CHAINS OF MAGNETITE CRYSTALS IN THE METEORITE ALH84001:EVIDENCE OF BIOLOICAL ORIGIN.
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Introduction: The suggestion [1] that the Martian meteorite ALH84001 contains relics of early life was based, in part, on the presence of magnetite crystals in carbonate globules. Thomas-Keprta et al. [2] proposed that the magnetite crystals are magnetofossils and suggested that the simultaneous presence of six characteristics, i.e. a definite size range and width/length ratio, chemical purity, crystallographic perfection, unusual crystal morphology, elongation of crystals in the [111] crystallographic direction and the arrangement of crystals in linear chains, should constitute evidence of biological origin. These authors demonstrated the presence of the first five characteristics but not of the sixth, the chains of magnetite crystals.

By using high power backscattered scanning electron microscopy (SEM-BSE) in the stereo mode, we were able to picture the *in situ* spatial orientation of magnetite crystals and chains in the carbonate globules in a non-intrusive way through the intact surface.. While in conventional SEM (SEM-SE) images of surface structures are formed by reflected secondary electrons, SEM-BSE uses backscattered electrons which originate *below* the surface. SEM-BSE does not record surface morphologies but chemical compositions, as structures composed of heavier elements appear brighter than lighter ones.

Terrestrial magnetotactic bacteria form magnetosomes, single-domain crystals of magnetite or greigite, surrounded by a biological membrane. The magnetosomes are arranged in linear chains, held together by organic material, and orient the bacteria along the prevailing magnetic field lines. This enables the bacteria to find and maintain optimal position along a vertical oxygen concentration in an oxic-anoxic transition zone which is characteristic of their environment [3].

The formation of magnetite crystals in a definite (single-domain) size range and their arrangement in linear chains is in itself a conspicuous example of genetically controlled biomineralization (magnetite chains are energetically unstable.[4]). No inorganic process is known to produce such structures. We established five further criteria, listed below, which are present in magnetite chains of bacteria but not in chains which could be formed abiotically, like in a strong magnetic field, by crystals concentrated on grain boundaries or by being accidentally positioned in narrow channels in the rock substrate. (1) *Uniform crystal size and shape within chains.* Despite considerable range of variation within a bacterial species [2], the crystals within individual chains are of similar size and shape (isodiametric or elongated). No abiotic process would result in such sorting of crystals from a mixed pool of sizes and shapes (*2).Gaps between crystals.* Crystals in chains are separated by gaps due to the biological membrane bounding the magnetosomes and the organic substance between them. In non-biological chains the crystals would abut without gaps. (*3). Orientation of elongated crystals.* In chains of elongated magnetosomes, the crystals are oriented with the long axis along the chain, an energetically unstable configuration. (*4). Halo around chains.* Fossilized traces of the biological membrane surrounding magnetosomes should be detectable as a thin halo. (*5). Flexibility of chains.* Magnetosome chains in dead bacteria are known to undergo, under mechanical stress, strong but smooth bends due to the elastic property of the organic substance between them [5]. This would be impossible in non-biologically-formed chains because no inorganic (mineral) substance occurring in nature is known to have a high modulus of elasticity.

Methods: We used backscattered scanning electron microscopy at high magnification and in stereo mode, both with embedded, sectioned and polished specimens as well as with freshly fractured ones, in the latter case imaging through the intact surface. This method made possible the *in situ* direct visualization of the spatial arrangement of nanometer size magnetite crystals and their chains, up to ca 1000 nm deep under the intact surface of carbonate globules. These stereomicrographs can be viewed in high quality prints with a stereo viewer, or on projected anaglyphic transparencies with a red/green eyeglass.

Results: In the rim region of carbonate globules, scattered or more-or-less dense clusters of magnetite crystals are present, among them numerous chains of different lengths. The presence of all five morphological features characteristic of biologically produced chains could be verified. Comparison of the SEM image of the surface of carbonate globules, and the SEM-BSE image which shows structures below the surface,

reveals that the entire area is covered by a low-electron-density (i.e. low atomic number) substance (LEDS) of unknown chemical composition. Most magnetite chains and single crystals are surrounded, at least partly, by LEDS and in the stereo images they often appear as though floating in the electron transparent LEDS. Other magnetite crystals and chains are embedded in large carbonate crystals.

No analytical method exists for SEM-BSE that would have sufficient resolution to determine the exact chemical composition of single nanometer-size particles, except that they contain a heavy element. We suggest, however, that the evidence listed below is strong, if not conclusive, that the electron-dense particles in the carbonate globules are crystals of magnetite: (a) It was demonstrated [2] that the Fe-rich rim of carbonate globules contain a large number of magnetite crystals of similar size range. (b) After dissolution of the carbonate in acetic acid, magnetite crystals are the only structures in the residue. (c) The chains show the morphological characteristics of magnetosome chains of bacteria. (d) Two microanalytical techniques, energy dispersive X-ray spectrometry and Auger electron microscopy have shown a good correlation between chains or clusters of particles and Fe- and O- content.

Syngeneticity of the magnetite crystals is evident from sectioned specimens where lobes of carbonate, containing chains, are embedded in plagioclas glass and orthopyroxene.

The frequency of magnetite crystal chains of different lengths shows a non-Gaussian distributioon, and a negative exponential relationship between the number of chains and the number of crystals per chain.

Conclusions: We conclude that the chains in ALH84001 are magnetofossils, remnants of magnetotactic bacteria. No other consistent interpretation would account for our observations. Yet it appears, that such organisms were never alive in ALH84001. All known magnetotactic bacteria are motile while all known endolithic microorganisms are sessile, attached to the substrate: swimming in microscopic crack of rocks would be impossible. Furthermore, the non-Gaussian frequency distribution of the number of crystals in chains is incompatible with the variability of chain lengths in a living population. We suggest the following scenario: Decomposed remains of dead magnetotactic bacteria suspended in a carbonate-rich fluid penetrated fissures of ALH84001, already crushed by asteroid impact, perhaps after the second impact event (I2) postulated [6]. Evaporation of the liquid lead to the deposition of the pancake-shaped carbonate globules which included the magnetite crystals and chain fragments.

References. [1] McKay D. S. et al. (1996) *Science, 273,*924-930. [2] Thomas-Keprta K. L. et al. (2000) *Geochim. Cosmochim. Acta, 64,* 4049-4081. [3] Bazylinski D.A. and Moskowitz B.M. (1997) *Rev. Mineral., 35,* 181-223. [4] Kirschvink J. L. (1982) *Earth Planet. Sci. Lett. 59,* 388-392. [5] Shcherbakov V.P. et al.(1997) *Eur. Biophys. J. 26,*319-326. [6] Treiman A. H. (1998) *Meteor. Planet. Sci. 33,*827-829.