CHAINS OF MAGNETITE CRYSTALS IN ALH84001: EVIDENCE OF BIOLOGICAL ORIGIN.

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Introduction: The presence of magnetite crystals in carbonate globules in ALH84001 was one fact leading to the suggestion that this meteorite may contain relics of Martian life [1]. These magnetite crystals are morphologically similar in shape and size to magnetosomes formed by magnetotactic bacteria, but less so to typical inorganically formed magnetite crystals [2,3]. The size range is significant, as within this range the magnetic moment of the crystals is maximal [4]. Terrestrial magnetobacteria produce magnetosomes, magnetite (Fe_3O_4) or greigite (Fe_3S_4) crystals assembled into chains, and the organisms use these chains for aligning themselves along the prevailing magnetic field [4]. No inorganic process is known to produce similar structures.

Methods and Results: We found numerous such chains composed of magnetite crystals in the Martian meteorite ALH84001 (Figs. A-E) by high-magnification scanning electron microscopy operating in the backscattered electron detection mode (SEM-BSE), a method that permits imaging of structures embedded in the rock substrate [5]. SEM-BSE images depict chemical compositions, not surface morphologies. BS electrons originate not from the sample surface but from below it: Calculations show that in our material, features can be imaged to a depth of about 400-1000 nm. BSE images are fuzzy because of scattering of BS electrons. Atomic number is positively correlated with brightness, which is also affected by, e.g., the atomic number of the substances below and above, so single magnetite crystals may appear in different shades of grey. Only chains lying approximately parallel to the image plane will be clearly visible as such. Those oriented obliquely will appear foreshortened, and the individual crystals will not be resolved. Similarly, crystals lying below or above the chain will appear superimposed, resulting in a stronger, blurred signal, as seen in Fig. B. We examined fine polished rock surfaces coated with 10 nm C. Elemental composition was identified by energy dispersive X-ray spectroscopy (EDS) microanalysis and by Auger Electron Spectroscopy (AES) with a 60 nm beam.

Figs. A and B show chains from pancake carbonate globules. Fig. C, from a small irregular carbonate globule embedded in orthopyroxene, shows on the left a cluster of magnetite crystals, probably a mixture of single crystals and chains, and a chain of 7 or 8 crystals on the right. Figs. D and E show chains from a small, irregular carbonate globule embedded in plagioclase glass, from the area marked by arrow in Fig. F. The chain in Fig. E appears to comprise about 15, perhaps more, larger magnetite crystals. The chains in Figs. C and E illustrate the approximate total size range of crystals. Their exact shape and size were studied by the method of [3]: cleaning with acetic acid and examination of the residue by TEM equipped with EDS microanalytical system. We confirmed the results [3] that the magnetite crystals are mostly paralellepipedal and, less frequently, bullet- or irregularly shaped, with a size range of 30-90 nm in length and 20-50 in width. This range of morphologies and sizes agrees well with those occurring in terrestrial magnetotactic bacteria. The magnetite crystals in the chain in Fig. E. are larger, >200 nm. The frequency of magnetite crystal chains of different lengths (4 crystals or more) in ALH84001 shows a non-Gaussian distribution, and a negative exponential relationship between the number of chains and the number of magnetite crystals per chain. This pattern suggests that the chains are disrupted fragments of originally longer magnetosome chains of magnetotactic bacteria.

Our findings also help with the interpretation of the small microfossil-like structures in ALH84001 [1]. Studies with atomic force microscopy [6] have shown that these structures are segmented and morphologically similar to the magnetite crystal chains described here. We suggest they are identical.

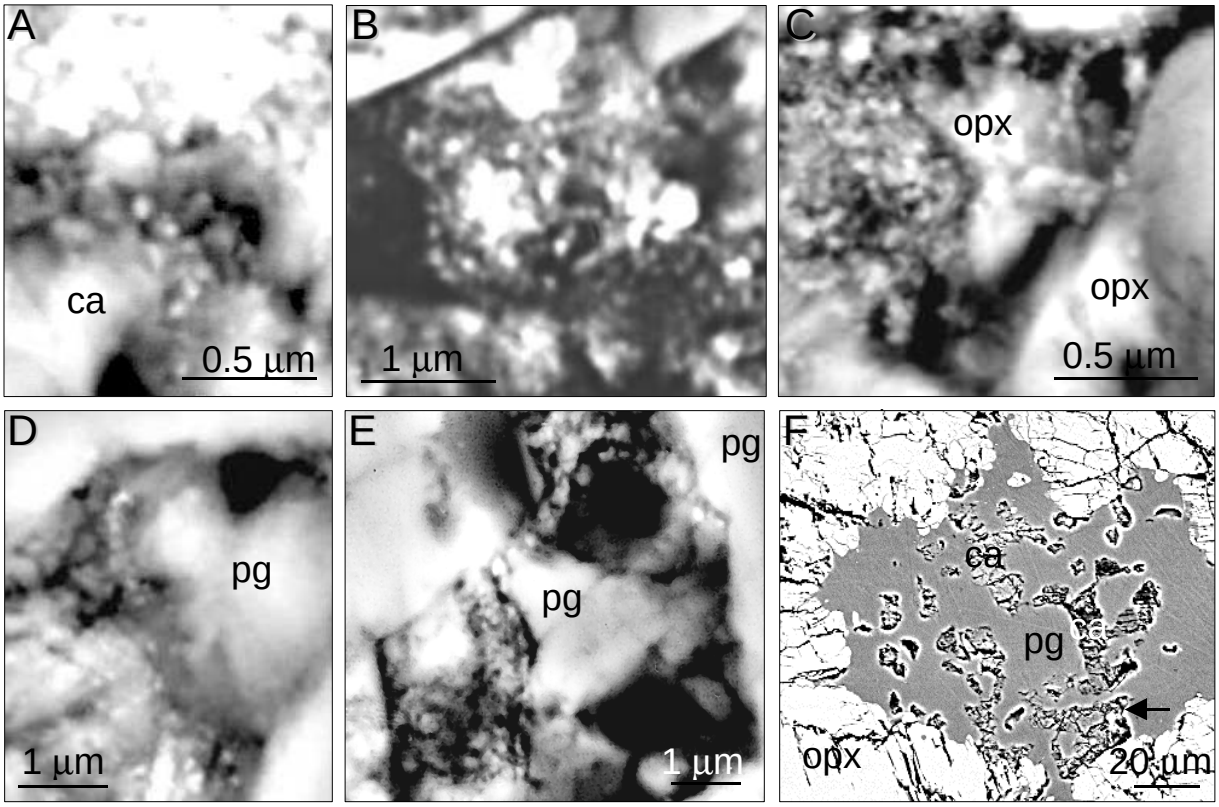
Although conditions favorable for microbial growth have been shown to exist in meteorites lying on the Antarctic ice sheet [7], contamination with terrestrial magnetobacteria in ALH84001 can be ruled out: (1) The Martian origin of the carbonate globules is not in doubt, (2) several carbonate grains containing magnetite crystal chains were enclosed in plagioclase glass (Fig. F), and (3) the insides of fragments of

ALH84001 kept in uranyl acetate solution under vacuum remained free of uranyl contamination.

Conclusion: We suggest the following scenario: Decomposed remains of dead Martian magnetobacteria, possibly suspended in a carbonate-rich fluid, penetrated fissures of ALH84001, already crushed by previous meteorite impact, perhaps after the second impact event (I2) postulated [8]. Single magnetite crystals and chain fragments were deposited in carbonate globules. Finally, the rock suffered additional impacts [8] resulting in melting, geochemical and morphological transformations, and displacement of mineral components.

All known magnetobacteria are microaerophilic or at least facultative anaerobes, and it has been proposed [9] that they evolved on Earth at the time when partial pressure of atmospheric oxygen began to increase. It has also been suggested that, if Earth-like life ever appeared on the surface, then such conditions should have existed on early Mars [10]. Our findings seem to support this suggestion.

References. [1] McKay D. S. et al. (1996) *Science*, *273*, 924. [2] Thomas-Keprta K. L. et al. (1997) *Lun. Planet. Sci.*, *28*, 1433. Golden D. C. et al. (1997) *Ibid.* 1675. [3] Thomas-Keprta K. L. et al. (1998) *Ibid.*, *29*, 1494. [4] Bazylinski D. A. and Moskowitz B. M. (1997) *Rev. Mineral.*, *35*, 181. [5] Wierzchos J. and Ascaso C. (1994) *J. Microsc.*, *175*, 54 [6] Steele A et al. (1998) *J. Microsc.*, *189*, 2. [7] Friedmann E. I., McKay C. P., McKay D. S., Harvey R. P. and Mittlefehldt D. W.: personal communication. [8] Treiman A. H. (in press) *Meteor. Planet. Sci.* [9] Chang S. R. and Kirschvink J. S. (1989) *Ann. Rev. Earth Planet. Sci.*, *17*, 169. [10] Hartman H. and McKay C. P. (1995) *Planet. Space Sci*., *43*, 123; McKay C. P. in *Chemical Evolution: Physics of the Origin and Evolution of Life*, Chela-Flores J. and Raulin F., Eds. (Kluwer, 1995), pp. 177-184.



Figs. A-F: Backscattered electron (BSE) images of magnetite crystal chains in ALH84001. **A, B**: Chains in pancake carbonate. **C-E**: chains in small irregular carbonate globules. **D** and **E** are from the area indicated by arrow in **Fig. F**. ca = carbonate, opx = orthopyroxene, pg = plagioclase glass. Further explanation in text.