

## Comets, Carbonaceous Meteorites, and the Origin of the Biosphere

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**Abstract.** Evidence for indigenous microfossils in carbonaceous meteorites suggests that the paradigm of the endogenous origin of life on Earth should be reconsidered. It is now widely accepted that comets and carbonaceous meteorites played an important role in the delivery of water, organics and life critical biogenic elements to the early Earth and facilitated the origin and evolution of the Earth's Biosphere. However, the detection of embedded microfossils and mats in carbonaceous meteorites implies that comets and meteorites may have played a direct role in the delivery of intact microorganisms and that the Biosphere may extend far into the Cosmos.

Recent space observations have found the nuclei of comets to have very low albedos (~0.03) and these jet-black surfaces become very hot ( $T \sim 400$  K) near perihelion. This paper reviews recent observational data on comets and suggests that liquid water pools could exist in cavities and fissures between the internal ices and rocks and the exterior carbonaceous crust. The presence of light and liquid water near the surface of the nucleus enhances the possibility that comets could harbor prokaryotic extremophiles (e.g., cyanobacteria) capable of growth over a wide range of temperatures. The hypothesis that comets are the parent bodies of the CI1 and the CM2 carbonaceous meteorites is advanced. Electron microscopy images will be presented showing forms interpreted as indigenous microfossils embedded in freshly fractured interior surfaces of the Orgueil (CI1) and Murchison (CM2) meteorites. These forms are consistent in size and morphologies with known morphotypes of all five orders of *Cyanobacteriaceae*. Energy Dispersive X-ray Spectroscopy (EDS) elemental data shows that the meteoritic forms have anomalous C/O; C/N; and C/S as compared with modern extremophiles and cyanobacteria. These images and spectral data indicate that the clearly biogenic and embedded remains cannot be interpreted as recent biological contaminants and therefore are indigenous microfossils in the meteorites.

## 1 Introduction

The origin and extent of the biosphere and the temporal and spatial distribution of life represent the most profound and fundamental problems of the rapidly emerging multidisciplinary field of Astrobiology. Astrobiologists are concerned with the origin and the distribution of life and seek answers to the questions:

*Is life on Earth endogenous or exogenous?*

*Is life restricted to Earth or is life a Cosmic Imperative?*

The recent discovery that microbial extremophiles thrive in hot rocks deep within the Earth's crust (Frederickson and Onstott 1996) and in hydrothermal fluids of deep-sea vents has established that the deep, hot biosphere first proposed by Thomas Gold does indeed exist (Gold 1992). The detection of viable, cryopreserved microorganisms in deep ice cores from the Central Antarctic Ice Sheet (Abyzov 1993; Abyzov, Hoover, Imura, Mitskevich, Naganuma, Poglazova, and Ivanov 2004), ancient permafrost (Gilichinsky, Vorobyova, Erokhina, Fedorov-Davydov, and Chaikovskaya 1992), and from deep marine sediments confirmed the existence and established the significance of the deep cold Biosphere. It is now known that the vast deep, cold biosphere (cryosphere) contains the majority of the prokaryotic cells on Earth (Whitman, Coleman, and Wiebe 1998). Cell counts indicate that the deep-sea sub seafloor sediments harbour  $1.3 \times 10^{29}$  cells which represent more than 50 % of all prokaryotic cells on Earth (Schippers, Neretin, Kallmeyer, Ferdelman, Cragg, Parkes, and Jorgensen 2005). It is now well established that the living component of the Earth's biosphere is comprised primarily of prokaryotic chemoautotrophs and chemolithotrophs of the deep (hot and cold) biosphere rather than more obvious larger multicellular eukaryotes (plants and animals) that are more popularly recognized as "life." The composition and the spatial and temporal distribution of the Biosphere of our planet is profoundly different than that which was widely accepted only a few decades ago.

Chemical and molecular biomarkers indicate that life appeared very early (~3.8 Ga) on the primitive Earth (Schidlowski 1988; 2001). The majority of the earliest definitively recognizable microfossils in ancient Earth rocks have sizes and detailed morphological features that are virtually indistinguishable from modern cyanobacteria and filamentous prokaryotes of benthic mats and hydrothermal vent communities (Walsh and Lowe 1985; Rasmussen 2000). Fossils from the 2.15 Ga Belcher Group, Canada (Hofman, 1976) were sufficiently well preserved as to be recognized as members of an extant clade of endolithic cyanobacteria. These ancient colonial microfossils exhibited recognizable packaging of cells within a mucilage envelope and the surface of the colony was interpreted as being darkened by pigmentation and they were interpreted as microfossils of cyanobacteria. The fossil forms were designated *Eoentophysallis* to reflect their similarity to living representatives of the genus *Entophysallis* (Knoll and Golubic, 1992). The colonial habit within a carbonaceous envelope is important for the recognition of the biogenicity. Spherical forms are produced by many physical processes and clearly abiotic forms resembling cocci or diplococci are present in lunar dust (Hoover et al, 2006). Carotenoids, Chlorophyll and other pigments are common in cyanobacteria where they play a

crucial role in photosynthesis and protection of the internal cells from UV radiation (Hoiczky and Hansel, 2000; Castenholz and Garcia-Pichel, 2000).

Filamentous cyanobacteria and sulfur bacteria have far more distinctive and unambiguously biological morphologies than the coccoidal forms (even when the coccoidal forms are in colonial assemblages). Many of the filamentous cyanobacteria have sheaths and exhibit polarized filaments taper or have distinctive basal and apical termini. The cells within the filaments often have precise sizes and shapes that are of definitive diagnostic value when combined with other morphological features of the organism. Compared with other bacteria and other prokaryotes, filamentous cyanobacteria are often very large and exhibit complex, unambiguous and recognizable morphological characteristics that historically formed the basis for their taxonomy. The filaments may be a simple linear chain of cells (trichome) that may be ensheathed. Filamentous cyanobacteria often possess distinctive differentiated cellular structures for nitrogen fixation (basal or intercalary heterocysts) and reproduction (hormogonia, baeocytes, akinetes and spores). Sheaths that envelope trichomes can be thick, thin, laminated or unlaminated, uniseriate (with one trichome), multiseriate (containing two or more trichomes). The filaments can also exhibit different types of false or true branching. Cyanobacterial sheaths are extracellular fibrillar carbohydrates and complex polysaccharides. Taphonomic studies have shown that the sheaths of cyanobacteria are better preserved in the fossil record, in preference to their peptidoglycan-rich walls of the cyanobacterial cells (Bartley, 1996). Bacterial paleontology studies have established that fossil bacteria and cyanobacteria can be extremely well preserved in a wide variety of Proterozoic and Archaean rocks and carbonaceous meteorites (Hoover and Rozanov 2005; Zhegallo, Rozanov, Ushatinskaya, Hoover, Gerasimenko and Ragozina 2000).

The morphological characteristics of cyanobacteria have remained phenomenally stable since they first appeared on Earth over 3 billion years ago. Ruedemann (1918) was the first to observe "arrested evolution" when he recognized many hundred million year old fossils that were morphologically indistinguishable from their modern analogs. This phenomenon was termed "bradetyly" (Simpson, 1944) and "hypobradetyly" (Schopf, 1992) to reflect the extreme morphological stasis of cyanobacteria that appear to have remained unchanged for over 3 Ga. Knoll and Golubic (1992, p. 453) noted - "Essentially all of the salient morphological features used in the taxonomic classification of living cyanobacteria can be observed in well-preserved microfossils." The similarity of size and detailed morphological characteristics are so great that names of fossil cyanobacteria are often formed by adding the prefixes (palaeo-, eo-) or the suffixes (-opsis, -ites) to the genus name of the modern morphological counterpart (e.g. *Palaeolyngbya*, *Palaeopleurocapsa*, *Eomicrocoleus*; *Oscillatorioopsis*, etc.). Over 40 genera of fossil cyanobacteria have been named using this convention (Schopf, 2000).

## 2 Comets, Meteorites, and the Origin and Distribution of Life

Comets and carbonaceous meteorites are some of the most interesting bodies of the Solar System. Evidence continues to mount that the CI and CM are fragments of cometary nuclei with most volatiles removed (Ehrenfreund et al, 2001; Hoover 2006a) and that these meteorites contain the mineralized remains of indigenous microfossils of cyanobacteria and prokaryotic mats (Hoover, 1997; 2006b; Zhmur et al., 1997). Therefore comets and carbonaceous meteorites may have played a crucial role in the origin and evolution of the Biosphere and the distribution of life throughout the Cosmos. It is generally accepted that the volatiles of the nuclei of comets are primordial ices that condensed on carbonaceous material and mineral dust grains in the proto-solar nebula (far away from the hot central region) during the formation of the Solar System. The "dirty snowball" model was first advanced by Fred Whipple (1950) who also recognized the close relationship between comets and meteors (Whipple, 1951). Comets do not develop comae or tails until they come closer to the Sun than the orbit of Jupiter (~5 AU) where solar radiation heats the nucleus to a temperature in excess of 200 K. Beyond this "snow line" the volatiles are solidified and the coma and tails disappear and the comet looks like an asteroid. It is a widely accepted hypothesis that although comets are rich in water ice, their porosity is so great the water ice sublimates directly to water vapour without transition through the liquid phase. The belief that liquid water cannot exist on comets has led to the conclusion that they must be sterile, since metabolism and active growth of all known life forms appears to be predicated upon the presence of liquid water. However, the phase diagram shows that the transition of ice into liquid water will occur whenever the temperature exceeds 0 °C as long as the pressure exceeds 6.1 millibars. Spontaneous flaring and the eruption of geyser-like jets from comets Halley and Temple 1 indicate pressures in excess of 6.1 millibars occur in cometary nuclei.

Impacts of comets, meteorites, and asteroids during the Hadean delivered water and ice to the Earth and Mars and may have played a significant role in the formation of early oceans of our planet (Delsemme 1997). The deuterium to hydrogen ratio for water molecules of comets Halley, Hale-Bopp and Hyakutake was found to be an order of magnitude higher than the D/H ratios for Saturn, Jupiter and the Interstellar medium but the D/H ratios not only overlap the Earth's oceans ( $1.6 \times 10^{-4}$ ) but they are also consistent with the values found for the indigenous water of the carbonaceous meteorites. (Delsemme, 1998; Eberhardt, et al., 1987). Chyba and Sagan (1997) pointed out that the cometary delivery of bulk of the Earth's oceans is quantitatively consistent with the Earth deriving its inventory of carbon from comets as well. Comets arrive from the volatile-rich outer regions of the solar system, which led to the suggestion that comets delivered pre-biotic organic molecules along with water and carbon to the inner planets (Oró 1961; Oró and Lazcano 1997).

The concept that comets are sterile continues to be widely held even though recent discoveries have shown that living microorganisms exist in ice (Abyzov, 1993; Abyzov et al., 2004; Pikuta et al., 2005) and that the surface of a comet nucleus becomes hot within the orbit of Mars (1.5 A.U.). Over two decades ago, the hypothesis was advanced that diatoms, bacteria and other microorganisms could live in the

ice and water beneath the organic rich carbonaceous crusts of comets and that comets might periodically deliver intact and possibly yet viable microorganisms to Earth and to other bodies of the Solar System. Consequently comets could thereby have played a crucial role in the origin of life on Earth as well as the distribution of life throughout the Cosmos (Hoyle and Wickramasinghe 1980; Hoover, Hoyle, Wickramasinghe, Hoover and Al-Mufti, 1986).

Spacecraft observations of comet P/Halley in March, 1986 provided important data about the nature, behavior, surface temperature and chemical composition of the nucleus and coma. The Vega Dust Mass Spectrometer found the Halley nucleus material to have a composition similar to carbonaceous meteorites with water as the primary volatile (75 - 80 %). The Vega 1 IR spectrometers found the dayside surface of the 16x8x8 km nucleus of comet Halley at perihelion was astonishingly hot ( $T \sim 400$  K) (Emerich et al., 1987). ESA's Giotto spacecraft determined the Halley nucleus was one of the darkest objects in the solar system with an albedo  $\sim 0.03$ , that is comparable to CI and CM carbonaceous meteorites and P- and D- class asteroids (Hiroi et al., 2004). An inert black crust may build up as comets lose ices and dust and carbonaceous materials concentrate on the surface (Wallis and Wickramasinghe, 1991, Wickramasinghe and Hoyle, 1999). Giotto obtained spectacular images from 600 km showing the full contour of Halley's jet-black nucleus as two very bright geyser-like jets of water vapor, dust and ice particles were being ejected. Giotto measured the D/H ratio of the water of comet Halley at  $5.5 \times 10^{-4}$  which is similar to seawater ( $1.5 \times 10^{-4}$ ); carbonaceous meteorites ( $\sim 1.4-6.2 \times 10^{-4}$ ) but very different from the D/H ratio of Jupiter ( $1.5-3.5 \times 10^{-5}$ ); Diffuse Interstellar Medium ( $1.5 \times 10^{-5}$ ) and Proto-Solar Nebula ( $2.1 \times 10^{-5}$ ) (Eberhardt, et al., 1987). Evidence for microfossils in CI and CM carbonaceous meteorites supports the hypothesis that comets were the parent bodies of these meteorites (Hoover et al., 2004; Hoover, 2006a; 2006b).

Sunshine et al. (2006) found exposed regions of water ice on the surface of comet Temple 1 at 1.5 AU (near the orbit of Mars). Their measurements indicated the temperature was slightly above 273 K (melting temperature of water ice) over a large area of the surface of the nucleus with the maximum of 330K in the hottest regions exposed to direct sunlight. Infrared spectra of comet Temple 1 as observed by the *Deep Impact* spacecraft showed a tremendous increase in the  $3.2 \mu\text{m}$  CH-X band when compared with the  $3.2 \mu\text{m}$  H<sub>2</sub>O band and the  $4.25 \mu\text{m}$  CO<sub>2</sub> band indicating a strong surge of material with high organic content from the inner regions of the nucleus. These observations suggest liquid water can exist on cometary nuclei. Hence, cyanobacterial and prokaryotic mats could form within regimes between a semipermeable carbonaceous crust and interior ice where pressure and temperature allow liquid water films/pools trapped between ice, rock, and carbonaceous crust.

### 3 Microfossils of Cyanobacteria in Orgueil and Murchison

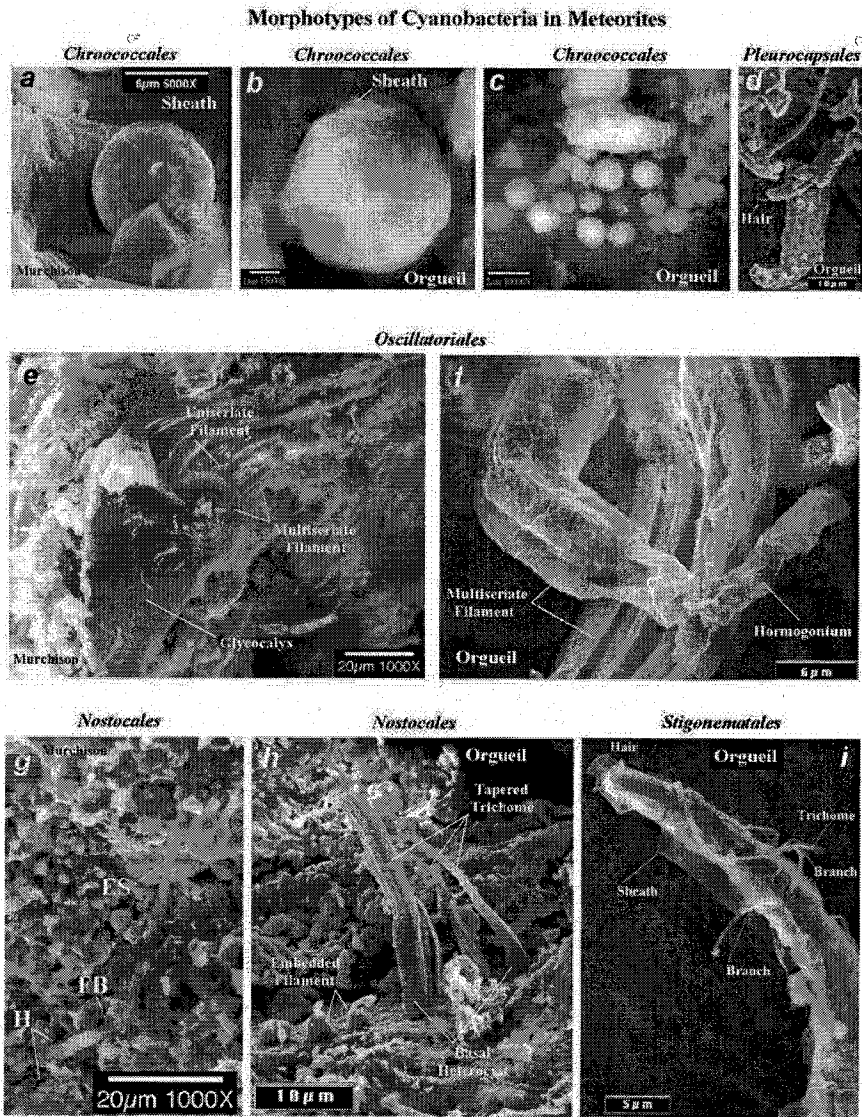
High resolution Scanning Electron Microscopy imaging of meteorites and living and fossil cyanobacteria and microbial extremophiles have been carried out at the Astrobiology Laboratory NASA/MSFC/NSSTC. This research employed the Elec-

troScan Environmental Scanning Electron Microscope (ESEM); the FEI Quanta 600 FEG and Hitachi S-4100 Field Emission Scanning Electron Microscopes (FESEM) operating with Secondary and Backscattered Electron Detectors. Uncoated, freshly fractured, interior surfaces of meteorites, proterozoic rocks, Vostok ice, living and fossil cyanobacteria and other prokaryotic and eukaryotic extremophiles were studied. All of these instruments have Energy Dispersive X-ray Spectroscopy (EDS) systems capable of obtaining quantitative elemental composition (spot and 2-D X-ray Maps) for elements with atomic number  $\geq$  Boron. Several thousand images and EDS spectra have been produced during the past decade

Mineralized and embedded remains of clearly biogenic, large, filamentous forms have been found in all of the CI1 (Orgueil, Alais, Ivuna); CI Ungrouped (Tagish Lake); CM2 (Murchison, Murray, Mighei, Nogoya) and some CO3 (Rainbow, DAG 749) and CV3 (Efremovka) meteorites investigated. Similar forms were not detected in studies at NASA/MSFC of the CV3 (Allende); CK5 (Karoonda); L4 (Barratta; Nikolskoye); L/LL6 (Holbrook); Diogenites (Tatahouine); Nakhilites (Nakhla; Lafayette) or Nickel/Iron (Antarctic) meteorites studied. The CI and CM carbonaceous meteorites contain a large number of complex and embedded coccoidal and filamentous forms consistent in size, shape, and morphology with known species of cyanobacteria and prokaryotes. Many of the forms are clearly embedded in the meteorite rock matrix and have C/O, C/N and C/S ratios dramatically different from those measured in living and dead cyanobacteria, prokaryotic extremophiles, and eukaryotes (fungi, diatoms, wood and moss). Consequently, many of these complex and recognizable filaments have been interpreted as indigenous microfossils of cyanobacteria in the meteorites rather than recent microbial contaminants (Hoover, 1997; Zhmur et al., 1997; Hoover et al. 2004, Hoover and Rozanov, 2005; Hoover, 2006a). Representatives of all five orders of cyanobacteria (corresponding to Section I-V of Rippka et al. 1971) have been found and a few examples are presented herein.

### 3.1 Morphotypes of Cyanobacteria in Carbonaceous Meteorites

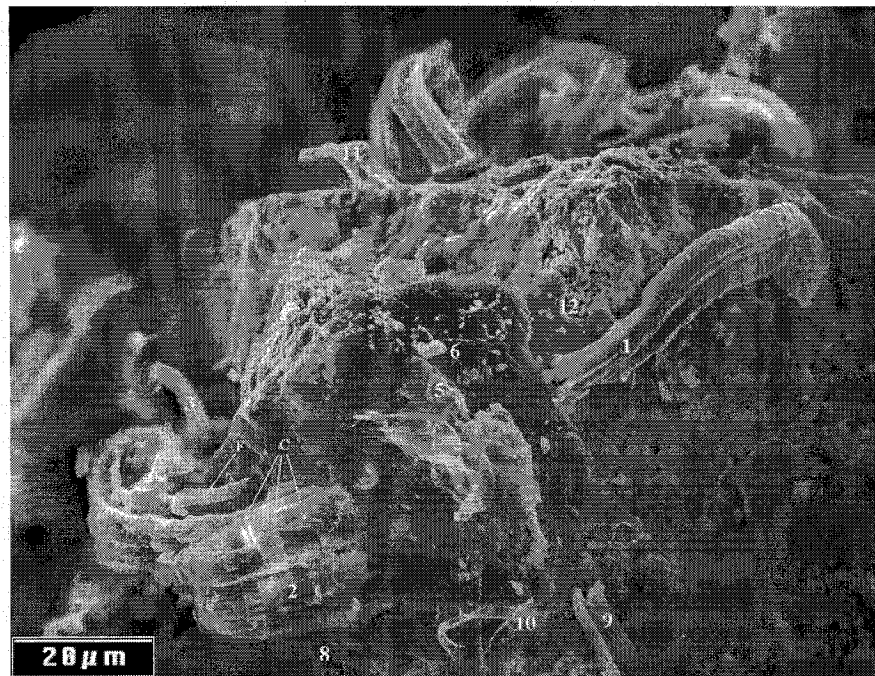
Coccoidal and nanometric scale spherical microstructures have been found in all of the meteorites studied. Since simple spheres can be produced by many abiotic mechanisms most of these forms found in meteorites were presumed to be abiotic. Unicellular Chroococcalean cyanobacteria (e.g. *Synechococcus*, *Gloeotheca*, *Gloeocapsa*) reproduce by binary fission. Even though coccoidal forms can be abiotic, the forms shown in **Fig. 1** are encapsulated within a carbonaceous sheath and they are interpreted being biogenic in origin. These forms exhibit the appropriate sizes and size ranges of are morphotypes of Cyanobacteria of the Order Chroococcales, such as are found encased within carbonaceous sheaths (**Fig. 1.a, b**); or as colonial assemblages in carbon-rich mucilage envelopes (**Fig. 1.c**). Other irregular or polygonal coccoidal forms have been found in pseudofilaments encapsulated within carbonaceous sheaths such as unicellular members of the Order Pleurocapsales that reproduce by multiple fission producing reproductive cells (e.g. baeocytes) of diverse sizes (**Fig. 1.d**).



**Fig. 1.** Well-preserved mineralized microfossils of morphotypes of all five Orders of *Cyanobacteriaceae* (Chroococcales a-c; Pleurocapsales d; Oscillatoriales e,f; Nostocales g,h; and Stigonematales i) embedded in freshly fractured interior surfaces of the Murchison CM2 (a, e, g) and the Orgueil CI1 (b, c, d, f, h, i) meteorites.

By far the most abundant and recognizable microfossils found in the carbonaceous meteorites are morphotypes of filamentous non-heterocystous cyanobacteria that divide in only one plane. These are the cyanobacteria that belong to the Order Oscillatoriales ((Section III of the Bacteriological Code). Morphotypes interpreted as representative of species of the genera *Oscillatoria*, *Spirulina*, *Arthrospira*, *Microcoleus*, *Phormidium*, *Lyngbya*, and *Plectonema* have all been encountered in the Orgueil meteorite. Microfossils of Oscillatorialeean cyanobacteria are shown in **Fig. 1.e.** from Murchison and **Fig. 1.f** from the Orgueil meteorite.

The most complex and highly distinctive are the Nostocalean cyanobacteria. Examples of these in the meteorites include the morphotype of filamentous *Nostoc* sp. with emergent hormogonia and hollow empty sheath (**Fig. 1.g**) in the Murchison CM2 meteorite. **Figure 1.h.** shows the funnel-shape apical regions of three almost completely embedded filaments beside a thin embedded benthic mat of several tapered filaments that are attached to the Orgueil meteorite rock matrix at smooth bulbous structures that are interpreted as the basal heterocysts of cyanobacteria consistent with members of the family *Rivulariaceae*. These forms are consistent with size, morphology and ecological habit with known modern morphotypes of *Calothrix* spp. **Fig. 1.i.** shows is a morphotype of a complex trichomic filament of *Stigonemalalean* cyanobacteria with a terminal hair and both true and false branching.



**Fig. 2.** Cyanobacterial filaments embedded in the Orgueil meteorite.



Figure 2 is 1000 X Hitachi FESEM image of a densely populated region of Orgueil with several different well-preserved embedded filaments and electron transparent sheaths that exhibit complex morphological features consistent with the known characteristics of several major groups of cyanobacteria. The numbers correspond to the filaments and sheaths for which the C/N and C/S ratios are given in Fig. 3. The values are typical of the filaments and sheaths measured in many samples of Orgueil from different Museums. Irregular longitudinal striations of filaments 1 and 2 indicate multiseriate trichomes consistent with the Oscillatorialean genus *Microcoleus*. The smaller multiseriate filament 1 and the solitary filament F (2  $\mu\text{m}$  diameter hook-shape with a narrowed terminus) are interpreted as representing morphotypes of the genus *Trichocoleus Anagnostidis* which has trichomes  $\sim 0.5\text{--}2.5\ \mu\text{m}$  diameter.

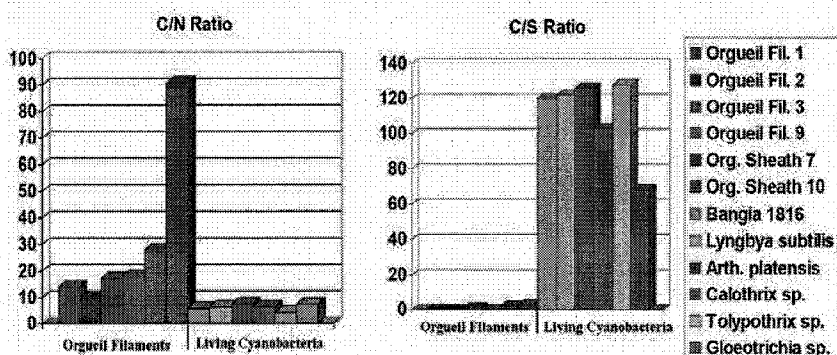


Fig. 3. Comparison of C/N and C/S ratios of the numbered Orgueil meteorite filaments and sheaths (from Fig. 2) with a filament in an 1816 herbarium sample and living cyanobacteria grown in culture at the NSSTC Astrobiology Laboratory.

### 3 Conclusions

The discovery of indigenous microfossils of cyanobacteria in carbonaceous meteorites clearly indicates that the Biosphere of Earth is open rather than closed. The possibility that biological matter has been transferred into space by impact of large comets and asteroids onto shallow marine sediments must be considered as well as the possibility that terrestrial microbial extremophiles arrived on Earth during the Hadean bombardment from other regimes of the Cosmos. The images provided in Figures 1 and 2 are undeniably biogenic. These filaments, sheaths, and mats are clearly recognizable as associated with morphotypes of highly distinctive and very well-known polarized and differentiated benthic filamentous cyanobacteria. The Orgueil meteorite is immediately destroyed by contact with liquid water and therefore it is impossible that these photosynthetic microorganisms which require liquid water to grow and a water/substrate interface in order to form mats could have constructed the observed mats and benthic ecological consortia within the dry black Orgueil rocks

subsequent to the arrival of Orgueil on Earth. Furthermore, there are dramatic differences between the C/N and C/S ratios of the Orgueil filaments and sheaths than those found in living cyanobacteria and old dead forms encountered in herbarium material. Therefore it is concluded that the indigenous microfossils of cyanobacteria found in the CI and CM carbonaceous meteorites provide strong evidence that the Biosphere is open and is not restricted to the planet Earth.

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