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Meteorites, Microfossils, and Exobiology

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ABSTRACT

The discovery of evidence for biogenic activity and possible microfossils in a Martian meteorite may have initiated a paradigm shift regarding the existence of extraterrestrial microbial life. Terrestrial extremophiles that live in deep granite and hydrothermal vents and nanofossils in volcanic tuffs have altered the premise that microbial life and microfossils are inconsistent with volcanic activity and igneous rocks. Evidence for biogenic activity and microfossils in meteorites can no longer be dismissed solely because the meteoritic rock matrix is not sedimentary. Meteorite impact-ejection and comets provide mechanisms for planetary cross-contamination of biogenic chemicals, microfossils, and living microorganisms. Hence, previously dismissed evidence for complex indigenous biochemicals and possible microfossils in carbonaceous chondrites must be re-examined. Many similar, unidentifiable, biological-like microstructures have been found in different carbonaceous chondrites and the prevailing terrestrial contaminant model is considered suspect.

This paper reports the discovery of microfossils indigenous to the Murchison meteorite. These forms were found *in-situ* in freshly broken, interior surfaces of the meteorite. Environmental Scanning Electron Microscope (ESEM) and optical microscopy images indicate that a population of different biological-like forms are represented. Energy Dispersive Spectroscopy reveals these forms have high carbon content overlaying an elemental distribution similar to the matrix. Efforts at identification with terrestrial microfossils and microorganisms were negative. Some forms strongly resemble bodies previously isolated in the Orgueil meteorite and considered microfossils by prior researchers. The Murchison forms are interpreted to represent an indigenous population of the preserved and altered carbonized remains (microfossils) of microorganisms that lived in the parent body of this meteorite at diverse times during the past 4.5 billion years (Gy).

Keywords: SNC meteorites, Murchison, carbonaceous chondrites; exobiology; extremophiles, microfossils

1. Introduction

The evidence obtained by McKay et al.[1] of biogenic activity and possible microfossils in the ancient Martian meteorite ALH84001 appears to have triggered a profound paradigm shift. Scientists are now actively searching for additional evidence to confirm this evidence for the existence of extraterrestrial microbial life. Exobiology, which the evolutionary biologist George Gaylord Simpson called "a science looking for a subject matter," may have been delivered subjects. Exobiological research into prebiotic organic chemicals could conceivably expand into the investigation of the biochemistry and biology of extraterrestrial microbiota. Nanofossils and microfossils carried to Earth in meteorites could stimulate the newly emerging field of Exopaleontology and provide guidance for the development of instruments and missions which will seek additional evidence for living and fossil organisms on other planets, satellites, comets, and asteroids. The minerals, complex organics, polymers, lipids, aromatic and aliphatic hydrocarbons, amino acids, nucleic acid bases, and porphyrins indigenous to carbonaceous chondrites and the Shergotty-Nakhla-Chassigny (SNC) class of meteorites have already been well documented. Research is now underway to obtain additional proof of indigenous biological activity in these meteorites. The search continues for biomarkers, including indigenous stable isotopes in amino acids, steranes, lipids, isoprenoids, chiral biomolecules, homochirality, microfossils, and cell walls. (Although several terrestrial microbial groups lack cell walls.) Recent discoveries of nanofossils and living nanobacteria have shown that initial objections to the ALH84001 structures being microfossils on the basis of the diminutive stature were without merit. Studies of terrestrial extremophiles and extraterrestrial pre-biotic and biogenic chemicals and microfossils will be of great value to the NASA Origins Program. This research could facilitate the planning of future space missions designed to seek more information regarding the origin of life and its distribution throughout the cosmos. A more thorough understanding of extremophiles (and the limits of terrestrial microbial life) will help develop space instrumentation tailored to search for evidence of extant or extinct life on planets, satellites, comets, and asteroids in our solar system.

2. Meteorite Ejection and Planetary Cross-Contamination

Analysis by Bogard and Johnson [2] of the abundance and isotopic compositions of trapped gases in the Elephant Moraine shergottite (EET79001) found in the Antarctic in 1979 was correlated with the Martian atmosphere as measured in-situ by the Viking lander. Investigations by several groups[3-5] indicates the twelve known SNC meteorites are of Martian origin. Processes of meteorite impact ejection or spallation[6] may have allowed these meteorites to escape the gravitational field of the planet Mars and ultimately to arrive on Earth. Similar spall ejection mechanisms associated with large meteoritic or asteroidal impacts on Earth could have resulted in the ejection of terrestrial rocks that could have fallen on the planet Mars. Melosh[7-9] used the theory of spall ejection to demonstrate that impacts producing terrestrial craters >100km in diameter would have each ejected millions of tons of rocks from the Earth's near surface. These rocks could have transported living microorganisms into interplanetary space. Even small rocks would shield viable microorganisms from UV radiation and low energy solar cosmic rays and large boulders could shield interior microbes from galactic cosmic rays. Dormant spores and living microbes might remain viable for very long periods of time. Microorganisms active at the time of ejection could be preserved by the hard vacuum of space. Bacteria remained alive and preserved by this process during their 3 year stay on the lunar surface[10] residing within the Surveyor 3 camera assembly. Melosh concluded that *"Planets of the Solar System should therefore not be thought of as biologically isolated, from time to time large impacts may inoculate Mars and the other planets of the inner Solar System with a sample of terrestrial life."* [9]

Over the past two decades, extensive research has established that microorganisms live within the Earth in deep aquifers, oil deposits, sedimentary, and igneous rocks.[11-13] These discoveries were highly controversial and many scientists argued that the microbes detected were the result of contamination from near surface microorganisms. In an effort to resolve contamination issues and explore the possibility of deep microbial life, the Department of Energy launched the subsurface science program. It is now conclusively established that there does exist a vast indigenous assemblage of microorganisms[14-16] which live in sedimentary and igneous rocks, deep oil deposits and aquifers at depths over 3 km beneath the Earth's surface. Many microbial species living in deep terrestrial rocks derive energy from materials within the rocks via chemolithotrophic metabolism. These recently discovered life-forms increase the possibility that impact ejected rocks could contain communities of living microorganisms. Some of these deep microbial communities may have remained alive (trapped in granite or basalt) for tens of millions of years.[17] This far exceeds the time required for the transit of impact ejecta from one planet to another. (Gladman and Burns[18] have produced numerical simulations indicating that a tiny fraction of Martian ejecta could make extremely fast (<1 year) passages to Earth.) Furthermore, the ability of terrestrial extremophiles to survive intense radiation and temperature extremes indicates that the possibility of cross-contamination of microbial life from one planet to another, or to a comet, satellite or asteroid must be seriously considered. The origin of the microfossils possibly associated with carbonate globules of ALH84001 is unknown. They could represent microbial life that originated on an ancient warm, wet Mars; or be descendants of ancient life that originated on another parent body and were then transferred to the planet Mars by impact ejection/spallation processes.

The possible significance of comets to planetary contamination with organics and possible biologicals should be considered. The "dirty snowball" model for comets is well supported by observations. Cosmovici et al.[19] imaged water in the coma of comet Halley. The 1994 impact of comet Shoemaker-Levy 9 with the planet Jupiter dramatized the effects of a large comet colliding with a planet. This catastrophic impact event permitted the first detection of planetary water MASER[20] emission by observation of the 22 GHz line with the 32 m dish of the Medicina radio telescope. There are indications that comets are responsible for most of the water ($1.6X10^{24}$ g) in the Earth's oceans.[21] Comets are the principal source of external volatiles[22] and almost all terrestrial carbon (10^{22} g) and it is widely recognized that comets are very rich in organic chemicals. They may well have delivered pre-biotic organic materials to the early Earth.[23] Instruments aboard the Polar spacecraft[24] recently provided additional information indicating that small comets may continually rain down upon our planet. Hoover et al.[25] considered terrestrial ice-diatoms as possible models for types of microbiological communities that might find cometary ice and conditions habitable. On the basis of the scientific evidence, it can not be considered impossible for comets, carbonaceous chondrites, and even rocks ripped from the surface of other planetary bodies to transport extraterrestrial organic chemicals, amino acids, biological materials, dormant microbial spores or resting stages, and possibly even living microorganisms into the Earth's biosphere. For many years the prevailing paradigm has been that our pale blue dot was an isolated island Earth floating in the vastness of space. That concept was clearly erroneous. It is now well established that enormous amounts of extraterrestrial water, organic volatiles (and perhaps even biogenic materials, microfossils, and viable microorganisms) has been washing ashore for billions of years.

3. Organic Matter in Carbonaceous Chondrites

On March 15, 1806 a stony meteorite fell in Alais, France. It was analyzed by Thenard[26] and found to contain 2.5% carbon. Berzelius was so surprised upon finding water in the Alais meteorite (the first known carbonaceous chondrite) that he almost discarded his sample concluding that it could not be extraterrestrial. He was the first to recognize that this C1 meteorite consisted mostly of clay-like hydrous minerals. He also noted the similarity of carbonaceous compounds within the Alais meteorite with terrestrial biological material.[27] Except for their volatiles, the chemical composition of carbonaceous chondrites is similar to that estimated for the primordial solar nebula, and they are among the oldest objects in the solar system with a crystallization age ~ 4.4 to 4.6 billion (Gy) years ago.

According to eyewitness accounts, on the beautiful May 14, 1864 evening in good weather a brilliant blue-white fireball streaked over southern France at 8:00 P.M., illuminating the entire town of St. Clar. The fireball turned dull red in color as thunderous explosions and the sounds of cannon were heard lasting for two to three minutes. Over 20 black stones (some >2 kg. mass) rained over an 18 km. east-west ellipse crossing the villages of Nohic and Orgueil, France.[29] Thus, the most extensively studied type I carbonaceous meteorite arrived on Earth. Villagers collected jet black stones (many with complete fusion crusts) immediately after the fall. One landed in an attic and burned a farmer's hand as he touched it.[30] Orgueil 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. Its silicate minerals are more properly designated as serpentine rather than peridotite.[31,32] The stones disintegrate into a fine dust when they come into contact with liquid water. This explains why similar meteorites are only encountered as falls (except for preservation as afforded by Antarctic ice). 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. However, its chemical composition is dramatically different. Volcanic ash usually has less magnesium and more silicon, aluminum and calcium oxides than found in meteorites. Wiik[28] classified the carbonaceous chondrites as Type I (e.g. Alais, Orgueil, Ivuna, Tonk, and Revelstoke) containing small spherical silicate chondrules and with a high abundance (up to 7% by weight) of carbon compounds, ~ 20% water, and 22% SiO_2. Type II (e.g. Murchison, Mighei, Murray, Cold Bokkeveld, etc.) contain ~ 4% carbon, ~13% water and 27.5% SiO_2. Type III (e.g. Mokoai, Felix) contain <1% carbon.

The carbon content of the Orgueil stones was so high that it was at first attributed to terrestrial contamination. The carbon compounds of the carbonaceous chondrites are predominantly polymer-like materials; coal-like (kerogen) organic compounds[33] (similar to peat or lignite coal) that are not soluble in common solvents. They also have been found to be in the form of aliphatic and aromatic hydrocarbons, racemic and chiral amino acids, purine and pyrimidine bases, fatty acids and lipids, porphyrins, and a wide array of complex organics of no known significance to terrestrial biochemistry. An extensive presentation of carbonaceous meteorites, petroleum geochemistry and complex polymers, kerogens and hydrocarbons indigenous to the carbonaceous chondrites has been provided by Nagy.[34] In a search for evidence of extraterrestrial life, Hodgson and Baker[35] detected indigenous porphyrin pigments in Orgueil that spectrally resembled terrestrial sedimentary rocks. They found absorption bands consistent with vanadyl porphyrins (encountered in coal, petroleum and oil shales). Vanadyl and nickel porphyrins are considered by petroleum geologists as one of the most important indicators of the biogenic origin of crude oil. These bands were not found in the solvent blank, granite, or ordinary chondrites. Porphyrin metal complexes are potential biomarkers, as they play a crucial role in the electron transport in oxidation-reduction reactions in almost all living organisms on Earth. The porphyrin ring is formed when four pyrrole rings (tetrapyrroles) condense with one of various metal atoms at the center of the porphin ring. (*Chlorophyll* pigments of phototrophic organisms consist of light sensitive Mg tetrapyrroles and *Heme* is the Fe porphyrin ring in proteins known as cytochromes.) Hodgson and Baker[36] detected substantial metal porphyrin complexes in Orgueil (Type I,C1), Murray and Cold Bokkeveld (Type II,C2) and Mokoia (Type III,C2) carbonaceous chondrites. They obtained complete excitation spectra with soret (390 nm-413 nm) and non-soret (490 nm-615 nm) excitation bands present. Tests were negative for Vigarano (Type III,C3) chondrite, Indarch (Enstatite,E4), Bruderheim and Peace River chondrites (L6). The infrared spectra resembled organics in ancient terrestrial sedimentary rocks (e.g. Posidonia shale). There was a lack of chlorins (porphyrin derivatives where pyrrole rings have hydrogen additions) in the meteorites. These closely related pigments are in almost all terrestrial organisms and should be found if the porphyrins were recent terrestrial contaminants. Chlorins slowly convert to porphyrins and are also absent in ancient terrestrial sediments. Indigenous porphyrins in Orgueil suggests the "strong possibility of biogenic agencies in the origin of the meteorite." Lack of chlorins indicates the indigenous meteoritic porphyrins are from pre-biotic synthesis or ancient life, rather than recent terrestrial contamination.

4. Prior Investigations of Possible Microfossils in Carbonaceous Meteorites

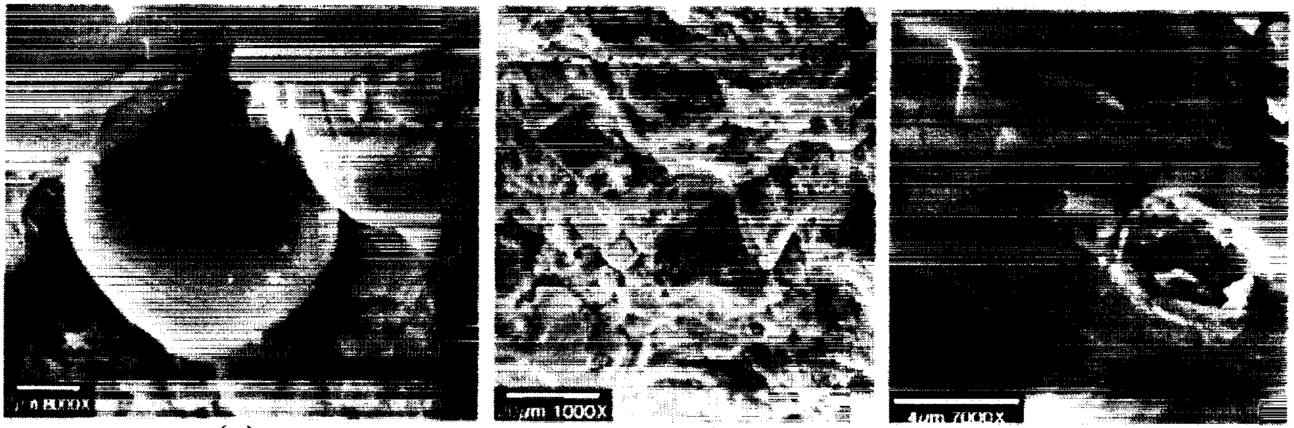
In 1961, Bartholomew Nagy and his colleagues[37] reported that mass spectrometry analysis indicated that the organics of the Orgueil meteorite exhibited a similar pattern of molecular fragments, including fragments of aliphatic and aromatic carbon compounds as is found in terrestrial fossil biological material and petroleum. Claus and Nagy[38] conducted a microbiological examination of the Orgueil and Ivuna Type I carbonaceous chondrites which revealed the presence of numerous (~1600/mg) minute (~10 μ diameter) microscopic sized "organized elements" resembling fossil algae. They were found in several different morphologies in many carbonaceous chondrites, but they were notably absent in the non-carbonaceous Holbrook and Bruderheim meteorites. They found and discounted some recognizable terrestrial contaminants in each sample and concluded that the "organized elements" were microfossils indigenous to the carbonaceous chondrites.

Anders and Fitch[39] also found these structures (but in fewer numbers and only of the simplest morphology) in their sample of the meteorite, and considered the complex structures as artifacts or contaminants. Anders[40] challenged the organic analysis and biogenic nature of the material, arguing that fossils in meteorites would be "unprecedented" and the biological theory should be rejected.[41] He found one sample (from the Mantauban museum) to be clearly contaminated, perhaps intentionally, in the last century.[42] Fitch and Anders became persistent critics of "organized elements" and published numerous rebuttals[40-45] of virtually all reports of microfossils in meteorites. They suggested these bodies were not biological and dismissed all other biological-like as recent terrestrial contaminants, "museum dust", or pollen grains.

Claus and Nagy[38] were acutely aware of contamination problems and discussed them in detail in their original paper. All identifiable terrestrial microbes or particles were noted and considered contaminants. They detected ~100 bacteria, 3 diatoms, 2 sponge spicules, 1 starch granule and 16 cellulose fibers, among the more than 5000 unidentifiable "organized elements" extracted from the Orgueil and Ivuna meteorites. A detailed survey of biological materials in the soil and sedimentary rocks in the vicinity of Orgueil,[46] facilitated the evaluation of terrestrial contamination effects. They also found microstructures in the Tonk and Alais meteorites that were essentially identical to those in Orgueil. This indicates local contamination effects were not the source.[47] They found organic "organized elements" embedded in minerals in Orgueil and Ivuna, ruling out recent contamination effects. Claus and Nagy used standard micropaleontology and palynology morphological methods and conducted extensive biological staining of these microstructures to distinguish between organic and mineralogical particles. The staining behavior[48] and ultraviolet spectra[49] of the microstructures found within the meteorite, led them to conclude that the "organized elements" were biological. Tasch[50,51] carried out careful studies of contamination effects. Identifiable terrestrial contaminants were found in carbonaceous chondrite material but did not account for the great majority of the indigenous, apparently biogenic, structures that were not identifiable by the numerous micropaleontologists, phycologists, palynologists and microbiologists who examined the original microscope preparations and conducted their own investigations of the carbonaceous chondrites. However, the critics were so vociferous that it was recently asserted by a distinguished scientist that the "organized element" controversy was due to pollen grains that had landed on museum meteorite samples and were squashed flat and rendered unidentifiable.

However, the Claus and Nagy "organized elements" research was vindicated by Elso Barghoorn, the world's leading authority on ancient microfossils. Using standard palynological techniques with a clean interior sample of Orgueil, Rossignol-Strick and Barghoorn[52] demineralized the material using Schultzes reagent (HNO_3 and $KClO_3$), and concentrated hydrofluoric acid (HF) 52% at 60° C for one hour. After decanting and siphoning (preventing centrifuge destruction of fragile organic structures) they found large numbers of hollow spheres and ovoids, and some membranes and "funnel" or "mushroom" shaped structures with rounded caps and tapering "stalks". Many of these Orgueil bodies (See Ref. 52 Plate 1-Figs. 14-15, Plate 3-Fig. 3) are similar in size, shape and appearance to the Gunflint chert *Huroniospora sp.* microfossils, even those suggestive of germination (Compare with Ref. 101 Plate 14-1 K). These spheres had the same color, consistency, and chemical composition as the surrounding brown organic residue. They also exhibited well delimited walls (similar to cell walls) with smooth inner surfaces. They had irregular outer surfaces due to particles of matrix adhering to the wall. Some of the walls were broken and exhibited elasticity. These organic bodies reacted negatively to the palynological stain safranin and could not be confused with pollen grains, fungus spores, and textile fibers. These acid resistant structures are similar in size and exhibit characteristics of the "organized elements" investigated extensively by Claus and Nagy. 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."

The Orgueil hollow spheres were also similar (by morphological criteria) to the acid resistant 6-20μ hollow spheres they had found in sediments underlying the Fig Tree Series (Onverwacht series > 3.2 Gy ago). Histograms revealed the size distribution of Orgueil hollow microstructures were evocative of the populations of microfossils of the 2 billion year old Gunflint banded iron formation of Ontario, Canada. Many of the "organized elements" are similar in size, shape and appearance to a wide variety of Precambrian microfossils (e.g. *Eosphaera tyleri, Melasmatosphaera sp., Huroniospora sp.*). Although there was liquid water[37] in the Orgueil parent body, there is no sedimentary structure and "on the Earth, fossils are found only in sedimentary layers." [52] They considered this "*extrinsic* criteria for biogenicity, related to the environment" and since the meteoritic rock was not sedimentary these forms must have been produced abiogenically. At that time, microbial life in volcanic hydrothermal vents, deep basalt and granite, and microfossils in volcanic tuffs were unknown. All paleontologist knew better than to search for fossils in igneous rocks. Consequently, they invoked abiogenic explanations[52] (organic coatings on olivine microchondrules, etc.) for abundant "organized element" type organic hollow spheres. They also *concluded these objects were indigenous to the Orgueil meteorite and of extraterrestrial origin.*

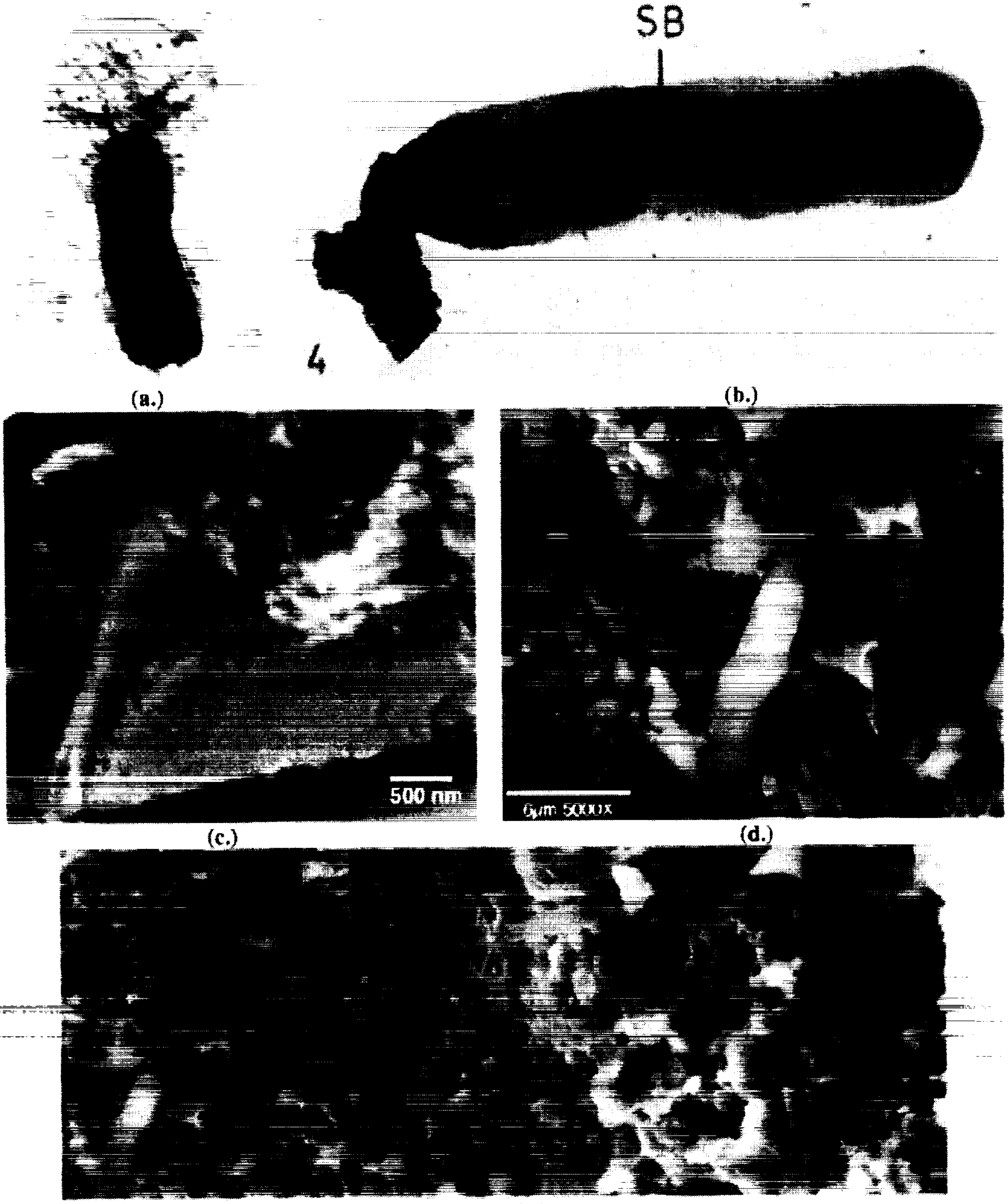


(a.) (b.) (c.)

Figure 1.(a.) Murchison (6-8μ) microchondrules **(b.)** with broken "mushroom" and **(c.)** micro-crater.

I have found similar spheres or microchondrules (6-8μ dia.) in the Murchison meteorite. **Figures 1.a.-b.** show several of these spheres *in-situ*. They have grooved surfaces and thin sheets peeling away. They are in the vicinity of a broken, carbon-rich (~20 μ wide at base of cap) hollow "mushroom" structure projecting out of the matrix, and an elliptical micro-crater (**Figure 1.c**). (EDS spectra for this sphere and micro-crater are in **Figure 10.a.&b**). In addition to simple spheres, with and without spikes, other researchers reported finding different structures of very complex morphologies (jointed filaments, budded filaments, ovoids, rods, bacillus-like, and "mushroom-shaped" structures). They considered them microfossils of biological origin, which appeared to be indigenous to the meteorites. These bodies were not identified with known microorganisms, or they would have been dismissed as terrestrial contaminants. Timofejev[53] extracted from the Mighei Type II meteorite (by nitric acid maceration and centrifugation) large numbers of nitric acid insoluble algal-like fossilized structures similar to Precambrian *Protospheridae* algae. Briggs and Kitto[54] found complex unicellular microorganism-like bodies in the Mokoia Type III meteorites. Nagy et al.[55] used the electron microprobe to show some "organized elements" were impregnated with limonite containing small amounts of nickel, and others were impregnated with silicates. Using HCl and HF to remove minerals, they found most remaining carbonized bodies contained no elements with atomic number above Magnesium, which they interpreted as evidence of fossilization and thereby eliminating recent terrestrial contaminants as the source.

Staplin,[56] VanLandingham,[57,58] and other micropaleontologists also concluded these biological-like structures were fossilized microorganisms in meteorites. These electron opaque objects that were found deeply embedded in the interior of the meteorite were obviously not recent terrestrial contaminants. Furthermore, fluorescent microscopy studies also indicated that most of the organic matter in Orgueil was in minute spheres ~ 1μ diameter.[59] Ross[60,61] found "mushroom shaped" hollow tubes with torn membranes in the lightest portion of Orgueil material which he extracted using controlled cadmium borotungstate suspensions. To minimize possible contamination, Ross used sterile tools to remove meteoritic material taken from the interior of a complete, fusion encrusted, Orgueil stone from the British Museum.



(a.) (b.)

(c.) (d.)

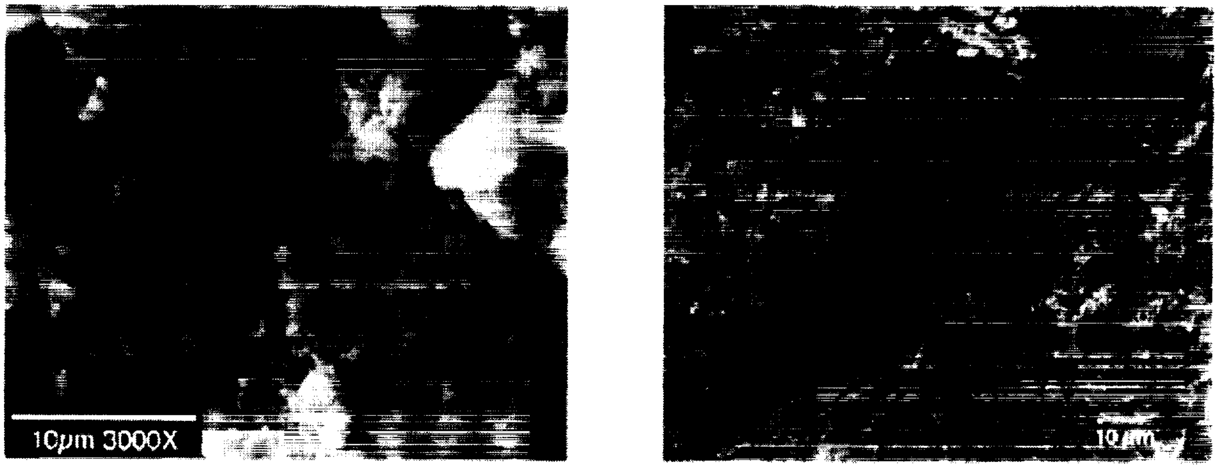
(e.)

Figure 2. Acid resistant microfossils in **Orgueil**[62] **(a.)** 2.6μ tall body with .5μ dia. stalk **(b.)** branched (0.6μx3.2μ) filament electron dense attachment features. **Murchison** microfossils **c.)** 2.5μ tall "mushroom" with 0.25μ diameter stalk **(d.)** (2.7μx10.2μ) main body of **(e.)** long branched *in-situ* algal-type filament with break showing hollow "cell wall".

Tan and VanLandingham[62] obtained electron microscopy images of many acid resistant bodies they considered to be microfossils indigenous to Orgueil. The strong oxidizers and nitric, hydrochloric and hydrofluoric acids used would destroy the carbonate and siliceous microfossils which account for most terrestrial microfossil assemblages (e.g. diatoms, silicoflagellates, foraminifera, and coccoliths). They found many morphologies present, including "mushroom' shaped structures with electron dense "stalks" and a more electron transparent, membrane-like cap with folds (**Figure 2.a.**). This body has similar size, shape, and electron transmissive properties to the carbonaceous nanoparticles found in 3.3 billion year old Fig Tree barite.[63] They also found tube-shaped filament-like bodies with one end rounded and an electron dense structure attached to the other end (**Figure 2.b.**) containing electron dense (SB) solid bodies. These acid-resistant biological-like bodies in the Orgueil meteorite are clearly not "pollen". Using the ESEM, I found similar biological-like bodies *in-situ* in Murchison including a "mushroom"-shaped form of very similar size (**Figure 2.c.**) and a somewhat larger tube-like filament body (**Figure 2.d.**) with one end rounded and the other attached to a very long (**2.e.**) branching filament.

a. **b.**

Figure 3. (**a.**) Palik[64] drawings of microfossils in Orgueil similar to (**b**). 3μ diameter end of curved "stalk" in Murchison.



(a.) **(b.)**

Figure 4. (**a.**) 3μ diameter toroidal feature at surface of matrix (**b**). filament (15μ x 130μ) or fungal hypha in Murchison.

Palik[64] of the Microbiological Institute of the Eötvös Lorand University in Budapest, discovered complex structures similar to filamentary algae in crushed (non-acid treated) samples of Orgueil. She illustrated **Figure 3.(a.)** several of the Orgueil filamentous forms, which reminded her of algae. Some filaments were curved, ranging in width from ~3μ to 16μ and in length from~40μ to ~170μ. She described her fascinating filament #2 as *"Part of the filament is 4μ wide and 55μ*

long. It is covered with a follicle, the apex is rounded off." These structures are *"slightly tapering toward the apex. The apical cell is like a head."* **Figure 3(b.)** shows a strikingly similar filament found *in-situ* in the Murchison meteorite. This "mushroom" stalk-type filament is also seen in **Figure 9**, just behind the curling "stalk" of the large body. It also curves (but lacks longitudinal wrinkles as seen in the other long stalks) and has a peculiar follicle-like structure at the apex. **Figure 4(a.)** shows a feature of similar morphology and rich in Sulfur and Iron (perhaps Troilite, FeS) embedded in the lower sulfur matrix.**(Figure 10.c.-d.)** The follicle-like apex in **Figure 3(b.)** is 1.8 μ diameter and the visible length of the curved small stalk is 16μ. Palik says *"On the double wall here and there small warts can be seen."* Similar features are seen in the hollow Murchison "stalks" shown in **Figures 3.b - 9.** The other end of Palik filaments 2 and 3 terminate in a widened structure, indicating she might only have fragments of "mushroom" cap like are in Murchison.

The existence of extraterrestrial life-forms was sufficiently well accepted by 1962 that many scientists began to consider the systematic taxonomy of extraterrestrial microfossils.[65,66] However, strong criticism ensued and the controversy associated with the "organized elements" was so vigorous that by the mid-1970's most scientists had ceased to conduct any exploration for possible microfossils in meteorites. Recently, articles in the popular press concerning the ALH84001 observations have dismissed all "organized elements" as being due to simple misidentification of tree pollen or "a squashed ragweed pollen grain". This position is obviously not supported by the scientific literature. Pollen and spore contaminants were found[68,69] but terrestrial contamination cannot account for the many biological-like bodies (found deep within meteorites by different researchers) with complex morphologies that were unknown to micropaleontology, palynology, and microbiology. Similar bodies were in many carbonaceous chondrites (e.g. Orgueil, Tonk, Ivuna, Alais; Murchison, Murray, Mighei, and Mokoai) but not in non-carbonaceous meteorites (Holbrook, Bruderheim, Indarch and Peace River).

In 1966, Harold C. Urey[70] (1934 Nobel Prize in Chemistry) reviewed biological materials in meteorites. After noting that organic substances 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."* Many lines of evidence strongly indicate indigenous biogenic materials exist in meteorites. Microfossils in meteorites challenged existing paradigms concerning the properties of life on Earth, volcanic rocks, and meteorites. Urey observed *"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."* In that era, volcanoes and life were mutually exclusive. Microfossils should only be found in sedimentary rocks and meteoritic minerals indicated volcanic processes. Chemolithotrophic microorganisms of the hot deep biosphere were unknown. It was thought that the wonderful double helix, crucial to all life, would surely be destroyed if subjected to boiling water. At that time, hyperthermophilic microorganisms and the rich assemblage of life in hydrothermal vents associated with volcanoes deep within the oceans would have undoubtedly been met with severe skepticism.

5. The Murchison Meteorite

A brilliant fireball was seen over Victoria, Australia on the morning of September 28, 1969. It appeared as a bright orange fireball with a silvery rim and dull orange conical tail to Terry Said, a television technician operating a matrix switching device in Sheparton, 28 km N of Murchison. He accurately established the event as occurring at 10:58-10:59 A.M. Australian Eastern Standard time (00:58-00:59 UT). William Hollyman, also of Sheparton, saw the meteorite as moving almost parallel to the southern horizon and leaving a blue smoke trail.[71] Another witness saw a tight cluster of three objects which varied in color from orange to red. One of the objects appeared to be tumbling violently and flashing silver. In Mildura (426 km NW of Murchison) the meteorite was seen as a bright light moving almost vertically downward. Many dozen black stones hailed down at 36°37'S and 145°14'E around the town of Murchison in a mile wide and ten mile long scatter ellipse that indicated the trajectory of the meteorite was from the south-east.

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. Pollack et al.[72] noted that infrared (0.4 to 1.1 μ) observations of Phobos (the inner moon of Mars) reveal a remarkable similarity to the spectral properties of the Murchison (C2), Murray (C2), and Orgueil (CI) carbonaceous chondrites, but not to basalt or other materials tested. They suggested that this tiny (20 km) moon may be a carbonaceous chondrite that was captured by Mars in the early history of the solar system when Mars had a more extended gaseous envelope. The spectral reflectance properties of Murchison also resemble those of the 1018 km diameter asteroid Ceres.[73] Asteroids are considered the most probable parent bodies for the CI and the CM meteorites, but extinct cometary cores or protocometary bodies are also possibilities.[74] Detailed accounts of the fall from Mildura and Sheparton allowed estimation of the astronomical coordinates of the apparent radiant ($\alpha=17^{hr}21^{m},\delta=-50^{\circ}$) and a probable orbit.[75] After correction for diurnal aberration and zenith attraction, the preferred geocentric radiant ($\alpha=286^{\circ},\delta=-37^{\circ}$) is relatively close to the antapex of the Earth orbit. Hence, Murchison was very nearly overtaking the Earth from behind and hence the relative velocity must have been low. The low inclination orbit and perihelion just inside the Earth's orbit indicates entry velocity within 15% of 13 km/s. Using 13 km/s as the preferred initial velocity and a value of 3 AU for the aphelion (which is appropriate to both the median for meteorite falls and peak concentration of C-type asteroids)[76], the derived perihelion lies between .992 AU and 1.002 AU. Hence, Murchison never got much closer to the Sun than Earth. This is consistent with indigenous volatiles and of great significance to the possibility of indigenous microbiological activity. During a portion of the orbit, Murchison would been close enough to the Sun for indigenous water to have been in a liquid state, but not close enough for the volatiles to be driven off or for heating or radiation to be detrimental to microbial life. Seargent[71] noted the similarity of this orbit with periodic Comet Finlay and the C-type Apollo asteroid 1979 VA. He considered the possibility that the Murchison body may have come from a comet. However, the cosmic ray exposure age of Murchison is 800,000 years.[77,78] This result led Seargent to suggest the meteorite may have formed as a large boulder "the cap of a pedestal" whose stem slowly eroded away through sustained cometary activity."

Murchison is a CM2 carbonaceous chondrite. Nagy[34] provides an extensive review of the mineralogy, petrography, and petroleum geochemistry of the carbonaceous chondrites. Mason[79,80] proposed that the carbonaceous chondrites formed in the solar nebula from primitive or near primitive matter. He described the mineralogy and chemical composition of the carbonaceous chondrite matrix. Murchison contains a rich array of polymeric matter and organics,[81,107] complex cycloalkanes,[82] pyrimidines,[83] and amino acids.[84] The distribution of polycyclic aromatic hydrocarbons (m/e = 178 (phenanthrene $C_{14}H_{10}$), 202 (pyrene $C_{16}H_{10}$), 228 (chrysene $C_{18}H_{12}$), 252 (benzopyrene $C_{20}H_{12}$) in the Murchison meteorite are very similar to the PAH distribution found in the Martian meteorite ALH84001.[85,1] Hayatsu[86,87] found indigenous purines and triazines, 15 carboxylic acids and 11 aliphatic acids in Murchison and noted only a fair match for abiogenic production by Fisher-Tropsch synthesis. Gas chromatography (GC), mass spectrometry (MS) and combined GC-MS have been carried out. Murchison was collected immediately after its fall in 1969 and provides pristine samples for hydrocarbon analysis.[88,89] Cronin and Pizzarello,[90] using GC-MS, IR, and proton NMR spectroscopy, found the aliphatic fraction of the Murchison meteorite to be a structurally complex suite of branched alkyl-substituted, cycloalkanes (C# 15 to 30). They also found n-, methyl and isoprenoid alkanes in Murchison but interpreted them as terrestrial contaminants. Gelpi and Oro[91] found isoprenoid alkanes (found in crude oil) in 19 of the 20 carbonaceous chondrites analyzed, and concluded they resulted from contamination. The great petroleum deposits on Earth are considered the result of ancient terrestrial biological activity. In keeping with the current paradigm, the possibility that the large array of petroleum-like compounds that comprise a very significant component of the hydrocarbons of carbonaceous chondrites might partially or entirely have resulted from ancient biological activity on the meteorite or on its parent body has not been considered seriously.

Kvenvolden *et al.*[92] found 74 amino acids, including several non-protein species rare in terrestrial biology. They observed the amino acids to be racemic and of an unusual isotope distribution, and concluded they were indigenous and extraterrestrial. Many amino acids have chiral centers and are optically active (i.e. rotate the polarization of visible light). Terrestrial chemistry is indifferent to the two forms, but biology has a strong preference. In living cells of terrestrial organisms (with only a few notable exceptions) the amino acids are levo-rotary (the L-stereoisomer) and sugars are the D-stereoisomer. The most notable biological exceptions include the cell wall polymer peptidoglycan and certain peptide antibiotics. (Some prokaryotes can convert the D- to the L- form by specific enzymes.) Consequently, the detection of homochirality is an excellent biomarker indicating biological activity. It should be strongly emphasized that the absence of optical activity or the detection of racemic mixtures is not in any way an indication of abiogenic processes. The quantity of the D-enantiomers of amino acids were found to increase with age in Puget Sound sediments[93] and the indigenous biologically produced amino acids should be completely racemic in sediments older than 2 million years. Bada *et al.*[94] used the rate of racemization of L-isoleucine to determine approximate ages of core sediments from the mid-Atlantic Ridge. Consequently, the conclusion that racemic amino acids indicate abiogenic processes, would also lead to the absurd conclusion that racemic amino acids found in ancient terrestrial fossils must have also resulted from abiogenic processes. The amino acids found in the meteorites may have been produced by the biological activity of microorganisms that lived on the parent body millions to billions of years ago. These meteorites may contain a mixture of racemic amino acids from both abiogenic and biological processes associated with very ancient microbial life together with an indigenous suite of non-racemic amino acids produced by recent biological activity and even some later contaminants.

Stable isotope measurements indicated that the amino acid and carboxylic acid extracts were indigenous to Murchison and extraterrestrial.[95] Engel and Nagy detected an excess of the L-enantiomer in several Murchison amino acids.[96] Measurements of the ^{13}C enrichment of the D- and L-enantiomers of Alanine showed the L-excess was indigenous and not a terrestrial contaminant.[97] This very significant discovery was confirmed[98,104] by the recent observation of an excess of the L-stereoisomer of several (e.g. Alanine, Glutamic Acid, etc.) chiral amino acids indigenous to Murchison meteorite. This indicates pre-biotic chiral molecules may have existed 4.5 Gy in the early Solar System before life began on Earth. However, racemization with age should have converted the extremely ancient amino acids into racemic mixtures. Clearly, another possibility that must be considered is that some or all of the complex organic molecules (including amino acids) may have resulted from biological processes. Pflug[99] has made exciting discoveries of indigenous organic spherical structures (50-200 nm) diameter and tubular microvesicles (10-15 nm diameter and 400-500 nm length) in Murchison. He uses Transmission Electron Microscopy (TEM) and diverse microprobe techniques to study organics separated from the matrix by means of a special acid and membrane filter preparation technique developed for *"in-situ demineralization"* of the meteorite.[100] This revealed indigenous structures similar to (and some more complex than) the "organized elements" found by Claus and Nagy. Large numbers of diverse microbial communities may well have lived and died in the carbonaceous chondrites and their parent bodies over long stretches of time during the past 4.5 billion years.

6. Evidence of Microfossils in the Murchison meteorite

The exciting announcement of the discovery of biogenic activity and possible microfossils[1] in ALH84001 instigated the present search for microfossils in carbonaceous chondrites. The great success of Pflug[99,100] with the Murchison meteorite (and the relatively pristine materials available since Murchison was collected immediately after its fall in 1969) indicated this was the most logical avenue of pursuit. To reduce laboratory contamination effects, the handling and treatment of the meteorite would be reduced to the absolute minimum. Since many terrestrial microfossils are highly soluble in acids, the methods which have been employed to obtain acid-resistant microfossils were to be avoided. These techniques could destroy potentially important carbonate or siliceous microfossils. To eliminate all possible artifacts introduced by coating processes, the meteorite specimens were studied without coating. This research was made possible by the advanced Scanning Electron Microscopy tools within the Materials and Processes Laboratory of the Marshall Space Flight Center (MSFC) and the support of the Electron Microscopist Greg Jerman. Two ultra-high resolution scanning electron microscopy instruments were available which met this requirement: the Hitachi Field Emission Scanning Electron Microscope (FESEM) and the ElectroScan Corp. Environmental Scanning Electron Microscope (ESEM). These instruments were ideal for imaging biological and non-conductive specimens and they can be used without gold-coatings or other surface preparation techniques which could introduce contaminants and artifacts. A few initial observations were made with the Field Emission instrument. However, most of the research was carried out using the Environmental Scanning Electron Microscope. This instrument operates at a partial pressure of water vapor (10 Torr vacuum) to image, and thus non-conductive samples do not build up a negative charge. It has a 5-axis stage and is capable of magnification range from 90X to 100,000X with an operating voltage of 10 to 30KV. It is equipped with a Noran Instruments Energy Dispersive Spectrometer capable of detecting light elements Boron and above. The images were recorded digitally (4Pi Analysis system) with up to 4096X4096 pixel resolution and 12 bit (4096 grays) digital image depth.

The meteorite samples were extracted from the interior of a 1 gram piece of the Murchison meteorite. New Electron Microscopy Sciences (Dumont #7) Biology tweezers were employed to break off small pieces of the meteorite, which were then carefully mounted on the electron microscopy stub with the freshly broken interior surface exposed. The sample was mounted in the microscope sample chamber within 2 to 4 minutes to minimize any laboratory contaminants falling on the sample. Within an hour of the first sample being mounted in the instrument, interesting and complex "biological-like" structures were observed. The first objects found were small (~2 micron) "mushroom-shaped" structures. The first "mushroom" found had a stalk with parallel sides and a convex cap with a flat bottom surface. No images of this object were obtained, as the stalk disintegrated during high magnification focusing due to electron beam effects. Other similar (although somewhat less perfect) small "mushroom"-shaped bodies were soon found imaged at lower voltage (20KV). The right side of the cap is broken away and the stalk expands near the cap.**(Figure 2.c.)** The base of the stalk is only 250 nm in diameter and appears to be a hollow tube possibly representing a cell-wall. The microbiological affinity has not been established, so this can not be known with certainty. This form is morphologically similar and in the approximate size range to represent smaller protostelids and stalked or budding bacteria (e.g *Calobacter sp. Gallionella ferruginea*). However, a leading Protostelid authority[105] indicated this form is not a known species and may not belong to that group.

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Several possible "nanofossils"(50-100 nm in size), other "stalk" tips (**Figure 4.a.**) and large filaments (**Figure 4.b.**) have been found. Numerous bodies have complex morphologies and have been interpreted to represent *in-situ* microfossils indigenous to the Murchison meteorite. There appear to be two distinct populations of "mushroom" shaped bodies. The small group are in general about 2μ across the cap and 2μ –3μ tall. The other population of "mushroom" shaped bodies are much larger ~80μ–100μ across the cap and ~100μ –150μ tall. These large bodies are by far the most intriguing objects discovered in Murchison. These "mushroom"-shaped bodies and "stalks" seem to be attached to the matrix and indigenous to the meteorite. These forms are interpreted to be indigenous microfossils. They possess a highly complex under surface and long, tapering stalks with fine lines or ribs running longitudinally along the stalk. (**Figure 5**) shows one of the large "mushrooms" immediately after it was found. It has a round, tapering, stalk and a large bulbous lobe which comes to a sharp point protruding from one right side.(**Figs. 6,7.a-b.**) This structure appears to be some type of growth associated with the larger object. Above the rounded cap is a tall array of lath-like crystals. The EDS x-ray spectra of these crystals **Figure 11.a.** reveal them to be rich in oxygen, magnesium, silicon and iron similar to olivine or serpentine. (They have little calcium, and thus are not consistent with minerals that might be secreted by recent myxomycetes.) The underneath surface is of extremely complex morphology. These stalks have small tubules that project from the middle and end (**Figures 6**). The tubule projecting from near the tip of this stalk is clearly seen in **Fig. 3.b.**. The stalks have also been observed to wrinkle along the ribs and curl during prolonged exposure to the electron beam (**Figures 6,7,8,9**).

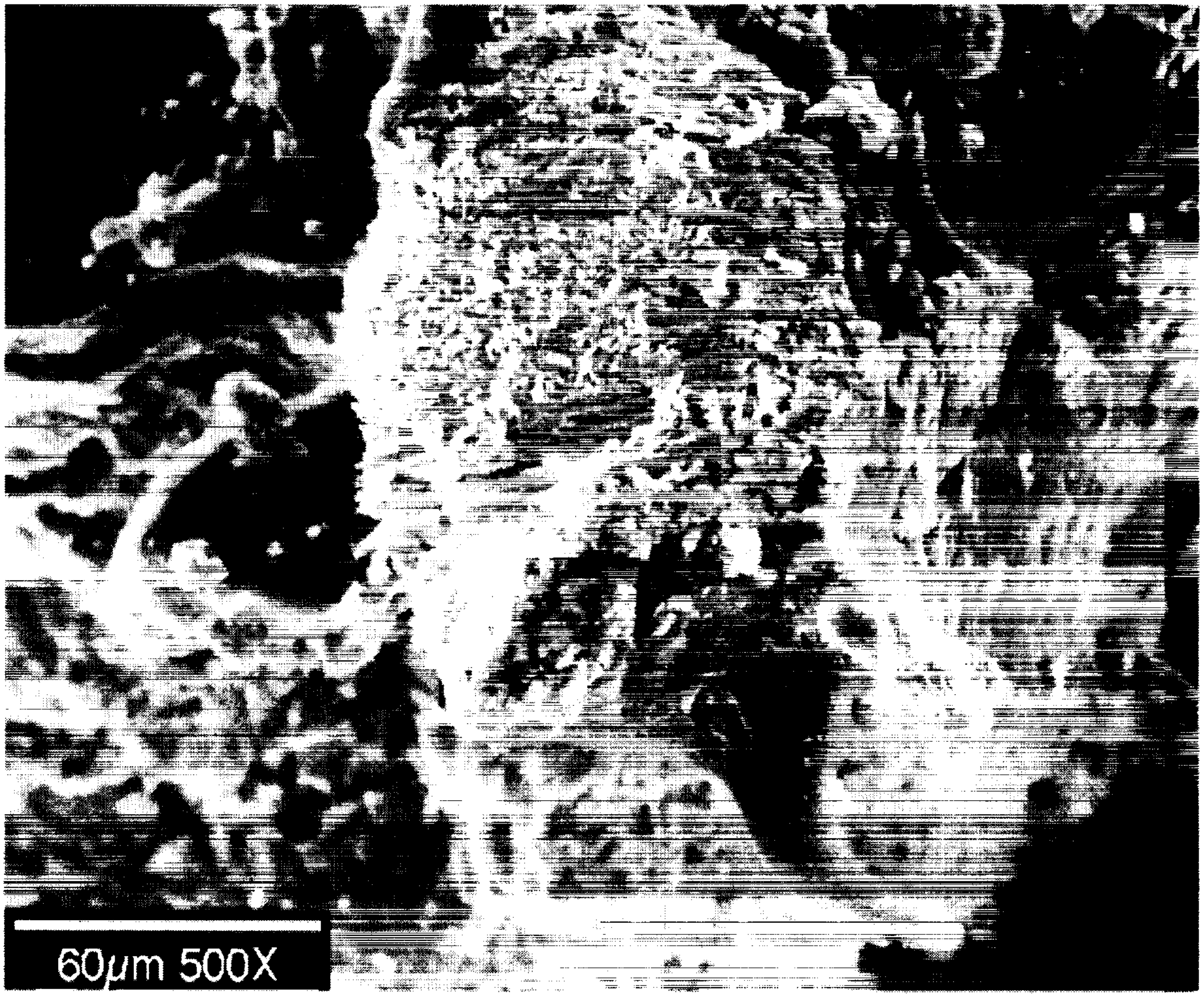


Figure 5. Large myxomycete-like ("mushroom") body with lath-like crystals over cap.

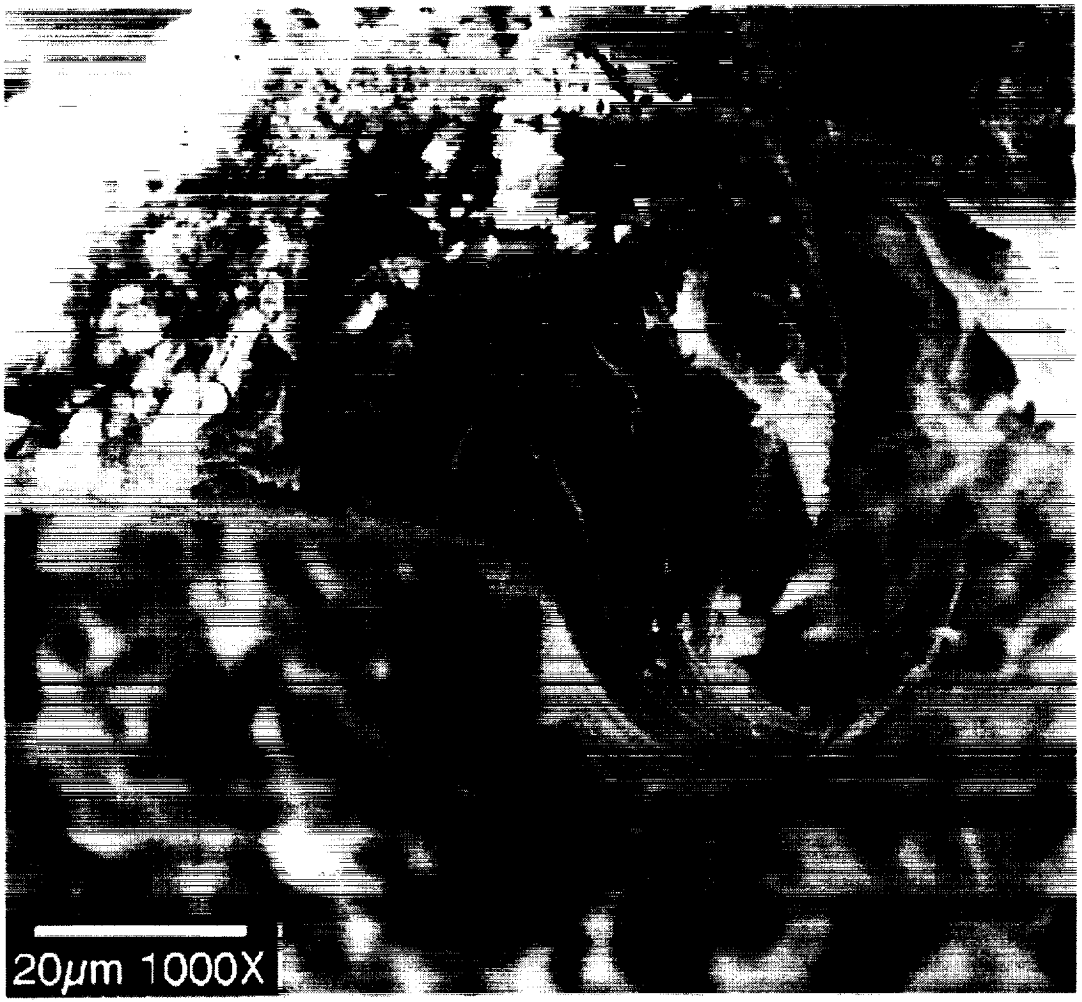
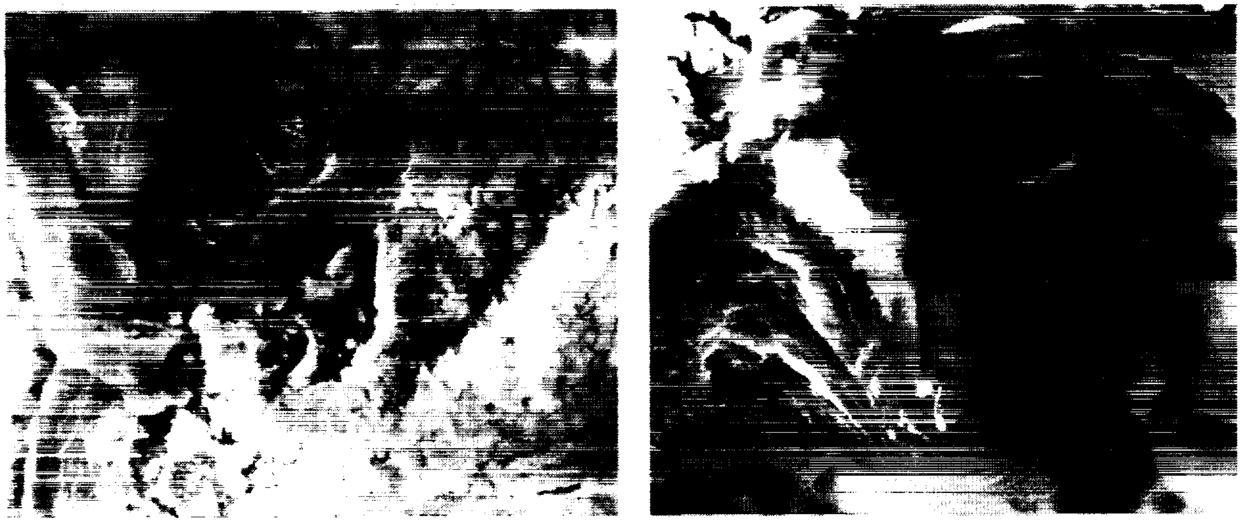


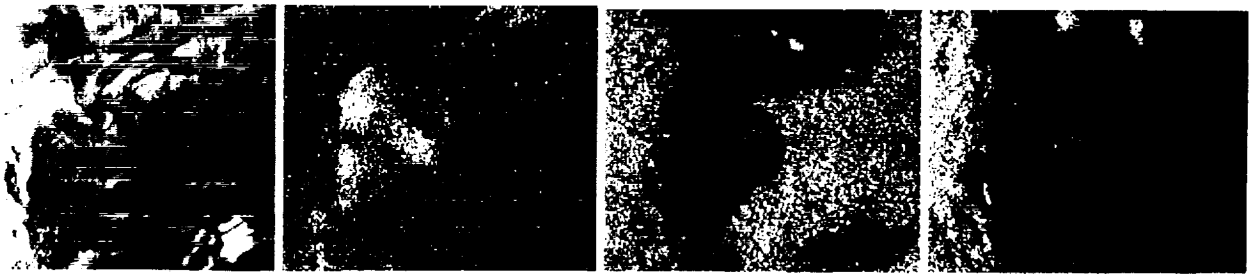
Figure 6. "Mushroom" wrinkles along ribs and curls with beam exposure. Small tubules on stalk are visible.



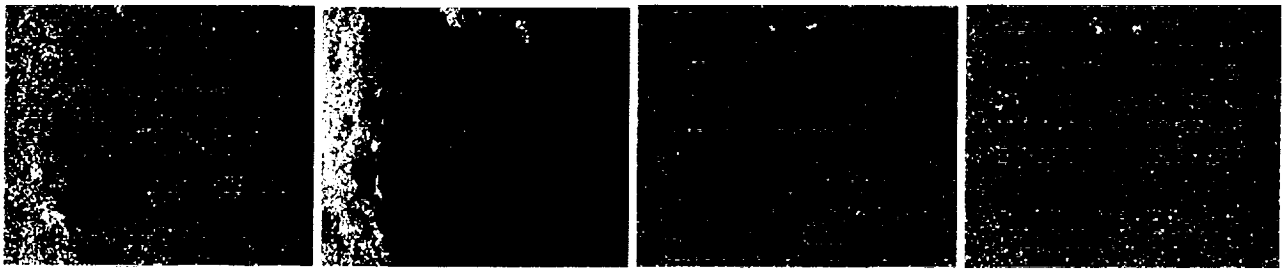
(a.) (b.)

Figure 7. (a.) "Mushroom" bulbous lobe and (b.) "lobe" situated under "smooth" region near attachment.

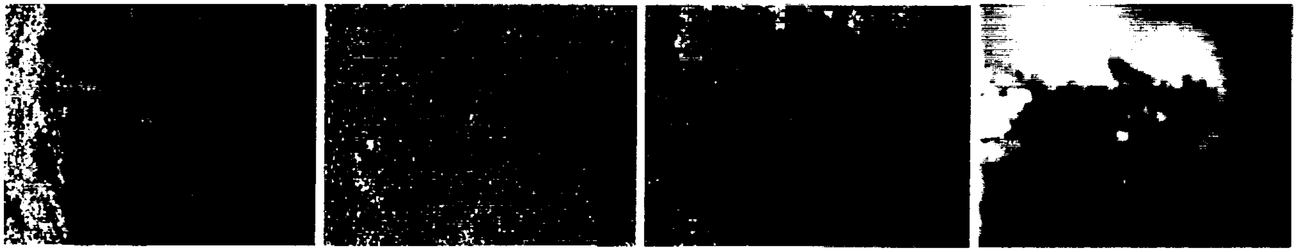
(**a.**) Carbon (R); Fe (G) (**b.**) Carbon (R); Si (G);Oxygen(B) (**c.**) Carbon (R); Mg (G); Fe (B)



(**d.**) ESEM image (**e.**) Carbon (0.277 keV) (**f.**) Iron (6.398 keV) (**g.**) Silicon (1.739 keV)



(**h.**) Calcium (3.690keV) (**i.**)Magnesium (1.253keV) (**j.**)Nickel (7.471keV) (**k.**) Chromium(5.411keV)



(**l.**) Oxygen (0.523 keV) (**m.**) Sulfur(2.308 keV) (**n.**) Aluminum(1.487 keV) (**o.**) Visible Light Color

Figure 8. (**a.-c.**) Pseudo-color (RGB) composites of X-ray maps on ESEM image; (**d.**)ESEM image of microfossils; (**e.-n.**) EDS 2-D X-ray maps at selected k_α lines of elements (**o.**) Color visible light image.

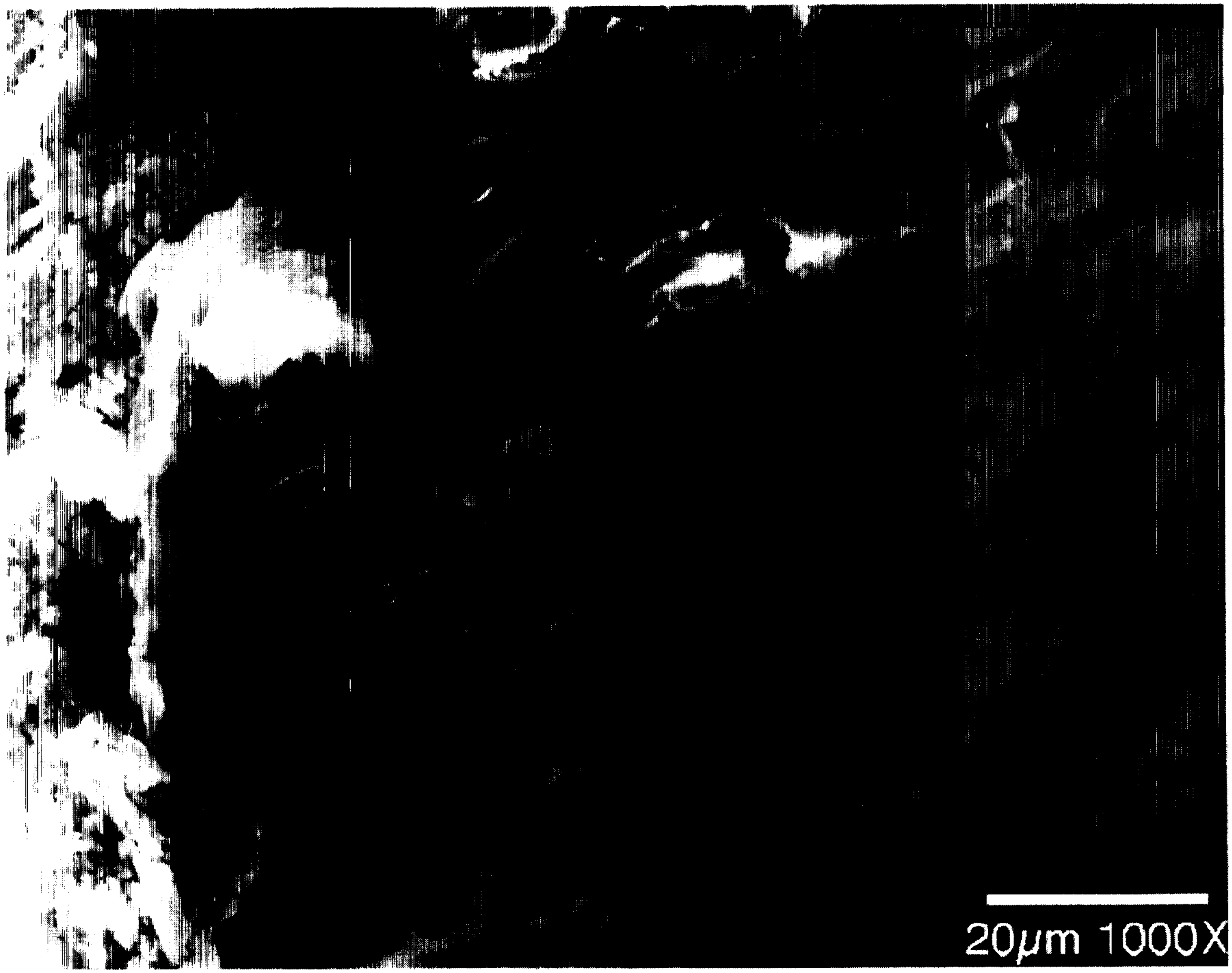


Fig. 9. Multiple small "mushroom stalks" behind complex myxomycete-like structure *in-situ* in Murchison.

The curling and wrinkling effect is probably not due to desiccation, since the "stalk" does regain shape after beam exposure terminates and the sample is returned to atmosphere. Gold[108] suggested that it is probably due to polymers being driven off or broken down. Visible light (Olympus BH-2 microscope/color video camera) images **(Fig. 8.o.)** clearly show the black color of the "mushroom". It resembles the black color of the bulk matrix of Murchison. Murchison is exceedingly heterogeneous with numerous minute colorful inclusions of diverse minerals (e.g. olivine, spinel, chromite, etc.) The images combined with x-ray analysis indicate these *in-situ* bodies are indigenous to Murchison and not recent contaminants.

In order to obtain more definitive information about the chemical composition of these bodies, x-ray energy dispersive spectroscopy (EDS) was carried out. The resultant two-dimensional elemental x-ray maps were used to create the composite pseudo-color overlays **(Fig. 8.a.-c.)**. When the elemental maps **(8.e-n.)** are superimposed on the ESEM image **(8.d.)**, it is easily seen that the "mushroom" is very rich in carbon (red) and poor (compared to the surrounding matrix) in iron, silicon, and chromium. The crystals above the cap contain large amounts of Si, Fe, Mg, O, and Ca. (A carbon rich (red) zone seen expanding toward the upper right probably is associated with a cluster of "stalks" and/or another embedded "mushroom".) Two dimensional EDS spot maps **(Fig. 8.e-n)** show the "mushroom" is extremely carbon rich, but also contains oxygen, silicon, and magnesium. The sulfur is fairly evenly dispersed, but there may be some enhancement in the tip of the "stalk" as compared to the central of the cap. The "mushroom" body is extremely lacking in iron.

EDS spot maps **(Figures 10-11)** show the relative abundance from feature to feature. (They are not quantitative as the detector varies in sensitivity as a function of wavelength.) **Figure 10.(a.)** shows data obtained from the center of the 8 micron microchondrule of **Fig. 1.a.** This object is poor in carbon, but very rich in magnesium, silicon and oxygen. **Fig. 10.b.** is taken within the 3 micron diameter microcrater just below the end of the broken partial "mushroom" feature of **Figure 1.b.** (Although it is not shown here, this partial "mushroom" is also rich in C.) The center of the small toroid of **Figure 4.a.** is very interesting. It appears to have a calcium sulfate enrichment) **Figure 10.c.** This feature strongly resembles (in size and morphology) the tip of the "mushroom" stalks illustrated by Palik and shown in **Figure 3.b.** However, moving the beam 10 microns away into the matrix, the calcium and sulfur amounts drop abruptly and the iron and silicon peaks increase. Calcium sulfate (anhydrite) may have been concentrated in the tip of the "stalk" if this is an embedded "stalk" as it looks. **Figure 11.a.** shows the elemental abundance in the array of lath-like crystals just above the cap of the large "mushroom" feature shown in **Figure 5.** It is noted that the carbon content is low. The "smooth" structure seen above the lobe in **Fig. 7.b.** is rich in carbon, silicon, and iron **(Figure 11.b)**. Near the center of the cap of the large "mushroom" the carbon abundance is exceedingly high.**(Figure 11.c.)** The tip of the "mushroom" stalk is represented in **Figure 11.d.** Although it has a high carbon content, both calcium and sulfur are enhanced with respect to the center of the "mushroom". Although there are dramatic differences in the relative abundance of the elements in the "mushroom" structure, the "mushroom" contains the same suite of elements as the other parts of the meteorite. These results are interpreted to indicate that these "mushroom" bodies are indigenous microfossils, rather than terrestrial contaminants. Mautner et al.[109] established that the meteorite organic matter is a proper nutrient material for terrestrial microbial life. Much aqueous activity has taken place during the past 4.4 billion years since formation of the Murchison rock. Large numbers of viable microorganisms ejected from diverse planetary bodies by impact ejection/spallation mechanisms may have contaminated the Murchison meteorite and established viable populations. This process may have repeatedly occurred in the past with many different microbial communities from widely dispersed points of origin consuming the remains of organisms long departed.

7. Comparison with Known Terrestrial Microorganisms

During more than 25 years of research on living and fossil diatoms, I have observed a very wide variety of unusual microorganisms and microfossils. However, the peculiar biological-like forms that I found in Murchison in no way resemble any of the diatoms, radiolarians, silicoflagellates, forams or other siliceous or carbonate microfossils I have encountered. A review of the microfossils illustrated the *Earth's Earliest Biosphere* [101] and *The Paleobiology of Plant Protists*" by Tappan[102] revealed some "mushroom" shaped (calcium carbonate) Cretaceous coccoliths (e.g. *Retecapsa crenulata* Fig. 9.42;2 and *Eiffellithus eximius;* Fig. 9.46;4) that somewhat resemble the complex "mushroom" shaped bodies and stalks in Murchison. *Brock Biology of Microorganisms*[103] describes eukaryotic myxomycetes and the prokaryotic gliding and fruiting myxobacteria, such as *Stigmatella aurantica* (Fig. 16.60) and *Chondromyces crocatus* (Fig. 16.63). These forms also have morphological characteristics similar to the Murchison bodies and are not dramatically different in size. (Phylogenetically these chemoorganotrophic gliding bacteria microorganisms fall into the delta subdivision of the purple bacteria (Proteobacteria),[103] which also includes sulfate reducing bacteria like *Desulfuromonas.*)

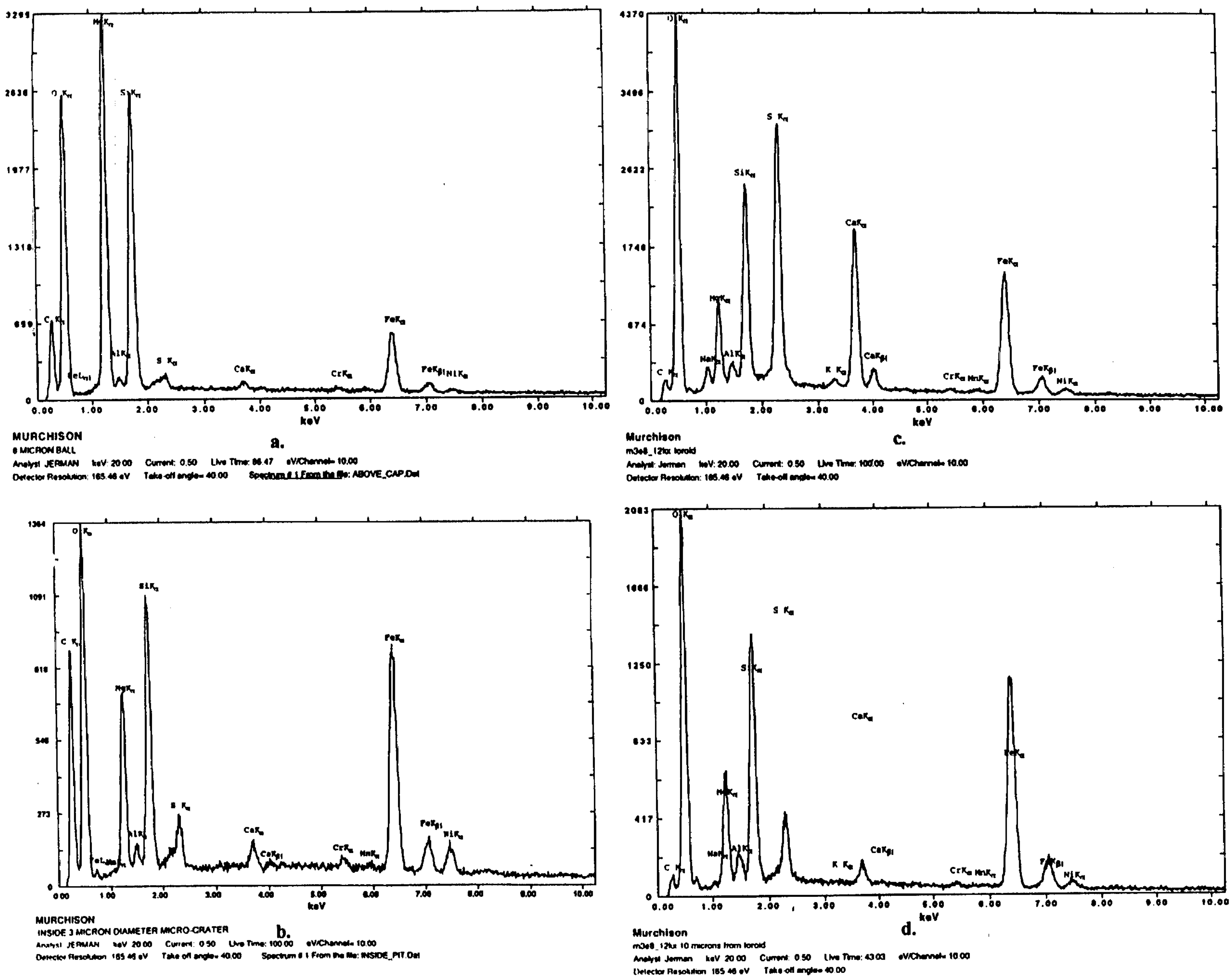


Figure 10. EDS spectra of (a.) 8μ diameter microchondrule; (b.) interior of 3μ diameter micro-crater; (c.) 3μ diameter sulfur-rich toroid of Fig. 3; (d.) 10μ from toroid.

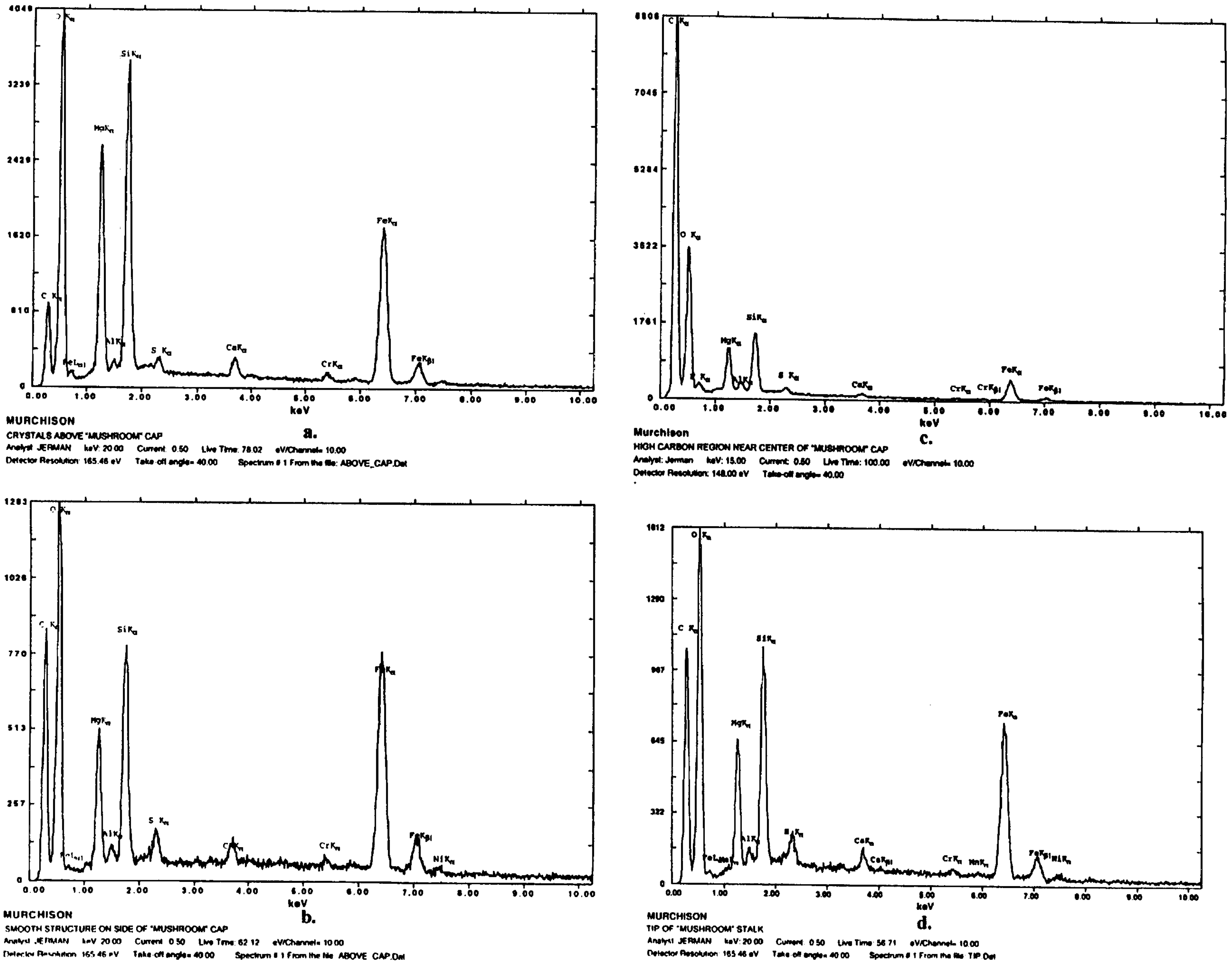


Figure 11. EDS spot spectra of (a.) crystals above cap of large "mushroom" microfossil of Fig. 6; (b.) smooth region; (c.) carbon rich center of cap; (d.) tip of stalk.

In order to evaluate the possibility that the Murchison forms might be the remains of recent contaminants from living terrestrial microorganisms, the ESEM images and EDS X-Ray maps were sent to leading microbiologists and myxomycologists for help in identifying these specimens. Dr. Lafayette Frederick of Howard University kindly considered the images and discussed them his colleagues. He concluded that "the objects in the pictures are biological in form and no doubt represent some kind of organism."[106] However, they were unable to associate the small (2μ) or large (100μ) "mushroom" forms and with any known biological organisms. The general morphology, discernible structural features, and the high level of carbonaceous content were considered clear indications of biological forms. The large filamentous fragment (**Figure 2.b.**) bears some resemblance to a portion of a fungal hypha. This body seems to have a thin wall and septum-like partition or break traversing the structure. The lower end seems to extend into the matrix, and the upper end is slightly enlarged and fringed as if it had been attached to something else. This form could be a part of a filamentous type of autotrophic prokaryote. The presence of porphyrins in carbonaceous chondrites might support that supposition. If this fragment is fungal, it could be a terrestrial contaminant, which would not be identifiable from hyphae alone.

The large "mushrooms" and "stalks"(**Figures 5, 6, 7, 8**) were considered much too organized in form and body detail to be crystalline in origin. (Small objects called callosities do exist in the cells of some Devonian fossil fungi, that have an organismal form but represent mineralized deposits within the cell. However, they lack the carbonaceous content and would not have responded to the electron beam the manner this specimen responds. The capillitium that extend en masse out of sporangium of Hemitrichia sp. are inert structures formed by the protoplasm of the myxomycete. They respond to an electron beam in a manner similar to the Murchison bodies.) The upper region of the "mushroom" structure appears to be the top of a body which has a supporting tapering stalk. This body was not identifiable as "any known kind of myxomycete or protostelid whose assimilative stage of wall-less, amoeboid, protoplasmic strands might have quickly migrated into the meteorite after it fell." High moisture levels are needed for plasmodia to be active. (In an inactive state, plasmodia may dry up to form thin leathery bodies called sclerotia that can remain dormant for indefinite periods. None of this material looks like a portion of a sclerotium.") [106] The upper portion appears to have been disk-like or cuplike in form and is not a flattened mass. The general form of the body is suggestive of some kind of a reproductive structure, as known in lower terrestrial organisms. These organisms typically move to the surface of their substrata and then form the reproductive structures. There is a smooth noncrystalline surface with ridges or folds and shallow depressions. It is unlikely that forms this distinctive and found fairly commonly in this sample, (clusters of "mushrooms" and "stalks" were found in the meteorite) would have been overlooked as a naturally occurring organism in the locale where the meteorite fell.

8. Conclusions

This paper reports the discovery of possible microfossils *in-situ* in the Murchison meteorite. A diverse assemblage of highly complex forms have been imaged using the Environmental Scanning Electron Microscope and analyzed by X-Ray Energy Dispersive Spectroscopy. They have been studied in visible light and photographed in color. This Murchison sample also contains minute spherical bodies of similar size range and appearance of types of Claus and Nagy "organized elements" and the spheres that prior workers have interpreted as abiogenic microchondrules coated with organics.

Based upon this evidence, it has been concluded that there exists in the Murchison meteorite a population of indigenous microfossils. These complex "mushrooms", "stalks", and algal-like filaments were found *in-situ* in the meteorite. X-ray analysis reveals that although the "mushroom"-shaped bodies have chemical constituents with the same basic elemental components found in the meteorite matrix, they have distinctive abundances of certain biologically significant elements that are closely associated with these forms. Consequently, these bodies are considered to represent the carbonized remains of biological forms. Extensive attempts to identify these forms with known terrestrial microbial groups have thus far all been negative. Although the bodies resemble some prosthecate bacteria, myxobacteria, and myxomycetes, they have not been identifiable as known members of those groups. The possibility that this meteorite was contaminated with a previously undiscovered population of terrestrial microorganisms is considered extremely remote. The Murchison bodies resemble other unidentifiable forms encountered in the Orgueil meteorite by prior researchers. It is concluded that this population of complex structures may represent remains of extraterrestrial microorganisms which lived within or contaminated the parent body of the Murchison meteorite at various times during the past 4.4 billion years. Further studies on Murchison and all other SNC meteorites and carbonaceous chondrites are clearly warranted and independent research is encouraged. These ESEM images will be made available to interested microbiologists, micropaleontologists, exobiologists, exopaleontologists, and meteoriticists. Research to find additional microfossils in Murchison and other meteorites and to determine their organic and chemical composition, measure indigenous stable isotopes, and establish the age nature of these bodies is underway.

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