Magnetotactic bacteria, magnetofossils and the antiquity of life

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The 4.5-Ga-old Martian meteorite ALH84001 houses 3.9–4.1-Ga-old magnetite nanocrystals, the likes of which in terrestrial environments are secreted by magnetotactic bacteria, that points to the evolution of a microbial biosphere on early Mars. Life appeared on earth around 4 Ga ago, while fossil evidence and chemical biomarkers confirm life's firm footing on the planet by 3.5 Ga ago. The biogenicity of these magnetite particles is contentious, but if they prove to be bonafide magnetofossils, they would predate the earliest microfossil life on earth by well over 500 Ma. The veracity of this amazing discovery should, however, await confirmation by future explorations, perhaps with the Mars sample return mission scheduled for 2013 and the proposed astrobiology field laboratory becoming operational by 2016.

THE origin of life remains one of the greatest enigmas in science; but equally enigmatic is the question of whether life exists elsewhere in the infinite universe. We have been posing this question ever since we began gazing at the skies and understood that planet earth is one among the myriads of heavenly bodies dotting the sky. Though we do not yet have a positive answer to this question, we continue to explore the outbacks of the universe for signs of life because the basic ingredients of life are omnipresent in the universe that gives us the hope that it would have evolved elsewhere too, lurking to be detected. From our knowledge of life on earth, though the sole sample representing the whole universe, one thing appears to be certain: if at all life exists anywhere else it must be based on carbon chemistry, as carbon is the chemical basis of all terrestrial life[1]. Besides, carbon is the only element known to polymerize and give rise to biopolymers like proteins and nucleic acids required not only for the metabolic functions of life but also for the storage of genetic information. Without such biopolymers life would be non-existent; it can neither function nor perpetuate.

Our entire search for extraterrestrial life has till now been disappointing. A major impediment arises out of the confusion of what to search for[1,2], because we know only of DNA–protein-based terrestrial type of life and life based on non-DNA molecules is unfamiliar to us[3]. The possibility of life based on 'silicon biochemistry' and 'ammonochemistry' on a cosmic scale has been recently hypothesized[4]. Should such life exist in extraterrestrial environments, our search is bound to be misleading because we simply cannot recognize them[2]. In the absence of direct evidence of life beyond earth, meteorites are our obvious targets to look for indications of outside life, as they are extraterrestrial samples, either ejected from other planets or stray fragments from the asteroid belt. Among the many meteorite types known[5], carbonaceous chondrites are significant from the exobiological point of view, since they contain a variety of indigenous carbon compounds such as aliphatic and aromatic hydrocarbons, amino acids, carboxylic acids, alcohols, aldehydes, ketones, sugars, etc. among them fullerenes and diamonds[5], some of which could be the products of bioorganic synthesis. No wonder carbonaceous chondrites are the most studied for signs of life beyond earth. However, available evidence based on amino acid stereochemistry and stable carbon and nitrogen isotope ratios confirms that these meteoritic hydrocarbon molecules are non-biogenic[6], perhaps representing chemical evolution predating the origin of life. Another group called the SNC (shergottites, naklites, chassignites) meteorites has attracted the attention of cosmogeochemists, because these meteorites are considered to be of Martian origin and could possibly enclose signatures of life, if at all life has ever evolved on Mars. Unfortunately, despite unprecedented research, astrobiology (exobiology), a converging discipline of geology, palaeontology, biology, astronomy, chemistry and physics will remain a field of scientific speculation till the time we detect alien life.

Until recently, only fossils in rock strata constituted unequivocal evidence of past life. These fossils, by and large, are exoskeletons composed of certain minerals precipitated by multicellular organisms that appeared in explosive abundance in the early Cambrian period, while the Precambrian fossil record is mostly ambiguous. Efforts by biochemists, palaeontologists and geneticists have made it possible today to detect and characterize a large variety of organic molecules in sediments, directly or indirectly related to life. Developments in high precision analytical techniques facilitate analysis of traces of organic compounds and stable isotopes ascribable to life process even

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in some of the oldest sedimentary rocks on earth[7–10], greatly supplementing fossil evidence. These chemical biomarkers or molecular fossils as they are called, besides extending the record of life on earth abysmally deep in time, provide new lines of evidence to look for life's presence elsewhere in the universe too.

The idea that magnetite could be employed to identify past biogenic activity evolved with the discovery by Heinz Lowensten, of magnetite biomineralization in the teeth of chitons[11]. Although biogenic magnetites were known since the early seventies, their ultrafine size posed great problems in their identification and separation from sediments. Subsequently, Kirschvink and Lowenstam[12] demonstrated that biogenic magnetite contributes substantially to palaeomagnetism of marine sediments. However, it was Kirschvink and Chang[13] who first reported biogenic magnetites in marine sediments and coined the term magnetofossils to designate them. Later work made it clear that bacterial magnetite is distributed widely in deep-sea sediments dating from about 2 Ga[14]; but its use as a marker of biological activity, constituting yet another line of evidence to trace the antiquity of life, is fairly recent[15].

Two recent developments have made our quest for extraterrestrial life more tantalizing: one is the burgeoning evidence that life can metabolize in extreme environments hitherto considered forbidding. These extremophiles[16–18], as life adapted to extreme environments is dubbed, proliferate in a plethora of extreme habitats, some of which range from the boiling point of water to the sub-zero temperatures that characterize the most isolated ecosystems on earth, such as the sub-glacial lakes and Dry Valleys of Antarctica[19–22]. The second is the startling discovery by NASA scientists[15] of suspected microbial fossil markings in a purported Mars-originating meteorite and the identification of ultrafine magnetite crystals in the same meteorite[15], which in the terrestrial environments are synthesized only by certain strains of bacteria called magnetotactic bacteria (MTB). This finding is taken as concrete evidence for the likely evolution of MTB on Mars and by inference that the planet once supported life. No terrestrial rock has been subjected to such an intense study as the meteorite in question following this discovery. The discovery also opened a Pandora's box among the scientific community all over the world and triggered unprecedented research in the field of astrobiology, more so because Mars is a potential target to search for extraterrestrial life in view of growing evidence that the planet's early habitats were more congenial for the evolution of life.

Biomineralization

Several organisms secrete minerals either inside or outside their cells, a process called biomineralization that is well known in the organic world. Biomineralization commenced in profusion, as a protective shield against predation, with the explosive radiation of metazoan life in the early Cambrian, 530 million years ago[23]. Calcite, aragonite, opal and apatite are the chief biominerals. Though biochemically precipitated magnetite was described by Lowenstam[11], and Kirschvink and Lowerstam[12] as capping material in the teeth of chitons, bacterial magnetite biomineralization came to light[24] only in 1979 following the discovery of MTB[25–27] in 1975. Subsequently, magnetite biomineral was identified in 2-Ga-old sediments from Canada[14], these being the oldest rocks yet known housing biogenic magnetite. This discovery confirmed that although the major event of biomineralization began with the Cambrian radiation of life, magnetite biomineralization predates Cambrian explosion by 1500 million years!

Biomineralization is either biologically induced (BIM) or biologically controlled (BCM). In the former, the mineral is secreted outside the cells as a by-product of metabolism and the organism does not exert much control on the mineralization. Iron-reducing bacteria, for instance, excrete ferrous iron that can oxidize to deposit magnetite in the vicinity. On the other hand, in BCM the mineral is secreted within the cells and the organism exerts tight control on the size, shape, composition and morphology of the crystals. Biologically controlled magnetite mineralization is now known to be ubiquitous, occurring in as diverse organisms as salmon, butterflies, shrimps, barnacles, bats, rodents, bacteria and humans[28].

Magnetotactic bacteria

Magnetotactic bacteria (Figure 1) are prokaryotic, Gram-negative bacteria that synthesize nanometre-size (nm; billionth of a metre), membrane-bound magnetic iron oxide (magnetite, Fe_3O_4) or iron sulphide (greigite, Fe_3S_4)[29]. They are motile, aquatic microbes populating the oxic-to-anoxic-transition-zone (OATZ) of water column, where the oxygen concentration is neither too high nor too low. The organism utilizes the magnetic properties of magnetite or greigite to navigate in the earth's magnetitc field to reach the levels of right oxygen concentration in stratified water columns. The magnetites or greigites are arranged in linear

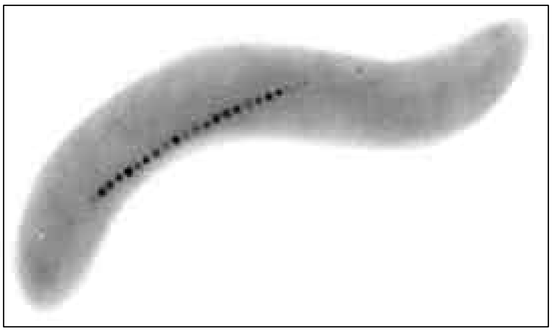

Figure 1. Electron photomicrograph of MTB species *M. magnetotacticum* showing magnetosome chains. Average size of magnetite grains is 45 nm (reproduced with permission from ref. 41).

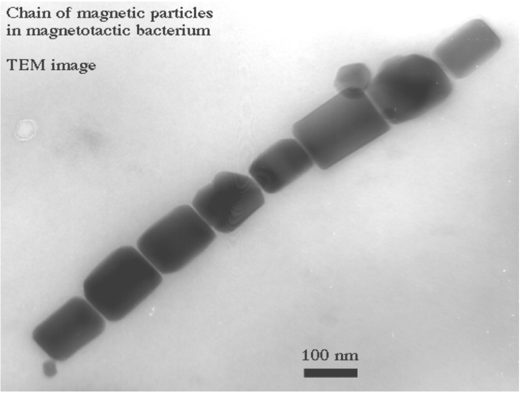

Figure 2. TEM image of magnetite chains in the magnetosome of MTB (courtesy: www.biophysics.uwa.edu.au).

chains (Figure 2) within the cell, that act as tiny magnetic compass needles; MTB are thus veritable-living lodestones dwelling in the northern and southern hemispheres (north-seeking and south-seeking MTB), besides the equatorial waters. Single-domain magnetite was discovered in MTB cells by Frankel *et al.*[24].

MTB were discovered quite accidentally by Richard Blakemore[26]. He was examining certain mud under the microscope and to his astonishment, observed that some bacteria in the mud always moved from south to north. The phenomenon was subsequently named by him as magnetotaxis, a kind of magnetic navigation by organisms. Blakemore's was a momentous discovery that opened the floodgates of research in fields as diverse as genetics, mineralogy, astrobiology and planetary evolution of Mars.

Membrane-bound crystals of magnetite or greigite within living MTB are called magnetosomes that enable the bacteria to orient and migrate along geomagnetic field lines. All MTB contain magnetosomes enclosed within organic membranes. Those from marine, sulphidic environments generally synthesize greigite magnetosomes, while freshwater MTB have magnetite magnetosomes. Magnetite particles in magnetosomes are oriented along $\langle 111 \rangle$ crystallographic axis while greigite particles are oriented along $\langle 100 \rangle$ axis. Few species of MTB have been isolated and studied in detail; the only valid species described belongs to the genus *Magnetospirillum*, and all that we know of MTB derives from isolation and mass culture experiments of species from this genus. After the death of the organism, the magnetite particles settle through the ambient water column forming part of the bottom sediments; such magnetites in sediments, which are of biogenic parentage, are called magnetofossils[13]. Magnetofossils are now considered to contribute solely to the natural remanent magnetism (NRM) of marine sediments, a property utilized extensively for palaeomagnetic studies[27] to understand the epochs of palaeomagnetic polarity reversals.

Biogenic magnetites

Thomas Keprta *et al.*[30] identified six properties of biogenic magnetites, all of which are restricted to the organic realm. These six properties called magnetite assay for biogenesis (MAB)[30], have been considered to constitute robust biosignatures. They are enumerated below:

Size and shape

Biogenic magnetite grains fall in a restricted size ranging from 35 to 120 nm, with a restricted width to length ratio. This size range is typically that which is required for stable single domain magnetization within which the magnetic moment is uniformly distributed[31]. Below this range the grains become superparamagnetic, while above this size the magnetic moment becomes multi-domain that tends to annul the resultant dipole moments. Magnetite crystals outside this size do not hold any stable dipole moment and such grains are of no use to the organism.

Chemical purity

Magnetite so abundant in igneous and metamorphic rocks often has impurities like Cr, Ti, Mn and Al occurring within the crystal lattice of the mineral. However, biogenic magnetites are chemically pure stoichiometric crystals almost devoid of trace-element impurities. Mass-culture studies on strain MV-1 in medium containing many trace elements confirm that the bacteria do not permit entry of these elements into the magnetosome structure. Impurities tend to reduce the magnetic moment of the grains and so the organism effectively eliminates them as the crystal grows.

Lack of crystallographic defects

Magnetites of the mineral world invariably exhibit lattice defects such as slippages and twinning. Biogenic magnetite crystals are almost devoid of such defects, as lattice deformities tend to reduce the magnetic moment of the particle.

Unusual crystal morphology

Magnetite is a cubic mineral, but biogenic magnetites often defy cubic symmetry. They display various sizes and shapes but the combination of octahedral, dodecahedral and cubical faces with elongation along the octahedral axis produces an unusual morphology, designated as truncated hexa-octahedral[32]. Such morphology is unknown among magnetites of inorganic origin.

Elongation in (111) axis

Magnetite particles in the magnetosome invariably display crystallographic elongation along octahedral (111) direction. No magnetites of igneous or metamorphic rocks show this character.

Magnetosome chains

The magnetosomes in MTB are arranged in linear chains within the cell. Such an arrangement facilitates the organism to acquire a strong magnetic moment, which is the vector sum of the moments of the individual magnetosome.

The above characteristics are believed to be the outcome of natural selection over eons of evolution during which the organism has eliminated disadvantageous variations, optimizing them for its best use.

Martian meteorite ALH84001

Well over 22,000 meteorites have been characterized on the earth so far. Of these, roughly 20 have been recognized as of Martian source. These are SNC meteorites that have gaseous inclusions with nitrogen and noble gas isotopic ratios close to those of the present atmosphere of Mars[33,34], and therefore are believed to have originated from Mars during early events of heavy planetesimal and cometary impacts of the inner planets of the solar system. After ejection, these meteorites spend short sojourns in interplanetary space before being captured by the earth’s gravitational field. Bombardment of the meteorites with cosmic rays produces various short-lived radioisotopes that facilitate measurement of the time that the meteorite spent in interplanetary space.

ALH84001, petrologically an orthopyroxenite[15], belongs to the group of SNC meteorites and was recovered from the Allan Hills glacier of Antarctica in 1984. It has Rb/Sr isotopic age of 4.5 Ga and was ejected later from Mars as a result of an impact with an asteroid. The meteorite had a 16 Ma residence in interplanetary space before entering the earth’s gravitational field 13,000 years ago, and finally landing in Antarctic ice sheet. The meteorite weighs roughly 2 kg and has, besides the usual silicate mineral phases, secondary carbonate minerals filling fractures[15]. These carbonates have Rb/Sr isotopic ages of 3.90 ± 0.04 Ga that suggests formation of the carbonates while the meteorite was still part of the Martian crust.

Magnetite nanocrystals in ALH84001

In the highly oxidizing terrestrial environment, the mineral magnetite rapidly alters to haematite and maghemite. However, despite almost 13000 years of residence in Antarctica, the magnetite particles in ALH84001 do not exhibit any sign of oxidation as the grains were totally enclosed within carbonate globules when the meteorite was part of Martian crust[15] and thus had no opportunity to get exposed to terrestrial weathering. Thomas Keprta *et al.*[30] applied the MAB criteria mentioned above to the magnetite crystals recovered from ALH84001 and confirmed that approximately one-fourth of the magnetite particles in the meteorite are truncated hexa–octahedral and are chemically and physically indistinguishable from those produced by the magnetobacterial strain MV-1. These magnetites are also reported to share five of the six characters of biogenic magnetites enumerated above. These authors[30] are thus credited to have identified the magnetite minerals of the Martian meteorite as magnetofossils. The remaining three-fourths of the magnetite populations in the meteorites are unlike the rest, resembling terrestrial inorganic magnetites.

Do magnetofossils in ALH84001 provide evidence of life on Mars?

Do the magnetite nano crystals in ALH84001 represent veritable magnetofossils pointing to evolution of MTB on Mars? The magnetites in bacteria and meteorites are submicron size particles requiring special techniques such as transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) for characterization of their morphology; a daunting task considering their particle size. This exactly is the opinion of Busek *et al.*[35] who, based on holographic and tomographic methods in TEM, concluded that the detailed morphologies of bacterial magnetites differ considerably from those of the Martian meteorite, and the evidence is inadequate to support the hypothesis that life once existed on Mars. An intriguing fact that is baffling scientists is the failure of the ferrite industry to synthesize ultrapure, single-domain magnetites (with applications in the computer industry) by inorganic means, despite decades of research, confirming that bacterial magnetites defy replication in the laboratory.

The biogenic origin of ALH84001 magnetite, nevertheless, has been questioned by several researchers[36,37] based on laboratory evidence for the synthesis of magnetite by thermal dissociation of siderite above 450°C, implying that the heat of impact could decompose meteoritic siderite to magnetite. The presence of minute specks of a mineral called periclase (MgO, formed similarly by the dissociation of Mg-carbonates in the meteorite) in ALH84001 is taken as supportive evidence for decomposition synthesis of minerals during impact heating. However, substantial support for the biogenic origin of magnetite comes from palaeomagnetic data[38,39] of ALH84001, which confirm that the carbonate globules in the meteorite were never heated beyond 80°C, negating the possibility of magnetite production by impact dissociation of siderite.

Ribosomal RNA (rRNA) sequencing data of extant MTB show that they do not occupy any deeply branching lineages in the bacterial domain of life[40–42], indicating that they are not among the ancient group of organisms to populate the earth. The oldest magnetofossils recorded on terrestrial rocks are from the 2-Ga-old Gunflint formations of Canada, and still older magnetofossils are not likely to be discovered[14]. This period marks the transition from the oxygen-free reducing environment of the early earth to a more oxygenated earth of subsequent times. With the advent of cynobacterial photosynthesis and consequent liberation of molecular oxygen, the oceans became gradually oxygenated and the dissolved iron present till then was removed by oxidation. This posed a bottleneck to microbes that had to struggle hard to meet their cellular requirement of iron, leading to evolution of special mechanisms to store iron for their biochemical necessities[14]. Some of this stored iron in the course of evolution crystallized as matrix-bound magnetites or magnetosomes. Besides, the geomagnetic field prior to about 2.8 Ga was too weak to support magnetotaxis[43]. Obviously, the environments on earth prior to 2 Ga ago were not permissive for the evolution of MTB, while early conditions in Mars were more hospitable for microbes such as MTB to originate and proliferate[44].

Current understanding postulates that the evolution of MTB on Mars is subject to satisfying three basic requirements, namely a chemical environment characterized by high carbon dioxide and low oxygen, presence of standing reservoirs of water and prevalence of a strong magnetic field.

The Red Planet has been the cynosure of investigations with remotely controlled probes commencing from the Viking landing missions of the mid-seventies. Many robotic rovers have explored the planet in recent years with startling discoveries, the most exciting of which is the identification of sedimentary rocks and drainage channels on the planet[45,46], providing unequivocal evidence of a dynamic hydrosphere in the Noachian era (>3.5 Ga ago)[45], most of which was eventually lost due to runaway greenhouse warming. The planet does not hold a hydrosphere at present, although there are evidences of water ice combined with dry ice occurring in its polar regions and perhaps liquid water in subterranean environments. The recent discovery of haematite concretions[47,48] by NASA's Mars Exploration Rover 'Opportunity', and its analogy with terrestrial haematite 'blueberries'[49,50], constitutes new evidence for an early wet Mars. Besides, other minerals like phyllosilicates, carbonates and sulphates have been identified in SNC meteorites, suggesting water-mediated precipitation of these minerals.

The present thin atmosphere of Mars is dominated by CO_2, followed by N_2, Ar and O_2, with traces of CO and water vapour. There are evidences to presume that the planet had higher molecular oxygen in its early history[51], but by and large the present atmospheric composition has remained unchanged since its early history. If the past environments on Mars were mildly aerobic as it is today, it could have supported primitive life such as MTB[52]. The present Martian magnetic field is weak; however, recent Mars Global Surveyor explorations show that the planet had a strong magnetic field until about 4 Ga ago[53], sufficient to facilitate magnetotaxis.

The above discussions on the early Martian habitats lead us to the conclusion that the three fundamental requirements necessary for the evolution of MTB were present on primitive Mars. The detection of supposedly biogenic magnetite in Martian meteorite is a giant leap forward in our search for extraterrestrial life. If these were indeed magnetofossils, *sensu stricto* it would be suggestive of bacterial populations on Mars, at least when the meteorite that housed them was ejected, and by inference that the planet held a microbial biosphere in its remote past. Should these contentions prove right, we could all be ultimately Martians, though not intelligent Martians as contemplated by the Italian astronomer Giovanni Schiaparelli in 1857, popularized later by the American astronomer Christian Huygens. Judging from our current knowledge of exobiological environment, however, Martian palaeobiology falls in the realm of scientific speculations, confirmation of which should await return of the first Martian samples expected early next decade[54].

Panspermia

Many scientists like Lord Kelvin and Arrhenius[55] of the late nineteenth and early twentieth centuries had conceived of the idea of transport of viable life between planets, a hypothesis called 'panspermia'. British astronomers Fred Hoyle and Chandra Wickramasinghe[56] later popularized the theory, envisaging that life's 'seeds' are dispersed throughout the universe by bombarding comets. But one serious objection that has kept the theory in dormancy was the perception that the heat of impact would annihilate any microbe entombed within impacting comets. However, unheated interiors have been observed in some meteorite samples and palaeomagnetic data from ALH84001 reveal that it was never heated beyond the Curie point. Besides, higher fullerenes (C_{60} to C_{400}) containing trapped helium and noble gases[57] with ratios signifying extraterrestrial sources have been discovered in Allende and Murchison meteorites and also in Cretaceous–Tertiary boundary sites. These developments, besides confirming that meteorites and comets could be potential carriers of interstellar organics to be delivered to target bodies, witnessed the re-emergence of the theory of panspermia[58]; it now appears distinctly possible that microbes (or at least microbial biomarkers such as magnetofossils) could hitch-hike across planetary distances piggyback on impacting bodies[55]. If life thus really journeyed through space, it would also explain its rather early appearance on earth.

The antiquity of life on earth

The question of how long life has been flourishing here on earth is debatable. We have no direct evidence of life in the rock record of the Hadean period (3.9 to 4.6 Ga ago); in fact, sedimentary rocks themselves become increasingly scarce as we go back in time. However, gene sequencing technology is providing a new dimension to our understanding of life's ancestry: for instance, genome sequencing of representative organisms from the three domains of life[42], namely Archaea, Bacteria and Eukarya presents astonishing results that the Last Common Ancestor of all life originated 4 Ga ago[59]; nevertheless, molecular and fossil data are often mutually contradictory, attested by the confusing evidence provided by sequencing data on the timing of metazoan emergence[60]. The geological literature is replete with information on Precambrian stromatolites and microfossils[61]. Microfossils of the Warawoona Group Apex Chert[62,63] of Western Australia were considered until recently to be the oldest unambiguously recognized fossils yet known on earth dated at 3.465 Ga. Microtubular structures ascribed to borings by ancient microbenthos have been identified recently in 3.5 Ga old basalts from the Barberton Greenstone Belt of South Africa[64]. Indirect evidence for photosynthetic life dating back to 3.85 Ga has been advanced based on stable carbon isotope measurements of organic matter from the Isua supracrustal rocks of Greenland[7,65]. In recent years, stable sulphur isotopes have been used increasingly to trace the history of life on earth[66]. Sulphur isotope signatures from the ~3.47-Ga-old North Pole barite deposits of northwestern Australia provide the oldest evidence of microbial sulphate reduction on earth [66]. Available data on sulphur isotopes thus clearly demonstrate the advent of sulphate-reducing microbes by early Achaean. In addition to fossil evidence, a variety of chemical biomarkers, both organic and inorganic, have been identified in sediments that attest to life's great antiquity on earth[7,9,10]. These evidences confirm that life had established a strong foothold by 3.5 Ga ago; they are also taken to extrapolate the origin of life on earth to about 4 Ga ago and photosynthetic life to 3.85 Ga ago. Continuous life has been present on the planet ever since, albeit punctuated at different times with mass extinction events.

A resurgence of interest is currently drawing researchers from diverse fields to Archaean palaeobiology. New results question earlier findings[54]; for instance, the authenticity of the Apex Chert fossils is now hotly debated[67,68] and observational and laboratory refinements dub them as just 'pseudofossils'[68]. In a similar way, the carbon isotope evidence of graphite from Akilia sediments, Greenland is also being put under rigorous test[69–71]. New data on Akilia sediments indicate considerable extraterrestrial components, with possible meteoritic source for the observed negative carbon isotope ratios[72]. Thus the 'Early Eden Hypothesis'[68], that life appeared on earth extremely early does not seem to stand on firm grounds, although molecular techniques render unexpected support to this reasoning[59]. It is in the backdrop of these that the discovery of Martian magnetofossils is exciting; if bonafide, they would open a new window to early life, a full 500–600 Ma earlier than the earliest fossils recorded on earth assuming of course that the Apex Chert microfossils are genuine. Could the cradle of primordial life in the solar system then be Mars?

Summary

It is now generally accepted that meteorite fragments can be catapulted from planetary bodies, and stowaway microbes could be transported to far-flung planets of the solar system, if not across galactic distances. In this context, the identification of magnetofossils in Martian meteorites, besides suggesting past life on Mars, sustains the hope of the planet still harbouring microbial life. Though the fossil record is restricted to 3.5 Ga of earth history, the suspected Martian magnetofossils would extend the palaeontological record in the solar system by over half a billion years. At the same time advances in genetics are opening a new window to life's ancestry than what the fossil and chemical biomarker evidences have hitherto provided. Future Mars explorations may lead to exciting discoveries, the most astounding of which could be the detection of our companions within our own neighbourhood.

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