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**BGD**

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Interactive Comment

# *Interactive comment on* “Comets, carbonaceous meteorites, and the origin of the biosphere” *by* R. B. Hoover

**R. B. Hoover**

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Reply to Comments by J. Fritz (Referee) regarding the manuscript “Comets, carbonaceous meteorites, and the origin of the biosphere”

I would like to thank Dr. Fritz for this careful review and many valuable comments. As the referee has requested the paper will be revised, re-structured and redundant passages removed. Recent discoveries concerning water on comets will be added that are directly relevant to the central thesis — the Biosphere is far more extensive than was thought possible only a few decades ago. Evidence of indigenous microfossils in carbonaceous meteorites suggests that that the biosphere extends into the Cosmos and that exogenous sources may have played a more significant role in the origin of the Earth’s biosphere than has previously recognized. The paper was originally prepared after the example.doc of the Biogeosciences guidelines, but I will re-structure it into Introduction, Results, and Discussion and Conclusions format t provide a sharper focus.

On Pg. S8. Par. 1. the referee suggests that some arguments should be presented that the investigated structures are not of abiotic origin. I agree and will include FESEM images and EDS data in the Results Section that will show the morphology and chemical composition of abiotic native epsomites and living filamentous cyanobacteria. The Discussion section will describe the samples used in the study and the hardiness of cyanobacteria and other extremophiles that suggest they might be capable of growing in water films, pools and pockets near the surface of comets will be discussed in support the fundamental thesis of this paper - the ecosystem of Earth is open (rather than closed) endogenous view of the origin of the biosphere merits careful reconsideration.

Pg. S8 Par. 1. I disagree with the comment: " The author did not consider an abiotic origin, which would be the most straightforward explanation, as the investigated structures are composed of Mg and S." The text and EDS data clearly show that the Orgueil filament contains over 10 % of the important biogenic element carbon in addition to the Mg, S, and O components of Epsomite (MgSO4).7(H2O). I will add text provide additional images to Figure 5 showing the microstructure and EDS spectra of abiotic native epsomite for comparison with the Orgueil filaments. As the referee suggests, I will also add the EDS spectrum for the living Calothrix filament of Fig. 5.a.

I will also add text to the Introduction to clarify the significance of the biogenic elements nitrogen and phosphorus in living systems and present new data showing how N and P are typically detected in EDS spectra of the living and recently dead microorganisms but rarely detected in fossils because of diagenetic loss. This will hopefully prevent confusion concerning absence of the nitrogen signature in the meteorite microstructures provides evidence that these biomorphic microstructures are not the result of recent biological contamination. The EDS detectability limits for the observed elements at the given accelerating voltage will also be presented. New text in the Discussion section will consider other lines of evidence (i.e., nature of photoautotrophic prokaryotes, solubility of the Orgueil meteorite, missing protein amino acids, and carbon isotope data) that support the conclusion that these biomorphic microstructures can not be dismissed as recent biological contaminants.

Pg. S8, Par. 2: I do not agree with the suggestion that this paper should be divided because the meteorite data supports the argument that the biosphere may extend into the Cosmos and that the origin of life on Earth may have had a significant exogenous component. Recent Cassini evidence for ice geysers and liquid water on Saturn's icy moon Enceladus and the recent Deep Impact data concerning water ice on comet Tempel 1 greatly strengthen this argument. It is clear that extensive aqueous alteration occurred on the parent bodies of the CI and CM meteorites indicating liquid water on the parent bodies. A new section will more thoroughly discuss the current thinking about the meteorite parent bodies. The new results about liquid water on other Solar System bodies combined with the evidence for indigenous microfossils in the carbonaceous support the fundamental thesis of the manuscript and to remove either of these components would greatly weaken the scientific significance of the paper. As the referee recommends, I will add additional images and EDS data to the revised paper to support the position "that the investigated structures are not of abiotic origin but represent the remains of living organisms." A new Figure 7 will provide FESEM images and EDS data on the hormogonia and filaments of living cyanobacteria to help the reader to understand the appearance in the FESEM and the chemical composition of the sheath, trichomes, and hormogonia of living Plectonema wollei. I will also present a new Figure 4.b., to detail the emergent hormogonia of current Fig. 4 and present EDS spectral data that shows that the biomorphic microstructure has mineralization consistent with the meteorite composition but there is a strong carbon overprint situated on the microfossil providing additional chemical evidence that the form is indigenous and biogenic. As the referee requests, new text will be added to describe the biogenic elements, biomineralization, and the petrology, mineralogy and geochemistry of these meteorites and the different opinions of the scientific community concerning their parent bodies.

Pg. S9, Par. 1 & 2: The referee encourages speculation about the origin of the microbial remains found in the carbonaceous meteorites. I chose not to do so as I wanted to constrain to paper to hard evidence and to avoid speculation. I do not know how or where life originated and do not intend to suggest that I do in this paper. However, the possibility that life may be transferred from one body to another may significantly alter the initial conditions of those researchers who are seeking answers to this most important fundamental question. It is now known that the surfaces of comets can get very hot ($>$320 K @ 1.5 AU and $>$ 400 K @ 1 AU). Consequently regimes beneath the outer surface layer may contain pockets and crevices filled with hot water suitable for the growth of hyperthermophilic and thermophilic photoautotrophs and chemolithotrophs. At the same time other regions beneath the crust may contain pools of water suitable for mesophiles or psychrophiles. Ward and Castenholz (2000) have shown that many genera (e.g., Calothrix, Oscillatoria, Phormidium, and Spirulina) of motile filamentous cyanobacteria are capable of growing in hot springs, geysers and other geothermal habitats at temperatures ranging from 320K to 345K. The biomorphic microstructures are consistent in size, differentiation, and morphology with representatives of all of these genera of cyanobacteria.

Ward, D. M., and Castenholz, R. W., Cyanobacteria in geothermal habitats. in: The Ecology of Cyanobacteria. Their Diversity in Time and Space. (B. A. Whitton and M. Potts, editors), Klewer Academic Publishers, Dordrecht, The Netherlands, pp. 37-59, 2000.

Pg. S9, Par. 3: In this paper I did not ever advance or imply any hypotheses or suggestions concerning the co-evolution of life on Earth and the different meteorite parent bodies. It is conceivable that the presence of the mineralized remains of cyanobacteria on these meteorites may have resulted from the parent bodies passing though an ejecta debris field that originated on Earth, Enceladus, Europa or Mars. The accretion of only a small quantity of viable microbiota might be capable of triggering populations and ecosystems if the microbes found conditions within certain niches of the parent body capable of sustaining life. Since this transfer process could happen in either direction it is not possible to say with certainty if microbial life found on ancient Earth actually originated here endogenously or was exogenously inserted into the Earth's biosphere. The referee argues: "It has to be mentioned that aerobic organisms appear late in the evolution of life on Earth, and the first terrestrial organisms considered oxygen poisonous." I do not agree since the most ancient life forms known on Earth are represented by the most deeply branching lineages of the bacteria and archaean which are viewed as being closest to the Last Universal Common Ancestor (LUCA) on the Universal Phylogenetic Tree. These include the deeply branching aerobic bacterium Aquifex aeolicus, and the aerobic hyperthermophilic archaea (e.g., Aeropyrum pernix) and the thermoacidophiles (Picrophilus oshimae and Picrophilus torridus) isolated from solfataras in northern Japan. These species had optimal growth at 330 K and both grew heterotrophically under aerobic conditions. Aquifex aeolicus is one of the most thermophilic and ancient of all bacteria (capable of growth at 365 K) and it has machinery that allows it to function as a chemolithotroph with the ability to grow on hydrogen, oxygen, carbon dioxide, and mineral salts. None of these ancient microorganisms could be correctly characterized as organisms that considered oxygen to be poisonous.

Pg. S9, Par. 4: The referee questions the identification of microfossils on the basis of morphology. Clearly I need to add additional text to clarify the situation. The size, size distributions and detailed morphological characteristics play a critical role in the identification of cyanobacteria.. The taxonomic system for cyanobacteria was developed during the 19th century and is based almost entirely on morphology. These oxygenic photosynthetic prokaryotes (also referred to as the cyanophyta or blue-green algae) have traditionally been treated as a group of algae under the aegis of the International Code of Botanical Nomenclature. Phycologists developed the system of classification of these organisms and it is based on their morphological, developmental and ecological characteristics from natural samples rather than pure cultures. Although it is now absolutely certain that the cyanobacteria are true bacteria, the efforts to fully incorporate them into the International Code of Nomenclature of Bacteria have met with extremely limited success. As of 2004, only thirteen species of cyanobacteria had



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been proposed and only five species had been validly published. Many species exhibit simple morphologies (e.g. small unicellular cocci or rods), but others are large thalloid forms with differentiated cells and a high degree of developmental and morphological complexity and in cyanobacterial systematics morphology and development remain the primary criteria for the taxonomy of both living and fossil cyanobacteria. Without the application of morphology to the mineralized remains of all manner of life forms there would be very little left to study in the field of Paleontology.

Pg. S.10 Par. 2. In the Discussion Section, I will provide more information about contamination and protection of carbonaceous meteorites.

Pg. 27 Line 22: The referee objects to the statements regarding the possibility of chemolithotrophic microbial communities being able to inhabit the nuclei of many comets as they approach perihelion. This objection is not supported by the current state of knowledge concerning the physics and chemistry of the nuclei of comets and recent discoveries in the field chemolithotrophic microbial extremophiles. The surfaces of the nuclei of Halley and Tempel 1 were found to be very hot (330 - 400 K) and high temperatures in water films and pools trapped in voids and cavities just beneath the surface would in fact comprise excellent environments for thermophilic cyanobacteria, bacteria and archaea.

Pg. 28, Line 16. Sunshine et al. (2006) reported temperature data for the surface of a comet Temple 1 (out of the Sunlight) at 280 K ś 8K when the comet was near the orbit of Mars at 1.5 AU. This temperature range is ideal for the growth of phychrophilic and psychrotolerant cyanobacteria and bacteria. Several genera and species of filamentous cyanobacteria (e.g., Microcoleus chthonoplastes, Phormidium sp. Oscillatoria sp., and Calothrix sp.) whose morphotypes were found in Orgueil are capable of growing in either hot or cold environments and they can survive freezing to temperatures below liquid nitrogen. These characteristics are ideal for candidates for life that might have to tolerate wide swings of temperature that could easily occur just beneath the surface of a spinning comet nucleus.



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Pg. 28, Line 21, Missing references will be added. Pg. 31 Line 25-28. The first two sentences will be combined and modified to clarify the point. “From the standpoint of the origin and evolution of the Biosphere and the potential for the cometary delivery and distribution of water, complex organic chemicals and possibly even genetic material and intact and viable microbiota, comets are among the most important and interesting bodies of the Solar System.” I fail to see the argument that the moon has played nearly as significant role as comets in the origin and evolution of the Biosphere and the importance of the Earth and Sun is obvious so I do not see the need to point it out.

Pg. 32, Line 6. I agree that “dominant paradigm” is not the best choice and the overused word “paradigm” will be replaced with “model”. The references called out here are old, but I think they should remain since they refer to the classic papers of Whipple.

Pg. 32 Line 11: The modified sentence will be: “Based on the Giotto/Vega mass spectrometer data indicating that the organics and rocky/particulates component constituted 45% and the water ice component of comet P/Halley was only 30% (by mass), it now appears that comets are more like “frozen mudballs” than the “dirty snowballs” envisioned by Whipple (Greenberg, 2002).

And the reference added: Greenberg, J. M.: Cosmic dust and our origins, Surface Science, 500, 793-822, 2002.

Pg 33, Lines 2&3 Reference missing: This section is not clear and text will be deleted from the end of Pg. 32 line 29 through Pg. 33 lines 1-6 and replaced with a clearer statement and the proper references inserted:

Pg. 32 line 29: “the ecliptic plane and have elliptical (typically prograde) orbits. Short period (Jupiter family) comets were probably primarily induced by collisions in remote regions of the Solar System near the plane near Neptune in the Edgeworth-Kuiper belt (Edgeworth, 1949, Kuiper, 1951, Holman and Wisdom, 1993). The Edgeworth-Kuiper belt is thought to act as a reservoir for the short period comets in much the same way that the Oort cloud acts as a reservoir for the long-period comets (Jewitt, 1998). The long period comets which have a wide distribution of orbital inclinations to the ecliptic (the Oort cloud comets) are generally thought to have mostly originated in the Jupiter-Saturn-Uranus region of the early solar nebular disk (Whipple, 2000; Fernandez, 2002; de Moraes et al., 2006)."

The appropriate references will be added.

Pg. 33 Line 21- Reference missing: Zahnle, K. J. and Sleep, N. H.: Impacts and the early evolution of life. in: Comets and the Origin and Evolution of Life. (P. J. Thomas, C. F. Chyba, and C. P. McKay, Eds.) Springer-Verlag, New York. 175-208, 1997.

Pg. 33 Line 25. I will clarify this point by adding the following text just after line 27: Ě family of comets. Chyba and Sagan (1997) have pointed out that the deuterium to hydrogen ratio for comet P/Halley (0.6-4.8 X 10-4) is an order of magnitude higher than the D/H ratios for Saturn, Jupiter and the Interstellar medium (Eberhardt, 1987). However, the comet Halley D/H ratio is consistent with the values from meteorites and it overlaps that of the Earth's oceans (1.6 X 10-4) and they argue that the "cometary delivery of bulk of the Earth's oceans is quantitatively consistent with the Earth deriving its inventory of carbon from this source as well" (Chyba and Sagan, 1997, p. 155).

Pg. 35, Line 15-19 & Pg. 36, Line 13-20 References missing: This text is redundant and will be combined and duplicated information deleted. The Vega temperature data reference is Emerich et al. 1987 (Pg. 36 line 10).

Pg. 37, Line 32. The referee comments that the large amount of dust argues in favor of a comet being composed of loose sediments rather than cemented ones. I will add text to clarify. Even though the particulates of the Orgueil meteorite are now cemented by magnesium sulfate, I did not intend to suggest that the particulates would have been cemented together by these salts while on the comet, asteroid parent body. These salts are highly water soluble and would be in solution in the water of the parent body. They would precipitate and cement the grains together as the volatiles were removed from the meteorite. The point I want to make was that the particulates on the comet were already pulverized prior to the Deep-Impact collision. This would explain why more small particulates were released than would have been possible if they were entirely produced by the energy delivered by the Impactor. I suggest that these minute particulates were accreted cometary and interstellar dust particles combined with comet nucleus rock matrix that had been disintegrated by repeated freeze-thaw cycles and suspended in the slurry of liquid water in pools and pockets just beneath the outer surface or crust of the nucleus. In regimes where the temperature is below 273 K the particulates should be held together while frozen in water ice films within the interstices of the minute particulate grains of the outermost regions of crustal regolith which also contains the tarry (kerogen-like) carbonaceous material observed on the comet surface. The craters seen on the nuclei of several comets and asteroids provide evidence that impacts from meteorites and other bodies do occur. These impacts would deliver energy that could result in melting deep within the core and provide further energy for the production of liquid water on the nucleus that could support mot only aqueous alteration and freeze-thaw weathering process but also microbial growth if viable microbes were cryopreserved in the deeper layers of ice. The minute particulates observed in the Tempel 1 nucleus are consistent with the minute particulates in permafrost that result from the weathering effects of repeated freeze-thaw cycles. The breaking of the rocks and small rock particulates occurs because the water seeps into minute pores, cracks, and crevices and expands as it freezes fracturing the rock. This phenomenon would not take place if the phase liquid to solid phase transition can not take place. New Text: “Sunshine at al. (2006) have just published Deep-Impact data providing the first direct detection of exposed water ice deposits on the surface of comet 9P/Tempel 1. The IR spectral scans showed distinct 1.5 and 2.0 $\mu$m absorptions that are diagnostic for water ice. The maximum of 330 K was observed for the region of the nucleus in direct sunlight and the minimum measured temperatures of the surface of Tempel 1 was 280 ś8 K. This temperature is entirely consistent with the temperature of the solid/liquid water transition phase but it is far above the free sublimation temperature. At a distance on 1.5 AU from the Sun water ice converts directly to water vapor in a vacuum at a temperature of ˜200 K via the process of sublimation." This constitutes observational evidence for the existence of liquid water near the surface of comet 9P/Tempel 1.

P. 37 line 25. The grain size of Orgueil meteorite is important as it is consistent with the Tempel 1 observations and provides another piece of evidence supporting the hypothesis that the CI1 meteorites may be of cometary origin. The size of the Orgueil grains was discussed as a result of petrographic studies carried out by Nagy, (1975). I have also personally observed and measured both the sizes and elemental compositions of a very large number of mineral grains and biomorphic microstructures in many samples of CI1 and CM2 carbonaceous meteorites and my observations fall in line with the previously reported results.

Pg. 38, line 7. The gravity of comets is very low, but there is absolutely no evidence that the 100 M high cliffs and the pinnacles, spires and craters such as have been observed could remain in such sharp relief if the surface were a loose aggregate of dust and solidly frozen ice particulates and snow unless the particulates are frozen together by water ice. Furthermore, Sunshine et al. (2006) have found relatively large regions (total area 0.5 km2) of water ice at the surface of Tempel 1 with the largest area of ice in a depression 80 M ś 20M below the surrounding area.

Pg. 38, line 16. I did not speculate about whether or not there was sufficient time for life to have originated on comets. I do not know precisely where or how life originated. However, it should be recognized that if life's origin was exogenous rather than endogenous to Earth (as has long been assumed) then the initiating times, physical and environmental conditions and volumes in which the reactions can take place are dramatically altered. I would not suggest that comets might have captured microbiota "during passage through a planetary atmosphere" as I think in almost all cases an entry of a comet nucleus into a planetary atmosphere would most likely result in the total destruction of a highly volatile and fragile body such as a comet resulting in a

"Tunguska-like" event.. However, by their very nature, comets are the wanderers of the Solar System. They are continually accreting material as they sweep through debris fields in space that have been ejected by impacts of large asteroids and comets on planets, moons, asteroids, as well as other impacts on other comets and planetissimals. It is known that these kinds of impacts do occur, as was recently witnessed the Shoemaker-Levy collision with Jupiter. Furthermore we have meteorites on Earth that have unquestionably been delivered here from the Moon and Mars by impact ejection processes. The majority of this ejecta is most probably sterile, either because there was originally no life on the parent body from which the rock or ice ejecta originated or because the biological component was sterilized by the impact ejection process. This is the significance of the fact that intact and viable microorganisms have been found even very deep within the ice cores of the continental Antarctic sheet at Vostok, Antarctica and that chemolithotrophic microorganisms actively carry out metabolism and respiration and grow in deep marine sediments and deep rocks throughout the uppermost few kilometers of the crust of planet Earth. WE can not be absolutely certain that deep ice or deep crustal rock ejecta from Earth, Enceladus, Europa or Mars would be subjected to thermal heating sufficient to sterilize all microbiota that might be contained with the ejected rock or ice. This clearly would not be the case for ice ejected from small icy moons or comets and spewed out in ice geysers from bodies such as Enceladus. Therefore cross-planetary bio-contamination of Solar System bodies can not be ruled out or considered totally impossible. The rapid replication capability of microorganisms is such that if only a few viable microbes made their way into liquid water in pockets or thin films within the uppermost layers of the regolith of a comet, asteroid or other meteorite parent body that they could conceivably could give rise to large assemblages of microbes in a very short (weeks to months) time period. Although almost all cyanobacteria are photoautotrophs, a facultatively heterotrophic strain of the cyanobacterium Nostoc sp. has been reported (Juhász et al., 1987). Facultatively heterotrophic cyanobacteria have been reported to be capable of liberating ammonia during nitrogen fixation and many of the archaea and bacteria are also both



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photoautotrophic or heterotrophic.

Pg. 39 Line 13. Text will be modified to "This suggests that life first appeared on Earth in the Hadean during the period of heavy bombardment by comets, asteroids, and meteorites. and the subsequent text Line 14-17 will be moved to the conclusion section.

Pg. 41. Line 18-27. I agree that the CI chondrites are primitive bodies with elemental compositions (except for the volatiles) similar to solar photosphere. However, that does not agree that this implies that "aqueous activity on the parent body is, thus, strongly limited." It is the general consensus of the scientific community that the CI carbonaceous meteorites exhibit the most extensive aqueous alteration of all meteorites and that this alteration occurred in liquid water on the parent body. I will move the text of Pg. 41 Lines 14 through 28 into the Discussion section and add additional results.

Pg. 42. Line 1. As requested, I will add text and references to some of the major papers that challenge to McKay et al. results.

Paragraphs 5.3 and 5.4. I thank the referee for pointing out that these sections are badly mixed and will re-organize the text to correct this problem. Additional text will clarify the reasons for my conclusions that these microstructures are biotic rather than abiotic in origin. In the Discussion section I will also more extensively address the problem of recent bio-contamination of carbonaceous meteorites and provide arguments based upon observations of meteoritic stable isotopes and amino acid content that indicate the carbon and amino acids found in Orgueil and Murchison are extraterrestrial and cannot be dismissed as recent contaminants. I will also briefly address the problems of terminology for indigenous biogenic microstructures in meteorites and the solutions that have been adopted for ancient cyanobacterial biomorphs that exhibit dramatic similarities to known living genera and species.

Pg. 47, Line 7 I will more thoroughly clarify the problem of the application of molecular biology techniques to mineralized and fossilized remains.

Pg. 17 (50) Line 19. I do not agree with this argument. The presence of 10% carbon in these filaments clearly reveals that they are not simply abiotic crystals of the mineral epsomite, which has a chemical composition of only magnesium, sulfur and oxygen and which contains absolutely no carbon. It is also not correct to assert that the biological origin was deduced only by surface morphology and not by internal structures. The size and size range of the filaments is also important for the identification of cyanobacteria and filamentous prokaryotes. Genetic factors rigorously control the sizes or biological entities while mineral crystals can and do exist in a very wide range of sizes. Furthermore, all of the filamentous microstructures found during the last decade of study of internal microstructures within the meteorites have been found to be constrained to the sizes that are appropriate for known microorganisms and the biotic components associated with these microorganisms. I will add an additional figure showing the EDS composition and the appearance of the trichomes, filaments and hormogonia of living cyanobacteria as seen with the ESEM and FESEM instruments. In Figure 4, evidence is present for internal structures, which are recognizable in the cross-wall constrictions that can be observed in the short segments of trichome that have emerged as motile hormogonia and as the indications of septa in the flattened section of the sheath. These indications of cross-walls allowed an estimation to be made of the size of the cells that were made up the trichomes and hormogonia as mentioned in Figure 4 caption. This material will be moved to the Results and Discussion section anddiscussed in more detail there. The appearance of these structures in the scanning electron microscope is different than seen in optical microscopy of living cells or as is sometimes possible in thin sections of fossilized remains. I will also include references to the work of Manuel Garcia-Ruiz on abiotic structures reported to exhibit the morphology of filamentous microorganisms and the fibrous kerites studied by Academician Yushkin. I have yet to see a case where the abiotic microstructures prepared by chemical precipitates (and considered by to represent excellent biomimics) could actually deceive a trained microbiologist into thinking that they were genuine microorganisms. For this reason that it is extremely important that biomorphic microstructures should be carefully examined by specialists who have detailed knowledge of the size, size range, morphology, reproductive habits, ecology and appropriate consortia that make up a prokaryotic mat, microbial assemblage, community of ecosystem as well as the taphonomic and diagenetic alterations that take place during fossilization and mineralization processes. I will insert the following text at the end of line 18 of Page 44: "In an effort to detect abiotic microstructures of similar chemistry and morphology to the magnesium sulfate forms found in the Orgueil meteorite, FESEM studies were carried out on natural samples of crystalline and fibrous epsomite from Spain, the United Kingdom, New York, and from Poison Lake, Okanogan Co. Washington, USA. The morphologies, size distributions and chemical compositions of the microstructures encountered in these samples could not be confused with living microorganisms or with the mineralized remains of cyanobacteria or other filamentous prokaryotes or with the biomorphic microstructures that have been found in the carbonaceous meteorites and which are interpreted as indigenous microfossils."

Fig. 5. I agree with the referee that the EDS spectrum for the living Calothrix filament (Fig. 5.a.) should be included and will add that data as Fig. 5.d. and include appropriate text at Pg. 28, line 26. I recognize that the spectral data should also be included for the emergent trichome associated with the morphotype of the Nostocacean cyanobacterial filament shown in Fig. 4 as well as the data for the mineral matrix of the meteorite sampled only 3 μm above the trichome. Appropriate text will also be inserted in Pg. 25, Line 1.

I thank the referee for his careful review and many helpful comments that have assisted me to sharpen the focus and clarify the salient points of the paper for the reader.

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