satisfy this condition and provide strong evidence of biogenicity.
- V. **Occur in Geologically Plausible Context** (e.g. relatively unmetamorphosed sedimentary rocks). This condition is not satisfied for the meteorites, but it is also not even correct for terrestrial microfossils that can indeed be found in deep igneous rocks.
- VI. **Fit Within Well Established Evolutionary Context:** This condition is relevant for Archean microfossils, but can not yet be addressed for possible microfossils in carbonaceous chondrites. The parent body of these meteorites is still unknown and we also know nothing concerning associated evolutionary context.
- VII. **Be Dissimilar from Potentially Co-existing Abiological Organic Bodies.** (e.g. protenoid microspheres, carbonaceous "organized elements" and products of abiotic synthesis"): This condition presumes that the "organized elements" are not biogenic which is by no means certain. There are many spherical bodies in the carbonaceous chondrites, that may be abiogenic, while others may also represent the remains of lithified coccoidal bacteria and archaea. Many filamentous and toroidal cyanobacteria-like forms and complex myxomycete-like forms fall into this category, and we consider this criterion to be satisfied.

## 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 in the Murchison and Efremovka carbonaceous chondrites. Careful *in-situ* examinations of freshly fractured meteorite surfaces has revealed these microstructures to be embedded within the meteoritic mineral matrix. We interpret this as evidence that the bodies are indigenous to the meteorite rather than surface contaminants. Energy Dispersive Spectroscopy (EDS) analysis reveals that many forms have enhanced carbon content superimposed on elemental distribution characteristic of the chondrite matrix, and this is interpreted as evidence that the forms are lithified microfossils rather than recent terrestrial contaminants. Many of the forms detected exhibit size distribution, morphology, cell walls and other biogenic features, and the close association of different microstructures consistent with reproductive and other developmental life cycle characteristic of known living and fossil cyanobacteria that we have found in ancient Cambrian phosphate-rich rocks (phosphorites) of Khubsugul, Northern Mongolia and dictyonemic oil shales of the Baltic Ordovician and kuonamoc shales of the Cambrian and Siberian Platform. These studies have also revealed 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 frequently repeated assertion these “organized elements” were nothing more than “tree pollen” contaminants is scientifically suspect. The Orgueil meteorite has also been found to contain microstructures that exhibit morphological similar to fibrous kerites. Possible affinity with the kerite crystals has not yet been established, but is considered worthy of future research.

## 9.0 ACKNOWLEDGEMENTS

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