The contentious Archaean biosignatures

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If it looks like life, has the ecology of life, has the isotopes of life, and fits with all other evidences of life, then most likely it is life.

– J. William Schopf

Successive new discoveries in recent years have been pushing the rock record of earliest life to the first billion years of earth history, within the Palaeoarchaean (3.6–3.2 b.y.), though it is generally accepted that life on earth must have begun far earlier than what rock evidences have shown so far. Initially these discoveries were exciting, but in course of time many of them were discredited or their bona fides re-assessed, as the evidences advanced in support of their biogenicity and antiquity were becoming controversial[1]. This wave of rejections and revisions to the criteria for recognition of true life forms had come in the wake of several fresh findings from multidisciplinary investigations on a 3.9 b.y. old meteorite from Mars (ALH84001) reportedly carrying evidences for life. Also, advances in geobiology[2] and in the new branch of astrobiology, newer understanding of different types of microenvironment and sources of energy that could support the early Archaean life-forms[3,4], better perception about the deemed uniqueness of C-isotopes as indicators of life[5], inputs from inorganic synthesis of crystal-structures closely resembling microfossils[6] and advances in analytical technology particularly to study nano-morphologies[7] and fractionated isotopes have all awakened investigators to the pitfalls in relying purely on the conventional morphological clues to detect early life.

Presently, the hot debate is on the reliability of the morphological structures claimed as bioindicators of early life as these structures are found to be indistinguishable from non-biogenic or abiogenic imitations produced in nature[6,8]. Secondly, there is a strong view that earth's first billion years could not have supported life as this span was noted for heavy meteorite bombardment, intense volcanism, short-lived crusts and adverse ocean and atmospheric chemistry, all of which had given credence to the view that the reported >3.5 b.y. life forms may be natural artifacts. At the same time, recent geochemical studies indicate that earth's first billion years were not so inhospitable as made out and niches with right temperature and micro-environment, for the development of certain types of life having body chemistry with protective coating to adapt to harsh conditions, could still have existed[1]. In fact, O-isotope data of early diagenetic cherts has shown that a temperature of 55–85°C prevailed throughout the Archaean, which would have favoured the anaerobic microbes and those tolerating the highly saline and anoxic oceans of the period[4], and organisms using thermal energy, where light and chemical energies are not available, like the subsurface environments of early oceans[3]. Considering the bleak chances for the survival of rock records of life in early Archaean, known for its destructive geological recycling of rocks, it is no surprise that this period got labeled as lifeless.

Progress in studies on the origins of life on earth has always highlighted the close link of early life to the aquatic environment and this connection has narrowed down the searches for their fossils to the few surviving early Archaean sedimentary sequences. In these rocks, the imprints of life occur as mineralized moulds or casts of silica (cherts), Ca-carbonates (calcite, aragonite), Fe-carbonate (siderite, ankerite), Fe-sulphides (pyrite), Fe-oxides (hematite) or Ca-phosphate (apatite). Other evidences such as microbe generated methane encased in mineral grains as fluid inclusions[9], biogenic carbon recycled in sediments and biologically induced isotope shifts exhibited by C, Fe and S have also served as useful bioindicators[5].

Though life supporting microenvironments within the sediment horizons are the obvious habitat, microorganisms are reported even from sites normally reckoned as inhospitable or harsh, such as volcanic rocks and hydrothermal veins. In the 3.5 b.y. old submarine volcanic rocks (pillow lavas) – the Jamestown ophiolites of the Barberton Greenstone Belt, South Africa, tubular, vermicular or granular or coalesced spherical bodies seen protruding into the volcanic glass as micron-scale cavities or endoliths are actually bio-alteration features etched out by rock-boring microbes[10]. These endolithic microtubes are also reported from sandstone grains of 3.4 b.y. Apex and Strelley Pool Cherts in Australia, and such endoliths are believed to preserve evidences about morphology and metabolism of the organisms[8]. However, these rock-boring microbes are well-known contaminants colonizing rocks during later geological times, much after the host rocks had formed. It is imperative, therefore, that their syngenecity with the host Archaean rocks as well as timings and growth history of the microtubes are confirmed through geochemical and isotopic micro-mapping for biological connection before regarding them as proofs for biological activity in the Archaean[8,11].

Recent studies have brought out how several types of biosignatures including the microbially induced sedimentary structures, biologically controlled mineralization arising from metabolic activity of bacterial organisms and several microfossil-like structures can be produced abiogenically also. The current discredital of many of the Archaean age fossil findings was inevitable as they failed to meet some of the newly evolved criteria to test biogenicity or because of possible alteration to the original biosignatures by post-depositional metamorphism, metasomatism or deformation. Now, only two sites are regarded as possibly hosting Archaean life, one from the Pilbara and Warawoona Supergroups of the Pilbara Craton, in Western Australia and the other from Onverwacht Group in South Africa, where they are seen as laminated structures[11,12]. Incidentally, the reported laminated structures from the Dharwar Supergroup in India belong to the younger Neoarchaean period (2.8–2.7 b.y.).

The reported success in laboratory synthesis of structures closely resembling biogenic ones has further stressed the need for a re-examination of all the earlier discoveries of microfossils[2,6,13]. Filaments of self-assembled silicate carbonates, structures resembling the complex curved, helical, dendritic, polygonal and spherical morphologies of biogenic forms of >3 b.y. cyanobacteria from Greenland and South

Africa were grown in these laboratory experiments carried out under the ambient conditions of Archaean oceans. The experimenters could reproduce even the kerogen (heterogeneous polymer residue of life forms considered a 'hallmark' clue for life) coating the microfossil filaments, thus demonstrating that kerogen can develop even in the absence of biological activity[6]. These new insights have prompted the view that the life-forms reported from 3.5–3.4 b.y. old carbonaceous Apex cherts, Western Australia, as well as most of the >3 b.y. occurrences may be such self-organized abiotic structures[8]. However, this is contested as the synthetic structures are not found to be entirely identical to the biogenic structures. They cannot, therefore, be taken to disprove biogenicity, unless future studies on 'degradational features and biofabrics (disposition of cells and organisms in their ancestral biologic, environmental and geologic context)' prove to the contrary till which time they may be shelved as 'dubious fossils'[14]. Further, it is found statistically that morphological variations in abiological structures are invariably more than found in well preserved natural populations of true biogenic fossils[8].

Early life was carbon-based and only forms that needed either chemical compounds or light or heat as energy source for their metabolism could have flourished. All of them exerted fractionation effects on isotopes of carbon, preferentially absorbing ^{12}C, the lighter of its two isotopes. The Archaean earth had far less biological activity and under the scenario prevailing at that time only a small percentage of these life forms got preserved as microfossils in the rocks while the vast majority was decomposed to kerogen and recycled back into the sediments. Such recycled biogenic carbon in Archaean sediments with enriched ^{12}C is claimed to be indirect evidence for early life and as good isotopic biomarkers, provided their isotope ratios had remained undisturbed in post-depositional periods.

However, the weakness of C-isotopes as biomarkers lies in the fact that there could be a number of abiotic pathways operating in nature which could lead to various organic and reduced carbon compounds showing ^{12}C enrichment which is claimed as characteristic of biological activity[5]. Alkenes, polycyclic aromatic hydrocarbon (PAH) compounds, amino-acids, lipids, graphitic carbon, with typical biogenic C-isotope ratio can be produced from CH_4, CH_4-N_2-H_2O, CH_4-NH_3-H_2O, CO, CO-H_2 and CO_2, CO_2-H_2, under atmosphere-ocean (by spark discharge, UV photolysis), crust-mantle (through thermal, hydrothermal agencies) conditions, all of which assume greater relevance during Hadean and early Archaean when volcanic, tectonic and geothermal activities were much higher[5]. In spite of these limitations in their application to test biogenicity, isotopic evidences of C and a few other elements like Fe, S, N can still serve as effective tools for confirmation for Archaean life, if they are compatible with geological, sedimentological and other geochemical data[5].

Recognition of early Archaean life solely through morphological structures appears to be quite tricky, calling for application of advanced analytical methods, trace element and isotope analyses, molecular analysis of organic matter (if molecular biosignatures have not been erased to ordered graphite) and microanalysis as well as techniques to examine fossils of microorganisms at sub-microscopic resolution to distinguish between self-assembled and truly biogenic features[5,8]. In this respect, the fast developing secondary ion mass spectrometry for *in situ* analyses of nano-morphologies (nanoSIMS) with high resolution (50 nm) to map organic elements C, N ($^{12}C^{14}N/^{12}C$), S, Si and O, and their fractionated isotopic ratios, currently successfully applied to filamentous microfossils in Proterozoic cherts from Bitter Springs Formations, Australia, holds promise to trace early earth's life and help correct interpretation of controversial, poorly preserved organic structures from deep time[7].

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