CRITERIA FOR THE IDENTIFICATION OF BACTERIAL MAGNETO-FOSSILS ON EARTH OR MARS.

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One of the several lines of evidence used by McKay et al.[1] to argue for the presence of fossil life in the Martian meteorite ALH84001 was the morphologic similarity between ferrimagnetic minerals within the carbonate blebs and terrestrial magnetofossils. Several authors have erroneously cited the presence of crystal twins, elongate needles, spiral screw dislocations, and apparent epitactic relationships to argue against a biological origin of these particles[2,3]. As all of these features have either been observed in biological minerals on Earth[4-7] or have a trivial explanation like epitactic settling, they cannot be used to rule out a biological origin on Mars. Hence, it is important to review here the biologically distinctive criteria for recognizing magnetofossils produced by magnetotactic bacteria; these can serve as a basis for assessing claims for the biological origin of magnetite in ALH84001.

At least five distinctive features of the magnetite crystals in the magnetotactic bacteria have been identified which are the direct end result of natural (Darwinian) selection to improve their magnetic properties. As magnetotaxis is important to the survival of these organisms[8], natural selection will favor evolutionary innovations which increase the net magnetic moment per iron atom. Five features recognized so far are as follows:

I. Bacterial magnetosomes are always confined in size and shape such that they are single magnetic domains, as shown on Fig. 1 here. Natural selection for magnetotaxis will eliminate mutations yielding superparamagnetic or multi-domain crystals. All tests of the magnetosome crystals from living magnetotactic bacteria, done by comparing the physical size and shape requirements for single-domain behavior[9] with the measured size and shape of the magnetosome crystals, have confirmed this relationship. This narrow size and shape distribution of biological magnetites is a direct result of their growth within a lipid-bilayer vacuole termed the magnetosome membrane.

II. High-resolution TEM studies of the magnetite crystals formed by the magnetotactic bacteria show that they are extraordinarily free of internal crystal defects, with the minor exception of an occasional twin across the {111} plane[4,5,10]. This crystal perfection acts to increase the net magnetic moment of the particle by eliminating lattice

defects which would warp the internal demagnetizing field. The {111} twin planes tend to be perpendicular to the particle length and magnetization direction, so have no

Figure 1.
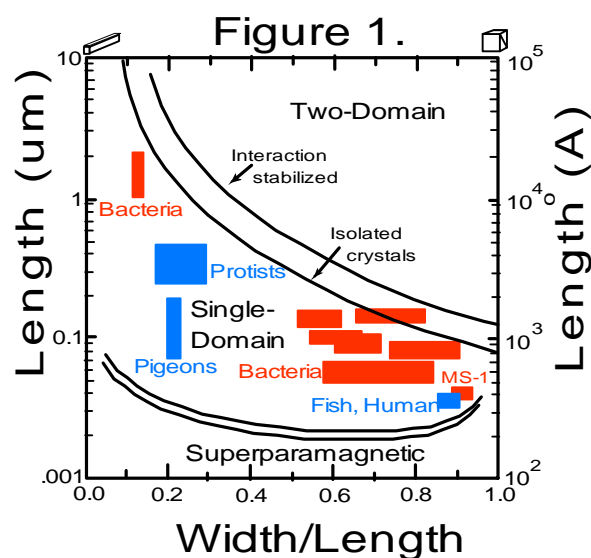
effect on their magnetization efficiency, and would not be eliminated by natural selection. In contrast, magnetite induced to crystallize extracellularly by dissimilatory iron-reducing bacteria is defect-rich, and has a wide dispersion in particle sizes[11]; these particles are not used for their magnetic properties. Spiral screw dislocations have not yet been seen (or searched for) in biogenic magnetites, as has been reported in some of the ALH84001 whiskers[2], although magnetotactic bacteria with similarly shaped particles have been seen[5] and screw dislocations are present in other known biominerals[7].

III. Virtually all magnetotactic organisms arrange their magnetite crystals into linear chains, which maximizes the total magnetic moment of the cell. However, this linear arrangement is dynamically unstable; the magnetostatic potential energy difference (ΔE) between a typical straight bacterial magnetosome chain and that of a clump of crystals is typically on the order of 10^3 kT. The magnetostatic binding energies are so large compared with that of Brownian motion (~ kT) that it is virtually impossible in nature to get organized chain structures to form spontaneously from an assemblage of crystals (p ~ $e^{-\Delta E/kT}$, and e^{-1000} is very small). In the bacteria, new magnetosomes are formed directly at the end of an

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existing chain and anchored in place, avoiding this problem.

IV. Magnetite crystals within these magnetosome chains are typically aligned such that their [111] crystal axes are parallel to the chain length, and most of the crystal types are elongated (stretched) in the [111] or close directions [4,5,10,12]. This is a result of genetic control, as the crystals produced within an individual cell are almost always of the same size and shape. Elongation of the magnetic crystals also introduces a shape anisotropy, which forces the magnetic moment of the crystal to lie parallel to the long axis. Similarly, alignment of the [111] crystal direction with the long axis yields about 3% higher magnetic moment for the particle than would be had if the [100] axis were elongated. This exploitation of the magnetic shape and crystallographic anisotropy energies to maximize the moment of the particles is a clear result of natural selection for magnetotaxis.

V. Many bacterial magnetites have a biologically distinctive feature which relates to the presence of crystallographically equivalent faces with gross differences in morphology[12]. Wulf's theorem on the equilibrium form of crystals indicates that particles below a few microns in size should obtain the equant, equilibrium forms on a short time scale[13]. Chemically equivalent crystal faces should have the same size and shape, such as the bacterial magnetosome morphologies shown on Fig. 2A &B (from[12]). However, the centrosymmetric hexagonal prisms often found in vibroid and coccoid cells (Fig. 2C) have three sets of small {110} and equivalent pentagonal faces near each end of the crystals, and the six elongate hexagonal faces which run the length of the particle are also {011} equivalents. Similarly, the elongated cubo-octahedral morphology (Fig. 2C from wild-type cells) has two sets of equivalent faces, including two square {100} faces near each end and two elongate rectangular {100} faces on the sides, and similar hexagonal and elongated hexagonal expressions of the {111} faces. These unusual shapes imply that something has blocked diffusion of ions to the elongate faces relative to those at the ends. In the magnetotactic bacteria this control turns out to be the shape of the magnetosome membrane vesicle itself [12], which physically inhibits diffusion of ions to the central portion of the growing crystallites once they have reached the desired width.

All five of these criteria have been used successfully to identify unequivocally the fossil remnants of bacterial magnetosomes (magnetofossils) in the sedimentary rock record here on Earth (for a review see[14]). Identification of these features in

magnetite from ALH84001 could greatly strengthen arguments for ancient life on Mars.

Figure 2.
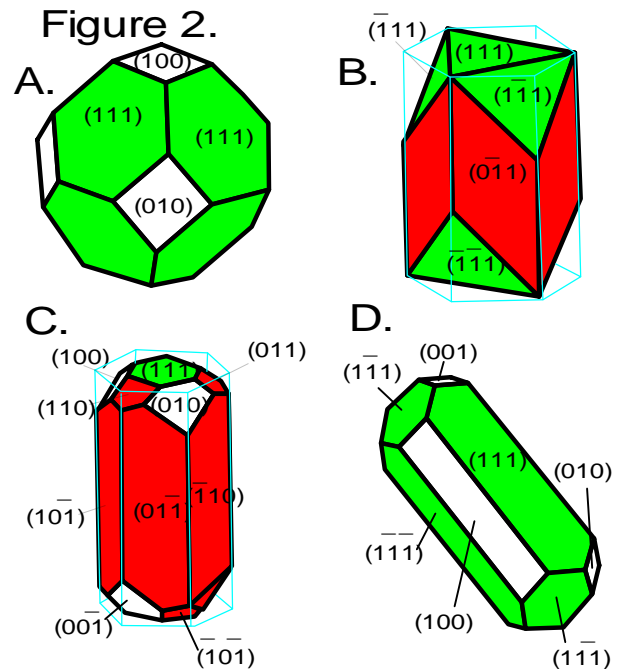
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