Early Archaean life in deep-sea hydrothermal ecosystem

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For many years, the beginning of life on earth during the Archaean period (3800–2500 m.y. ago) had remained an 'enigma clothed in mystery' and had provided considerable grist for speculation and debate. In the earlier half of twentieth century, the term Archaean was a synonym for 'Azoic', meaning lifeless, but over the last fifty years, this perception has changed after discoveries of primitive life forms during this period. In the wake of several reports about such discoveries, new theories on the probable origins of life on earth emerged. Apart from terrestrial pathways (endogenous origins), the proposed theories included extraterrestrial routes also (exogenous origins) based on evidences from objects that had fallen from outer space, but the views about their influence on evolution of life somehow remained in oblivion. However, with advances in remote and *in situ* observations on orbiting objects in the solar system, many prebiotic organic compounds in galactic space, interplanetary dust, comets, meteorites and asteroids came to be recognized[1–3]. Following the spate of recent studies on a meteorite of Martian origin, pointing to possible life on Mars[4], interdisciplinary research on cosmic connection to early life received a great boost. Presently, viability of both terrestrial and extraterrestrial routes continues to be debated, though there is a general agreement that life on earth, whether in a hot or cold setting, emerged first in the oceans[5–8].

Very early life forms in Archaean or pre-Archaean times were called *prokaryotes* – bacteria and single-celled archaea lacking nucleus and these led to development of *eukaryotes* with cells and nuclei, much later during late-Archaean. In the absence of recognizable fossils, the existence of such early life has been inferred mostly from biogenic carbonaceous inclusions, oil and bitumen found occurring within minerals of this period[9–12]. Oldest evidence of life that had lived within a little more than half-billion year after earth formed 4.5 b.y. ago comes from the banded iron formation (BIF) belonging to the Isua supracrustals in Greenland. This has been inferred from graphite inclusions having biogenic C-isotope signature, found locked within apatites (fluorophosphate of calcium) occurring in these BIFs that had formed 3.8 b.y. ago[13]. The parent organisms, apparently primitive cyanobacterial forms, must have lived much before the crystallization of these apatite grains. Direct evidences, as microfossils, scarce during this period, became abundant only after late Archaean and younger geological periods. Some of these life forms, a little more evolved, lived in communities by building layered organo-sedimentary structures, mats of cell filaments, by trapping and binding mud and other sediments. These are the well-known stromatolites (dome-shaped structures) and oncolites (rounded structures). The cyanobacteria and a few other early forms, the precursors of higher animals, are seen even today as living fossils flourishing in diverse marine environments – shallow to deep sea, sunlit oxygenated zones to dark anoxic depths as well as cold and dark ocean bottom to hot submarine volcanic environs. Many of the early organisms that lived in shallow depths or the surface of sea derived their energy through photosynthesis. In course of time, other types like the non-photosynthetic heterotrophs that thrived on organic molecules in the dark anoxic depths and, likewise, autotrophs that manufactured their own organic nutrients out of inorganic substances and similar variants adapted to different Precambrian (4500–544 m.y.) marine environments came to be discovered.

While the dawn of Cambrian period (600–500 m.y.) witnessed an explosion of multicellular forms of life[14], geological evidences about their Precambrian predecessors were scarce. With advanced optical tools aiding their search, microscopic primitive life belonging to the latter age also could be found from a number of localities around the world[9,15–24], including India[7,12,25–28] (Table 1). The Indian occurrences are reported from Archaean strata in southern, eastern and central parts of the country. A recent study of graphites from > 3.0 b.y. Dharwar and Sargur supracrustals in southern India has shown them to be biogenic[12] and, graphites from the adjoining Kolar Schist belt, as derived from methanogenic and methylotrophic microorganisms[12]; stromatolites have also been reported from Sandur Schist belt[25] here. Similar primitive forms were noted in the iron formations at Bonai, in Orissa[7], and recently from Bailadila in Madhya Pradesh, filamentous unicellular forms were recognized in > 3.0 b.y. rocks[28].

Systematic ocean bottom surveys undertaken over the years have revealed unusual habitats for bacterial colonies and other organisms – regions of extreme temperatures (130–175°F) prevailing around present-day hydrothermal volcanic vents and deep-sea mid-ocean ridge systems, where superheated waters carrying sulphur and associated metals gush out. Most of this life happens to be extremely simple primitive forms of bacteria (archaeobacteria). Known as hyperthermophiles or chemolithotrophic microorganisms, these forms met their energy requirements through chemosynthetic reactions involving S, C, and Mn compounds available in the surrounding waters[5,29]. Though vent ecosystems were extensive in Archaean oceans, existence of such primitive thermophilic forms of life has not been discovered so far from the rocks of this age. A breakthrough has been achieved and such heat-loving forms are now reported from Sulphur Springs, a locality forming part of the early Archaean Pilbara craton in Western Australia[20]. These new findings are cyanobacterial filaments from a 3235 m.y. old deep-sea volcanogenic massive sulphide (VMS) deposit made up of sulphides or sulphates of Fe, Cu, As, Zn, Pb and Ba, formed by replacement of volcanic and volcaniclastic rocks. The filamentous microfossils (0.5–20 μm diameter, up to 300 μm long) were non-photosynthetic, anaerobic forms and, as indicated by their replacement by submicroscopic pyrite (FeS_2), derived their energies through reactions involving sulphur[20], abundantly available in the heated waters gushing out of the hydrothermal vents in the ocean bottom.

With the current report of these Sulphur Springs organisms that had lived in a hot hydrothermal habitat, the domains of Archaean life have expanded and, more importantly, they may represent the fossil-links missing in the theories about deep-sea thermophilic origins of life. Understandably, this has galvanized scientists, and a section among them now feels that the new findings have strengthened the long-held view, based on studies of ribosomal RNA and proteins bearing Ni, Cu, Zn, Mo (all typical metals of hydrothermal deposits), that the first living system could be sulphur-metabolizing, thermophilic micro-organisms evolved around submarine hydrothermal vents, much before emergence of photosynthetic forms[3,5,6,8]. Such habitats are believed to have sensitized the early organisms to heat in course of time and gradually adapted them to light and led to the evolution of photosynthetic organisms in the shallower sunlit zones during subsequent geological periods[6]. However, this view is contested in the wake of results to the contrary from gene sequence evolution studies, carried out last year in France[30,31]. Their experiments, based on temperature-sensitive RNA molecules in the ribosome of the cells, have shown that the molecular building blocks (amino acids and nucleic acids) of early organisms would be chemically unstable at high hydrothermal vent temperatures. They feel that the reported Archaean hyperthermophiles, at best, may have lived only under moderate temperature settings as mesophiles[30]. The present-day high-temperature forms, seen around vents in mid-ocean ridges, are considered to have evolved subsequently as an adaptation developing from the earlier mesophilic species. This controversy may, hopefully, be settled if the on-going research on gene sequences of present-day high as well as moderate temperature archaeobacteria is able to answer the strange biochemistry of the Archaean hyperthermophiles and decide whether they were the earliest forms or a character (thermoadaptation) acquired later[31].

The wide-ranging debate on the hot or cold ambience for the early life addresses only the later part of evolution of life for which availability of basic organic compounds – the fundamental molecular building blocks, should first be present in the aquatic medium to initiate life. To answer this critical requirement to the beginning of life, exogenous implantation has been put forward by astronomers and astrobiologists through cosmic seeding of vital life-triggering organic compounds (polymers and other macromolecules), whose presence in the early or pre-Archaean marine ecosystem is otherwise difficult to explain[3]. These external sources assume significance when we take into account that during pre-Hadean (pre-3.8 b.y.)

Table 1. Some geological sites preserving archaean life

Age (m.y.)	Locality	Nature of organisms	Reference
	Greenland		
3850	Greenland, Isua supracrustals	Biogenic carbonaceous inclusions in apatites from iron formations	13
	Africa		
3200–3500	Onverwacht Group, Swaziland, Fig Tree formation, Barberton Mountainland	Cyanobacteria-like organisms, filaments, traces of microfossils, organic mats, stromatolites in cherts/volcaniclasts, in shallow marine environments	16, 18
	Canada		
2500	Beck Springs and Gunflint Iron Formation	Algae/pyritized filaments in cherts, shallow marine	22, 23
	Australia		
3400–3500	Pilbara block and North Pole	Shallow marine/subaerial cyanobacteria; oil inclusions (biogenic)	10, 18
3000–3400	Apex basalt, Pilbara craton	Cyanobacterium-like photo-autotrophs in cherts	24
3300–3500	Towers Formation, and Warawoona Group, Pilbara Craton	Unicell colonies in sedimentary rocks, shallow subaqueous (marine) to subaerial cyanobacteria; oil inclusions derived from earlier organisms	9, 10, 24
3235–3260	Sulphur Springs, Pilbara craton	Pyritized cyanobacterial filaments, deep sea, hydrothermal habitat	18–21
3000–3250	Musquito Creek, Pilbara craton	Oil inclusions (biogenic) within quartz grains; biogenic bitumen nodules	10, 11
2750	Tambiana Formations	Cyanobacterial filaments in sedimentary rocks, shallow marine	24
	India		
> 3000	Dodguni and Bhimasandra, Shimoga Schist belt, Karnataka	Stromatolites and other microbiota in Cherty limestone	26
> 3000	Kudremukh iron formations, Karnataka	Silicified/pyritized cyanobacteria	27
> 3000	Bailadila, Madhya Pradesh	Unicellular structures (stromatolites) in iron formations	28
~ 3000 ~ 3000	Sargur and Dharwar supracrustals, Karnataka	Graphite of biologic origin in schists and quatzites	12
2900	Kolar Schists, Karnataka	Methanogens and methylotropic forms	12
2900	Sandur Schists, Karnataka	Stromatolites of shallow marine habitat	25
2900	Bonai, Keonjar Dt, Orissa	Algal stromatolites in iron formations	7

history, earth was bombarded by meteorites, asteroids, comets and interplanetary dusts, all carriers of vital ingredients for life. The possibilities for such exogenous vectors for delivering prebiotic organic compounds appear more likely in an early carbon dioxide-rich terrestrial atmosphere[32], where mechanisms of endogenous production of organics for early life were known to be relatively weak[33].

Lastly, there is also the view that micro-organisms could have as well developed in comets and other cosmic objects and subsequently introduced, well shielded during the transit through thick early atmosphere[34], directly into early earth[1,3]. Such a possibility cannot also be brushed aside, especially when considered against reports about the tenacity of life to survive for extended periods under extremely harsh conditions. We have examples of living bacterial colonies entombed for millions of years deep inside crustal rocks[35]. There has been successful revival of bacteria from inside a bee entombed in amber for 25 million years[36], and reanimation of a similar species of *Bacillus* from a brine inclusion within 250 m.y. old salt crystal[37] not to mention the amazing viability of bacteria found within an operating nuclear reactor. Indeed, the prebiological history that had led to evolution of life forms, such as those seen in Sulphur Springs, are very difficult to evaluate at this stage and, small wonder, they still remain an 'enigma clothed in mystery'.

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