

Life on Earth Originated Where Later Microbial Oxygenic Photosynthesis Precipitated Banded Iron Formation, Suppressing Life Diversification for 1.4 Ga

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ABSTRACT

The earliest Precambrian microbial structures appear in successions with banded iron formations (BIF) suggesting genetic relationships. The hypothesis of the deep ocean origin of BIFs associated with Mid-Ocean Ridge (MOR) like features seems to have been recently supported by the discovery of peculiar microbial ecosystems with unique faunal assemblages restricted to these volcanic vents. However, new sedimentological evidence points to the accumulation of varved BIF in huge, very shallow lakes of hydrothermal-water situated on continental plates while passing through the Polar Regions, where UV radiation is minimal. The mineral-rich solutions seeped from numerous fumaroles, providing suitable conditions for chemical reactions between inorganic components, incidentally creating organic-like self-multiplying molecules long before the biologically-initiated BIF deposition. Some of these early chemoautotrophic prokaryotes developed oxygenic photosynthesis during half a year of solar illumination. The released oxygen formed iron oxides and carbonates deposited with amorphous silica (geyserite) in laminae as BIF during 3.8 - 1.9 Ga. BIF deposition consumed most of the photosynthetic oxygen for 1.4 billion years. Intensified cyanobacteria oxygenic photosynthesis during 2.4 - 2.2 Ga raised the atmospheric oxygen content (Great Oxidation Event) over the Polar Regions, forming an oxygen-ozone shield against UV radiation. It gradually extended to lower latitudes, enabling prokaryotes to leave their ecologically stable habitat and acclimatize in new ecosystems, where they diversified, leading to eukaryote evolution. The $23\frac{1}{2}^\circ$ inclination of Earth's rotation axis differentiated the solar effect on the Polar Regions, which controlled life evolution on Earth, as well as on planet Mars (25° inclination), where life probably did not evolve beyond early prokaryotes.

Keywords: Early Precambrian Earth; Life Cradles; Banded Iron Formation (BIF); 1.4 Ga Suppressed Life Diversification; Life on Mars

1. Introduction

The idea that life could have formed through reactions of inorganic components in a solution representing the early hydrosphere of planet Earth was corroborated by the Miller-Urey experiment [1,2] when electric currents passing through an aquatic solution of methane, ammonia and hydrogen ("primordial soup" = "prebiotic soup") under reducing conditions synthesized amino acids, hydroxyacids and urea. Additional experiments substantiated the possibility of a natural synthesis of prebiotic polymers, which may combine into self-replicating molecules [3,4]. The discovered hydrothermal solutions seeping out from

deep-ocean volcanic vents provided natural chemical setting where organic components could have formed, but perhaps not life [5]. Their mineral concentration is too low to facilitate spontaneous reactions of the inorganic components with each other when activated by some energy source, whereas the great difference in temperature between the hot solution and the cold seawater will have a negative affect on the life-forms. These life-units would need to be enveloped by a protecting membrane enabling osmosis with the ambient water [5,6]. It was suggested that life could have emerged from "hot (c. 150°C) extremely reduced, alkaline, bisulfide-bearing,

submarine seepage waters interfaced with the acid, warm (c. 90°C), iron-bearing Hadean ocean” across a membrane of an iron monosulfide (mackinawite) that would provide the protonmotive force of the energy transduction mechanism of life [7]. This scenario for the origin of life was corroborated in 2000 by the discovery in the deep ocean of vents from where hydrothermal, mineral-rich alkaline (pH 9 - 11) with methane and hydrogen well-up into the surrounding marine water with a pH of 5 - 6 [8,9]. The interaction of these two fluids presented a probability for an early process of chemiosmosis by a proton gradient over some kind of membrane [10].

All these hypotheses and reconstructions of the origin of life on earth through incidental reactions between inorganic components were related to sites of submarine hot-spring (hydrothermal) activity following the discovery of the Mid-Ocean-Ridge (MOR) volcanic vents. These mineral-rich solutions comprised the needed inorganic building-stones of early life-forms, as well as vesicular structures that could act as tiny cells with a membrane for ion transfer for the metabolic energy of the cell through the biochemical process of chemiosmosis without an external energy source [6]. Some of the deep-ocean vents (“Lost City systems”) yield unique geochemical settings of a high alkalinity (pH 9 - 11) and high concentrations of dissolved H₂, CH₄ and other low-molecular-mass hydrocarbons, but almost no dissolved CO₂ where life-forms could have emerged [9,10]. However, the occurrence of such inter-plate spreading centers during the Archean-Paleoproterozoic eons seems questionable, as is the existence of oceans in their Phanerozoic configuration [11]. The present-day deep-sea vents are scattered habitats of micro- and macro-faunal assemblages living confined to the sites of pecculating mineral-rich hydrothermal water, suggesting that an ecological (chemical) hindrance prevents them from acclimatizing to the ambient ocean water. If these hypothetical Archean vents were situated in the deep sea such as the Phanerozoic ones, their hosting early bacteria would have been beyond the reach of the solar energy required for the development of photosynthesis. These discrepancies in the reconstruction of the origin of life on Earth turned scientists to look for the source of life on other planets of our solar system such as on Mars [12], or on any other planet in the universe from where meteorites containing organic matter could have reached planet Earth [13]. The Murchison Meteorite (Australia, September 28, 1969) yielded a high molecule diversity of apparently organic matter [14]. The numerous organic-like chemical compounds might represent abiotic chemical compositions of the six major elements involved in life (C, H, O, N, S, P) [15], which occurred on early planet Earth as well. The current pursuit of extraterrestrial sources for life on Earth overlooks the problems of such “intrastellar panspermia”.

Even if these doubtful microorganisms survived explosive detachment from their planet surface and the transport through space while exposed to harmful solar radiation [16], they would have had to reach hospitable water where they would acclimatize and flourish. These hazardous constraints render low the hypothetical “intrastellar panspermia”, which is herein rejected by the identification on the early Earth of environments comprising most suitable physical and chemical conditions for the origin of life according to the latest biochemical scenarios. These archaic environments are the recently reconstructed depositional basins of the Early Precambrian (3.8 - 1.9 Ga) banded iron formation (BIF) based on the least altered varved BIF in Western Australia and South Africa [11,17].

2. Early Precambrian Paleogeography and Sedimentological Settings

2.1. Challenging the Hypothetical Deep Ocean Origin of BIF

The reconstruction of Early Precambrian sedimentary basins and water bodies on Earth is based on the understanding of the mode of transport and accumulation of clastic sediments and extensive lava flows alternating with extensive chemical deposits such as banded iron formation (BIF), silica and diverse carbonates and evaporates [18]. Nearly all these sediments occur throughout the Phanerozoic except for BIF, which disappeared some 1.9 Ga ago and its depositional setting remained disputable and speculative [18,19]. The recently published detailed review on this subject discussed 380 studies on sedimentology, tectonic processes, petrography and geochemistry (including REE) concluding that further research is required [20]. Despite the hitherto accumulated vast quantity of physical and chemical evidence the conditions under which the economically most significant iron source was deposited during a certain period in Earth’s history is still puzzling.

The well-bedded appearance over hundreds of square-kilometers of iron minerals embedded in amorphous silica referred to chert [21] associated in places with microbial features suggested precipitation in low-energy marine environments. This was apparently corroborated by the discovery of Mid-Ocean-Ridge (MOR) volcanic vents supplying dissolved iron and silica [22]. The occurrence of BIF within mafic and ultramafic volcanic rocks (metamorphosed into greenstone belts) and pillow lavas lent further support for the possible origin of BIFs from deep ocean spreading centers and volcanic island-arcs as in Phanerozoic times [18]. On the other hand, carbonates and clastics with shallow-water sedimentary features were discovered between these volcanic rocks in the 3.5-Ga-old Warrawoona Group (Pilbara Craton, W. Australia)

[23] together with evaporites [24]). Mafic and ultramafic rocks together with BIF and evaporates were reported from the 3.3 Ga sedimentary succession at Mt. Goldsworthy (Pilbara Craton, W. Australia) [25]. Likewise, the 3.5 - 3.3-Ga-old Barberton greenstone belt in South Africa yielded evaporites and subaerial microbial mats formed on the surface of volcanic rocks [26,27]. Accordingly, the Phanerozoic tectonic processes producing mafic to ultramafic rocks mainly along oceanic spreading centers cannot be applied to similar Archean volcanic rocks [28], suggesting that the latter erupted onto continental basement [29]. These observations corroborate earlier conclusions on the evaporitic nature of the associated BIF [30,31]. However, despite the evidence from various countries and stratigraphic levels attesting to the shallow-water nature and possible continental sedimentary setting of the BIF and associated sediments, the hypothetical deep marine origin was adopted by BIF scholars [32].

2.2. Sedimentary, Chemical and Mineralogical Aspects Defining BIF Depositional Setting

The earliest 3.8-Ga-old banded iron formation occurs in the Isua Greenstone Belt in south-western Greenland. This unique deposit appears later in other parts of the world and becomes abundant at about 2.6 - 2.2 Ga, declining in abundance toward its disappearance at about 1.8 Ga [33]. Most of these Early Precambrian BIF deposits were subjected to metamorphism and metasomatism, which changed their original composition. Among the least altered BIFs are the 2.475 Ga Dales Gorge Member of the Brockman Iron Formation (Hamersley Group, Western Australia) and the 2.48 Ga Kuruman Iron Formation of South Africa [20]. These BIFs were intensively studied as representing the origin of all other partly altered BIFs [33]. The Dales Gorge and Kuruman BIFs preserve millimeter to sub-millimeter thin lamination of alternating iron-rich and iron-lacking chert laminae [21]. The iron minerals in Western Australia are dominated by oxides (mainly magnetite and hematite), whereas in South Africa iron-carbonates are common (mainly siderite and ankerite). Sets of these laminae keep their relative thickness over 80 km of the Hamersley basin, reflecting remarkable lateral homogeneity [21,30]. The precipitation of these iron oxides under the Early Precambrian anoxic conditions was attributed to oxygen released by oxygenic photosynthetic cyanobacteria [34], whose microstructures were detected in the 2.0 - 1.9 Ga old Gunflint Formation BIF of Ontario. Microbial structures and stromatolites were observed in several BIF successions [35] and were chemically detected by C^{12} to C^{13} ratios [36] strengthening the biological control on BIF precipitation, though other factors were discussed. These benthic cyanobacteria formed mats and stromatolites in the euphotic

zone, hence in shallow water, contradicting the alleged deep marine origin of BIFs.

Unequivocal evidence for a shallow water level in the BIF sedimentary basins was provided by ring-in-ring sedimentary structures (**Figure 1**) discovered by H. Dalstra (Rio Tinto) in the Dales Gorge Member BIF of Western Australia. These were compared to circular bubbling mud wavelets (**Figure 2**) forming today at the exposed surface of mud pools in the volcanic terrain of Rotorua, northern New Zealand [11,17]. Both extant and fossil examples have a complete central bubble about 3 cm in diameter surrounded by elevated rings of sediment nearly 1 cm wide with a slit between them. The fossilized rings weaken with increasing diameter and the slit fades. However, most of the ring-in-ring sets are truncated or overlapped by adjacent sets (**Figure 1**), attesting to their mobility during formation, as in the extant example (**Figure 2**). The preservation of the fossil structure suggests that while it formed the sediment was wet and plastic, gradually drying out and consolidating. In the case of bubbling mud under water the ejected sediment would be suspended and then settle down nearby, forming small



Figure 1. Silicified ring-in ring structures on a bedding surface in the Dales Gorge Member BIF, Hamersley Basin Western Australia. Wavelet width about 1 cm (photo by H. Dalstra).

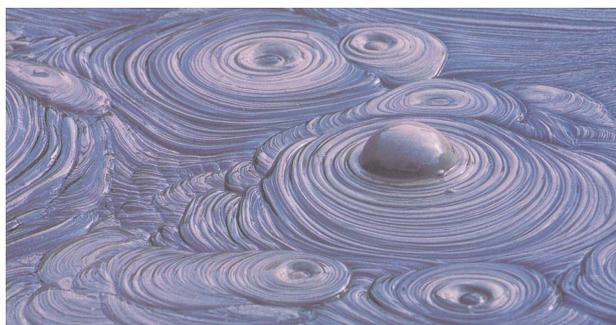


Figure 2. Bubbling mud circular wavelets at the surface of a mud pool in the volcanic terrain of Rotorua, New Zealand (photo by B. Beresford).

volcano-like domes, which were discovered in the Dales Gorge Member as well [17].

The alternating iron-rich and iron-lacking chert laminae indicate on-and-off periods of iron oxidation by free oxygen related to photosynthesis controlled by solar radiation [34]. Well-preserved iron-rich laminae in the Dales Gorge Member consist of layer of tiny crystals of magnetite ($\text{FeO}\cdot\text{Fe}_2\text{O}_3$) overlain by hematite (Fe_2O_3) and followed by magnetite [21]. This delicate mineralogical segregation reflects the rise (toward all Fe^{3+}) and fall in oxidation potential, which corresponds to oxygenic photosynthesis intensity, hence to changes in solar illumination. Cyclically alternating periods of illumination and darkness on Earth longer than diurnal changes characterize the Polar Regions, where solar radiation intensity gradually increases from mid-spring to summer and decreases toward mid-autumn, exactly as reflected by the mineralogical composition of the iron-rich laminae. It results from the $23\frac{1}{2}^\circ$ inclination of the axis of rotation of planet Earth differentiating two Polar Regions, being shaded for half a year from solar illumination, changing its intensity during the other half year. The low angle of the solar rays reaching the northern and southern Polar Regions adds to the climatic significance of these regions. No other environment on Earth could have resulted in this pattern of chemically precipitated minerals. Therefore, the alternating iron-rich and iron-lacking chert laminae are genuine annual varves [17] as previously suspected [30]. The deduced polar position of the BIF basins is further corroborated by the absence of detritus as the result of no terrestrial run-off and minor or lack of precipitation as reflected by the lateral chemical homogeneity of BIF laminae. Diamictite at the end of the BIF successions in Western Australia, South Africa and North America attest to glacier melting when the plate shifted to lower latitudes [17]. The wander path of the major plates passes through high latitudes or Polar Regions during BIF accumulation [37,38].

While under the freezing-cold dry weather in the Polar Regions the intensive evaporation of the warm hydrothermal solution concentrated the ion and gases content, whereby silica precipitated as geyserite (sinter silica) mixing with iron mineral during solar illumination. Carbon and sulfur volcanic gases dissolved in the water raised acidity during high rates of evaporation (shallow water column), preventing carbonate precipitation during BIF deposition. A rise in the water column diluted the silica concentration and lowered the water acidity facilitating the precipitation of limestone and dolomite crystals enriched in iron and manganese oxides without any associated BIF. These minor changes in rates of evaporation and hydrothermal-water supply controlled the alternation of BIF and carbonate units interbedded with mafic and ultramafic lava flows and volcanic ash (altered to stilp-

nomelane) deposited in shallow-water basins [27]. Actually, none of the Early Precambrian sedimentary successions (including greenstone belts) unequivocally attests to an oceanic setting. Even the assumption of marine salty water is based on microbial mats and stromatolites along Phanerozoic sea-margins, overlooking their occurrence in non-marine aquatic bodies [39]. Stromatolite-like structures could have precipitated non-biologically just as layered travertine structures from hot water [17, 40]. Accordingly, the 3.8 - 1.9-Ga-old BIFs accumulated in huge, shallow lakes of hydrothermal water in tectonically subsiding volcanic terrains situated on continental plates shifting over the globe on molten lava, passing through the Polar Regions [11,17]. These paleoecological and paleogeographical depositional settings are herein extended to pre-3.8 Ga times, prior to the origin of oxygenic photosynthetic cyanobacteria [41], or another biological oxidation process [42] when chemoautotrophic prokaryotes and other microbial forms (e.g. Archaea) lived in the shallow aquatic basins.

The new reconstruction of the Early Precambrian depositional setting of the least altered varved BIF [17] follows the concluded significant role of oxygenic photosynthetic cyanobacteria in the precipitation of the iron minerals and in enriching the anoxic atmosphere in free oxygen [34]. This pioneering work was challenged by a chemical model whereby dissolved ferrous iron species [Fe^{2+} , $\text{Fe}(\text{OH})^+$] could have been photooxidized into Fe^{3+} by high flux of ultraviolet photons, which would be further hydrolyzed to form $\text{Fe}(\text{OH})_3$ at circumneutral pH [43-45]. However, this sophisticated chemical process is contradicted by the delicately layered segregation of magnetite-hematite-magnetite microcrystals in successive iron-rich BIF laminae of the Dales Gorge Member [21], as well as by the different mineralogical composition of the iron minerals in the Australian (oxides) and South African (carbonates) BIFs, which indicate that no intermediate mineralogical phase common to all BIFs preceded their deposition. The speculations on the involvement of UV radiation in BIF formation, or BIF precipitation by the activity of anoxygenic phototrophic Fe^{2+} oxidizing bacteria in ocean water at a few hundred meters depth [46] are contradicted by the non-oxidized ferrous iron in siderite (FeCO_3) and ankerite [$\text{FeMg}(\text{CO}_3)_2$] dominated BIF of South Africa. The alleged role of UV radiation requires that the iron-rich solutions to be concentrated at the surface in contrast to their assumed origin in the deep-ocean. These speculations seem intended to diminish the previously suggested major role of oxygenic photosynthetic cyanobacteria in the accumulation of this highly economic iron ore deposit [34], which is corroborated by the associated gradual rise of free oxygen content in the Early Precambrian anoxic atmosphere toward its Phanerozoic level.

It should be noted that before these huge shallow basins entered the Polar Region where the varved BIF precipitated they passed through high latitudes under diurnal illumination and low to moderate UV radiation. The nearly continuous cyanobacteria oxygenic photosynthetic activity resulted in the enrichment of the precipitated silica and carbonate mainly in iron minerals. These accumulated in layers of several millimeters to centimeters in thickness without any internal varving, alternating with volcanoclasts, siliciclasts and carbonates. This non-varved BIF is represented by BIF units in the Marra Mamba iron formation at the lower part of the Hamersley Group followed by the varved BIF in the Dales Gorge Member and in the higher Weeli Wolli Formation comprising [30,47].

3. The Cradles of Life

The polar position of the aforementioned lakes during the precipitation of the varved BIF [11,17] comprised physical and chemical settings, which would have facilitated the earlier creation and preservation of life-forms. Hydrothermal solutions entered these lakes from numerous fumaroles scattered over the whole bottom [30] as attested to by the homogeneity of the chemical precipitates over most of the huge lakes. In addition to silica and a high content of ferrous iron precipitated as BIF this solution comprised dissolved gases such as H₂, CH₄, CO, SO, N₂ and a little phosphorous [48] needed for the creation of organic-like molecules. The paleotemperature of 60°C - 70°C of the solution analyzed on BIFs [49] and associated organic matter [50] reached the upper limit tolerated by extant cyanobacteria (<70°C - 73°C) [51]. The difference in temperature between the warm lake water and the freezing cold and dry climate in the Polar Regions intensified evaporation, considerably concentrating the hydrothermal solution. The varved structure of the Dales Gorge BIF along a sequence of about 140 m reflects the near lack of freshwater input from runoff or precipitation, and hence attests to rather constant chemical settings over most of the lake. These may have been affected by minor seasonal changes and periodical variations in rates of evaporation with respect to the water supply, which changed BIF to carbonates precipitation [11,17]. The occurrence of these huge, warm-water lakes in the Polar Region could have provided the energy source for the chemical reactions between the dissolved inorganic components according to the Miller-Urey experiment [2]. Lightning and thunderstorms develop over warm, mainly continental terrains where evaporation is very intensive and the friction between the particles of the turbulent moist circulation charges the clouds with static electricity differing between clouds and the ground [52]. Accordingly, the reconstructed BIF accumulation sites in the Polar Regions under intensive evaporation provide suitable settings for the generation of frequent lightning.

Though the involvement of an external energy in the creation of life-forms [1] was opposed by the latest biochemical reconstructions [6,9,53], the organic components which formed in the laboratory [4] could have been created in nature and contribute to the development of life.

All the hypothetical and studied ecosystems in which living cells might have evolved in nature are mineral-rich hydrothermal solutions such as flowing out from deep ocean vents. Although the reconstructed biochemical process seems possible in these sites, the early life-forms would have been subjected there to severe ecological hazards regarding their survival, dispersal and development. These hazards relate to severe chemical and physical differences between the seeping hydrothermal solution and the ambient seawater, which restricts the distribution of the created life-forms to the vents as evidenced by the extant vent communities. This would have prevented the development of photosynthesis in the dark abyss. All these ecological obstacles did not prevail in the BIF basins in the Polar Regions. There the chemical composition and the temperature of the water remained nearly constant over extensive and very shallow basins (enabling later photosynthesis). There organic components and early life were subjected to the weakest (low angle) solar UV radiation during half a year only, surviving the damaging effect UV radiation [26,54].

4. The History of Early Life on Earth

The pioneering evaluation of the atmospheric and hydrospheric evolution on the primitive Earth [34] was later partly abandoned by BIF scholars who assertively introduced other unsubstantiated ideas. Most of these latter publications dealing with the origin of life and BIF precipitation are based on the unproven assumptions that early Earth was comprised of oceans with active volcanic spreading centers and volcanic island arcs as in their Phanerozoic configuration supplying mafic and ultramafic rocks [18]. Meteorite showers were suggested as raising the water temperature [55] to the detected 60°C - 70°C [49,50].

The revised physical and chemical settings of BIF precipitation [11,17] seem to offer an alternative and more appropriate setting than the MOR volcanic vents may have provided in the proposed biochemical models [56]. All the latest scenarios relate to sites of hydrothermal activity although the precise process is still being argued. In the case of the BIF basins [11,17] the warm ~60°C - 70°C [59,50] hydrothermal water underwent intensive evaporation under the polar freezing cold, dry climate, condensing the inorganic compounds and volcanic gases in the solution, and resulting in spontaneous chemical reactions between H₂, CH₄, CO, SO and other inorganic components whereby organic-like molecules formed. These

combined into polymers, some of which became enveloped by a film (membrane) forming the earliest living cell [16,57]. They survived in the flattened, shallow water basins as the result of the low intensity (low radiation angle) and short duration of UV radiation in the Polar Regions. However, periodical cover by volcaniclast deposits (altered to stilpnomelane), carbonate (dolostone) and less common basalt flows as reflected by various BIF successions (e.g. Hamersley Group [32] might have killed part, or the whole benthonic microbial community. These were exposed to continuous UV radiation when the plate shifted beyond the Polar Regions, which in the lack of an oxygen-ozone screen must have resulted in their extinction. Therefore the origin of life-forms must have repeated itself in the Polar Regions several times whereby the early chemoautotroph Archaea and Bacteria evolved separately [6].

The association of prokaryote relics in successions comprising BIF units deposited throughout the Early Precambrian suggests that life-forms were incidentally created several times in this kind of stable ecosystem in the Polar Regions, and were eliminated when the ecological conditions in these shallow-water bodies considerably changed. Microbial mats formed on subaerially exposed surfaces of volcanic rocks (though probably wet) in an evaporitic environment in a 3.5 - 3.3 Ga-old formation from the Barberton greenstone belt in South Africa [27], where similar mat structures were found in 3.2 Ga tidal sandstone [58]. These examples corroborate the reconstruction of the origin of BIF [11,17] in which some earlier prokaryotes may have lived on the bottom of shallow-water lakes in the Polar Region exposed for half a year to solar radiation with minimal intensity of UV rays. Some of these chemoautotrophs developed the ability to utilize the solar energy to provide a new food source by introducing oxygenic photosynthesis about 3.8 Ga ago, as suggested by the Isua (West Greenland) BIF, and by the interpreted U-Th-Pb isotopic system of the associated metasediments [59]. This most significant process in Earth's history must have proceeded stepwise whereby there were many intermediate biochemical compositions until oxygenic photosynthesis was incidentally created, and an organic film or the already cell membrane protected the photosynthesizing cell against the damaging effect of the released oxygen [60]. The early-primitive photosynthesis process has further evolved into various types that are found today [40,61]. The anoxic conditions during these Early Precambrian times suggest that CO rather than CO₂ was involved ($6\text{CO} + 6\text{H}_2\text{O} + \text{light energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 3\text{O}_2$), as suggested by the precipitation of ferrous carbonates (mainly siderite) in the South African varved and non-varved BIF. There the oxygen released during solar illumination oxidized CO dissolved in the water to CO₃ while the ferrous iron did not change, in

contrast to its oxidation in the Australian BIF [11,17]. During half a year of darkness these bacteria resumed their chemoautotrophic metabolism. They left their fossil record in the form of mats and stromatolites, which appear in different configurations and were therefore assigned to different taxa [35]. Less common microstructures and biomarkers added to the compiled prokaryote diversity [35,62]. However, mat structures and stromatolites are the dominant relics of early life until 1.8 - 1.7 Ga when early eukaryotes evolved. This may suggest that all or most of these microbial communities inhabited the surface forming mats and stromatolites, whereas some penetrated into the sediment. Cyanobacteria diversity based mainly on biomarkers [63] reflects a low microbial biodiversity until the rise in atmospheric oxygen content detected on 2.32-Ga-old samples from South Africa [64]. They nearly correlate to the precipitation of the varved Weeli Wolli Formation in Western Australia [46] while being in the Polar Region [17]. This detected atmospheric free oxygen, which was referred to as the Great Oxidation Event, must have resulted from the extensive and intensive cyanobacterial oxygenic photosynthetic activity attested to by Western Australian and South African extensive BIFs [17]. The low evolutionary rate until the rise in atmospheric oxygen may be explained by the rather limited ecological fluctuations in the earliest Precambrian microbial ecosystems in the Polar Regions where UV radiation was minimal. The accumulation of atmospheric oxygen over the Polar Regions gradually extended to lower latitudes providing a shield against UV radiation over the high latitudes. Thereafter when the BIF basin shifted beyond the Polar Regions, part of the prokaryote assemblages were flushed by runoff water from melting glaciers and rain, flowing over the rather flattened topography into other open water bodies. There they adapted to colder temperatures and new ecological conditions while diversifying toward the evolution of eukaryotes. The timing of this evolutionary event was recently re-evaluated in respect to chemical analyses of biomarkers [6] compared to fossil evidence dating back to 1.78 - 1.68 Ga [65,66]. Organic-walled, rather large (up to 0.3 mm) spherical microfossils (unicellular) were recently reported from 3.2 Ga siliciclastic deposits in South Africa [67]. Similarly preserved younger (1.9 - 1.6 Ga) microorganisms were referred to acritarchs of uncertain biological affinity, contributing to their puzzling systematic position. It seems that the genuine eukaryotes originated at about 1.8 Ga when the atmospheric and hydrospheric oxygen content almost reached its present-day level. At that stage free oxygen in meteoric water oxidized and deposited the ferrous iron in the underground. Thereby the rising hydrothermal water was considerably depleted in iron, ending the accumulation of the Early Precambrian BIFs [17].

Most findings of life-forms came from BIF successions, which might suspect selective sampling of promising sequences for the study of ancient life. However, the herein optimal ecological setting attested to for the origin and survival of incidentally created life-forms in these restricted environments corroborates their original association with BIFs. The fossil record suggests that prokaryotes were the exclusive organisms on Earth for over 2 Ga. Earliest prokaryotes which were adapted to anoxia did not develop further into more advanced and complex microorganisms under these conditions. The incidental evolution of oxygenic photosynthesis created restricted habitats where most of the released oxygen oxidized ferrous iron as evidenced by the iron-lacking chert laminae in BIF varves, maintaining the general anoxic settings. The very low microbial evolution rate since the origin of oxygenic photosynthetic cyanobacteria up to the Great Oxidation Event suggest that life remained confined to the same conditions prevailing in the hydrothermal lakes where it originated free from any ecological pressure. These optimal and stable living condition under the minimal intensity of UV radiation lasted for 1.4 billion years. During this time the whole photosynthetic oxygen was consumed in BIF deposition forming the world's significant iron ore. Thereby BIFs suppressed the evolution of life on Earth until increased production of oxygen enabled the extension of microbial communities into new habitats under different ecological condition which promoted their diversification.

5. Possible Life on Planet Mars

The 25° inclination of the rotation axis on planet Mars suggests a similar early history to what planet Earth underwent despite their different distance from the sun. It is the inclination of the rotation axis which created the Polar Regions and their relations to the solar radiation. It is postulated that, like on Earth, early life-forms developed on Mars in hydrothermal lakes with concentrated solutions comprising H₂, CH₄, CO, SO and other components. The multiplying molecules incidentally created evolved into the early chemoautotrophic life-forms in the shallow water. Exposed to temporary solar illumination some developed oxygenic photosynthesis as developed on Earth at about 3.8 Ga. The oxygen released into the anoxic hydrosphere during half a year of illumination oxidized iron, manganese and other cations, but especially the volcanic CO. This is hinted at by nearly 95% CO₂ and only 0.13% oxygen in the present Martian atmosphere, suggesting that oxygenic photosynthesis ended rather quickly about 3.5 - 3.0 Ga ago before these cyanobacteria extended their activity over large areas as on Earth during the period of 2.5 - 2.2 Ga ago when their excess oxygen accumulated in the atmosphere as an oxygen-ozone

shield against UV radiation. Lacking more information from Mars, it seems that life did not evolve beyond prokaryotes, which perhaps were eliminated long ago.

6. Summary and Conclusions

The 23¹/₂° inclined rotation axis of planet Earth differentiated two Polar Regions which were differently affected by the sun radiation throughout the solar year. The sedimentary basins of the Early Precambrian BIFs were recently reconstructed as huge shallow lakes of hydrothermal-water situated on continental plates shifting over molten lava. While they passed through the freezing-cold Polar Regions, the warm water was intensively evaporated and the mineral solution concentrated, enabling incidental reactions between the inorganic components. These physical and chemical settings under minimal intensity and duration of UV radiation provided ideal conditions for the incidental creation of life-forms. Covered by extensive lava flows, volcanoclasts or carbonate precipitation probably eliminated much or the whole prokaryote communities. However, whenever such lakes passed through the Polar Regions, new life-forms were chemically created, as reflected by the different origins of Archaea and Bacteria. The shallow basins enabled chemoautotrophic bacteria to utilize sunlight as an additional source of energy, whereby some developed and improved the process of oxygenic photosynthesis in addition to chemoautotrophic nourishment during darkness. Most of the oxygen released oxidized the high ferrous iron content in these huge lakes into BIF for nearly 1.4 billion years (ca 3.8 - 2.4 Ga). The extensive oxygenic photosynthetic activity during 2.5 - 2.2 Ga produced more oxygen than needed for BIF precipitation as detected on 2.32 Ga samples. The gradually forming oxygen-ozone shield against UV radiation extended beyond the Polar Regions and enabled prokaryotes to enter other aquatic bodies, adapt to different ecosystems and diversify. Thus the accumulation of the economically highly significant iron source for modern life actually halted the evolution of life on Earth for nearly two billion years.

The 25° inclination rotation axis of planet Mars differentiated two Polar Regions like on Earth, which could have resulted in a similar geological and biological history as on early Earth. The possible creation of life-forms on early planet Mars is suggested by the present-day nearly 95% of CO₂ and only 0.13% oxygen in the Martian atmosphere. It suggested that oxygenic photosynthesis developed on Mars, and that the released oxygen oxidized the volcanic carbon-monoxide to CO₂ as well as iron, manganese and other cations to oxides staining the sediments. The fixation of all the photosynthetic oxygen probably occurred rather early in Martian history around 3.5 - 3.0 Ga.

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REFERENCES

- [1] S. L. Miller, "A Production of Amino Acids under Possible Primitive Earth Conditions," *Science*, Vol. 117, No. 3046, 1953, pp. 528-529. <http://dx.doi.org/10.1126/science.117.3046.528>
- [2] S. L. Miller and H. C. Urey, "Organic Compound Synthesis on the Primitive Earth," *Science*, Vol. 130, No. 3370, 1959, pp. 245-251. <http://dx.doi.org/10.1126/science.130.3370.245>
- [3] J. L. Bada and A. Lazcano, "Prebiotic Soup-Revising the Miller Experiment," *Science* Vol. 300, No. 5620, 2003, pp. 745-746. <http://dx.doi.org/10.1126/science.1085145>
- [4] A. P. Johnson, H. J. Cleaves, J. P. Dworkin, D. P. Glavin, A. Lazcano and J. L. Bada, "The Miller Volcanic Spark Discharge Experiment," *Science*, Vol. 322, No. 5900, 2008, p. 404. <http://dx.doi.org/10.1126/science.1161527>
- [5] S. L. Miller and J. L. Bada, "Submarine Hot Springs and the Origin of Life," *Nature*, Vol. 334, 1988, pp. 609-611. <http://dx.doi.org/10.1038/334609a0>
- [6] W. Martin and M. J. Russell, "On the Origins of Cells: A Hypothesis for the Evolutionary Transitions from Abiotic Geochemistry to Chemoautotrophic Prokaryotes, and from Prokaryotes to Nucleated Cells," *Philosophical Transactions of the Royal Society B*, Vol. 358, No. 1429, 2002, pp. 59-85. <http://dx.doi.org/10.1098/rstb.2002.1183>
- [7] M. J. Russell and A. J. Hall, "The Emergence of Life from Iron Monosulphide Bubbles at a Submarine Hydrothermal Redox and pH Front," *Journal of the Geological Society of London*, Vol. 154, No. 3, 1997, pp. 477-402. <http://dx.doi.org/10.1144/gsjgs.154.3.0377>
- [8] D. S. Kelley, J. A. Karson, D. K. Blackman, G. L. Früh-Green, D. A. Butterfield, M. D. Lilley, E. J. Olson, M. O. Schrenk, K. K. Roe, G. T. Lebon, P. Rivizzigno and the AT3-60 Shipboard Party, "An Off-Axis Hydrothermal Vent Field near the Mid-Atlantic Ridge at 30° N," *Nature*, Vol. 412, 2001, pp. 145-149. <http://dx.doi.org/10.1038/35084000>
- [9] W. Martin, J. Barross, D. Kelley and M. J. Russell, "Hydrothermal Vents and the Origin of Life," *Nature Reviews in Microbiology*, Vol. 6, 2008, pp. 805-814. <http://dx.doi.org/10.1038/nrmicro1991>
- [10] N. Lane, J. F. Allen and W. Martin, "How Did LUCA Make a Living? Chemiosmosis in the Origin of Life," *Bioessays*, Vol. 32, No. 4, 2010, pp. 271-280. <http://dx.doi.org/10.1002/bies.200900131>
- [11] Z. Lewy, "Banded Iron Formations (BIFs) and Associated Sediments Do Not Reflect the Physical and Chemical Properties of Early Precambrian Seas," *International Journal of Geosciences*, Vol. 3, 2012, pp. 226-236. <http://dx.doi.org/10.4236/ijg.2012.31026>
- [12] M. J. Russell, J. K. Ingham, V. Zedef, D. Maktav, F. Sunar, A. J. Hall and A. E. Fallick, "Search for Signs of Ancient Life on Mars: Expectations from Hydromagnesite Microbialites, Salda Lake, Turkey," *Journal of the Geological Society of London*, Vol. 156, No. 5, 1999, pp. 869-888. <http://dx.doi.org/10.1144/gsjgs.156.5.0869>
- [13] H. J. Melosh, "Exchange of Meteorites (and Life?) between Stellar Systems," *Astrobiology*, Vol. 3, No. 1, 2003, pp. 207-215. <http://dx.doi.org/10.1089/153110703321632525>
- [14] Z. Martins, O. Watson, M. L. Fogel, M. A. Sephton, D. P. Glavin, J. S. Watson, J. P. Dworkin, A. W. Schwartz and P. Ehrenfreund, "Extraterrestrial Nucleobases in the Murchison Meteorite," *Earth and Planetary Science Letters*, Vol. 270, No. 1-2, 2008, pp. 130-136. <http://dx.doi.org/10.1016/j.epsl.2008.03.026>
- [15] P. Schmitt-Kopplin, Z. Gabelica, R. D. Gougeon, A. Fekete, B. Kanawati, M. Harir, I. Gebefuegi, G. Eckel and N. Hertkorn, "High Molecular Diversity of Extraterrestrial Organic Matter in Murchison Meteorite Revealed 40 Years after Its Fall," *PNAS*, Vol. 107, No. 7, 2010, pp. 2763-2768. <http://dx.doi.org/10.1073/pnas.0912157107>
- [16] M. A. Line, "The Enigma of the Origin of Life and Its Timing," *Microbiology*, Vol. 148, 2002, pp. 21-27.
- [17] Z. Lewy, "Early Precambrian Banded Iron Formations: Biochemical Precipitates from Highly Evaporated Hydrothermal Solutions of Polar Region Lakes," *Carbonates and Evaporites*, Vol. 24, No. 1, 2009, pp. 1-15. <http://dx.doi.org/10.1007/BF03228053>
- [18] K. A. Eriksson, B. Krapež and P. W. Fralick, "Sedimentology of Archean Greenstone Belts: Signature of Tectonic Evolution," *Earth Science Reviews*, Vol. 37, No. 1-2, 1994, pp. 1-88. [http://dx.doi.org/10.1016/0012-8252\(94\)90025-6](http://dx.doi.org/10.1016/0012-8252(94)90025-6)
- [19] A. F. Trendall and J. G. Blockley, "Precambrian Iron-Formation," In: P. G. Eriksson, W. Altermann, D. R. Nelson, W.U. Mueller and O. Catuneanu, Eds., *The Precambrian Earth. Tempos and Events. Developments in Precambrian Geology*, Vol. 12, 2004, pp. 403-421.
- [20] A. Bekker, J. F. Slack, N. Planavsky, B. Krapež, A. Hofmann, K. O. Konhauser and J. R. Oliver, "Iron Formation: The Sedimentary Product of a Complex Interplay among Mantle, Tectonic, Oceanic, and Biospheric Processes," *Economic Geology*, Vol. 105, No. 3, 2010, pp. 467-508. <http://dx.doi.org/10.2113/gsecongeo.105.3.467>
- [21] R. C. Morris, "Genetic Modelling for Banded Iron-Formation of the Hamersley Group, Pilbara Craton, Western Australia," *Precambrian Research*, Vol. 60, No. 1-4, 1993, pp. 243-286. [http://dx.doi.org/10.1016/0301-9268\(93\)90051-3](http://dx.doi.org/10.1016/0301-9268(93)90051-3)
- [22] H. D. Holland, "The Oceans: A Possible Source of Iron in

- Iron-Formations,” *Economic Geology*, Vol. 68, No. 7, 1973, pp. 1169-1172.
<http://dx.doi.org/10.2113/gsecongeo.68.7.1169>
- [23] M. E. Barley, J. S. R. Dunlop, J. E. Glover and D. I. Groves, “Sedimentary Evidence for an Archaean Shallow-Water Volcanic-Sedimentary Facies, Eastern Pilbara Block, Western Australia,” *Earth and Planetary Science Letters*, Vol. 43, No. 1, 1979, pp. 74-84.
[http://dx.doi.org/10.1016/0012-821X\(79\)90156-0](http://dx.doi.org/10.1016/0012-821X(79)90156-0)
- [24] R. Buick and J. S. R. Dunlop, “Evaporitic Sediments of Early Archaean Age from the Warrawoona Group, North Pole, Western Australia,” *Sedimentology*, Vol. 37, No. 2, 1990, pp. 247-277.
<http://dx.doi.org/10.1111/j.1365-3091.1990.tb00958.x>
- [25] K. Sugitani, K. Mimura, K. Suzuki, K. Nagamine and R. Sugisaki, “Stratigraphy and Sedimentary Petrology of an Archaean Volcanic-Sedimentary Succession at Mt. Goldsworthy in the Pilbara Block, Western Australia: Implications of Evaporate (Nahcolite) and Barite Deposition,” *Precambrian Research*, Vol. 120, No. 1-2, 2003, pp. 55-79.
[http://dx.doi.org/10.1016/S0301-9268\(02\)00145-6](http://dx.doi.org/10.1016/S0301-9268(02)00145-6)
- [26] D. R. Lowe and L. P. Knauth, “Sedimentology of the Onverwacht Group (3.4 Billion Years), Transvaal, South Africa, and Its Bearing on the Characteristics and Evolution of the Early Earth,” *Journal of Geology*, Vol. 85, No. 6, 1977, pp. 699-723.
<http://dx.doi.org/10.1086/628358>
- [27] F. Westall, C. E. J. de Ronde, G. Southam, N. Grassineau, M. Colas, C. Cockell and H. Lammer, “Implications of a 3.472-3.33 Ga-Old Subaerial Microbial Mat from the Barberton Greenstone Belt, South Africa for the UV Environmental Conditions on the Early Earth,” *Philosophical Transactions of the Royal Society B*, Vol. 361, No. 1474, 2006, pp. 1857-1875.
<http://dx.doi.org/10.1098/rstb.2006.1896>
- [28] K. Sugitani, F. Yamashita, T. Nagaoka, M. Minami and K. Yamamoto, “Geochemistry of Heavily Altered Archaean Volcanic and Volcaniclastic Rocks of the Warrawoona Group, at Mt. Goldsworthy in the Pilbara Craton, Western Australia: Implications for Alteration and Origin,” *Geochemical Journal*, Vol. 40, No. 5, 2006, pp. 523-535.
<http://dx.doi.org/10.2343/geochemj.40.523>
- [29] M. G. Green, P. J. Sylvester and R. Buick, “Growth and Recycling of Early Archaean Continental Crust: Geochemical Evidence from the Coonterunah and Warrawoona Groups, Pilbara Craton, Australia,” *Tectonophysics*, Vol. 322, No. 1-2, 2000, pp. 69-88.
[http://dx.doi.org/10.1016/S0040-1951\(00\)00058-5](http://dx.doi.org/10.1016/S0040-1951(00)00058-5)
- [30] A. F. Trendall and J. G. Blockley, “The Iron-Formations of the Precambrian Hamersley Group, Western Australia, with Special Reference to the Associated Crocidolite,” *Western Australia Geological Survey Bulletin*, Vol. 119, 1970, pp. 1-365.
- [31] H. P. Eugster and I. Ming-Chou, “The Depositional Environments of Precambrian Banded Iron-Formations,” *Economic Geology*, Vol. 68, No. 7, 1973, pp. 1144-1168.
<http://dx.doi.org/10.2113/gsecongeo.68.7.1144>
- [32] A. L. Pickard, M. E. Barley and B. Krapež, “Deep-Marine Depositional Setting of Banded Iron Formation: Sedimentological Evidence from Interbedded Clastic Sedimentary Rocks in the Early Palaeoproterozoic Dales Gorge Member of Western Australia,” *Sedimentary Geology*, Vol. 170, No. 1-2, 2004, pp. 37-62.
<http://dx.doi.org/10.1016/j.sedgeo.2004.06.007>
- [33] C. Klein, “Some Precambrian Banded Iron-Formations (BIFs) from around the World: Their Age, Geologic Setting, Mineralogy, Metamorphism, Geochemistry, and Origin,” *American Mineralogist*, Vol. 90, No. 10, 2005, pp. 1473-1499.
<http://dx.doi.org/10.2138/am.2005.1871>
- [34] P. E. Cloud Jr., “Atmospheric and Hydrospheric Evolution on the Primitive Earth,” *Science*, Vol. 160, No. 3829, 1968, pp. 729-736.
<http://dx.doi.org/10.1126/science.160.3829.729>
- [35] J. W. Schopf, “Fossil Evidence of Archaean Life,” *Philosophical Transactions of the Royal Society B*, Vol. 361, No. 1470, 2006, pp. 869-885.
<http://dx.doi.org/10.1098/rstb.2006.1834>
- [36] P. Kenrick and P. Davis, “Fossil Plants,” Smithsonian Books, Washington, 2004, p. 232.
- [37] M. W. McElhinny and M. O. McWilliams, “Precambrian Geodynamics—A Palaeomagnetic View,” *Tectonophysics*, Vol. 40, No. 1-2, 1977, pp. 137-159.
[http://dx.doi.org/10.1016/0040-1951\(77\)90032-4](http://dx.doi.org/10.1016/0040-1951(77)90032-4)
- [38] M. Idnurm and J. W. Giddings, “Australian Precambrian Polar Wander: A Review,” *Precambrian Research*, Vol. 40-41, 1988, pp. 61-88.
[http://dx.doi.org/10.1016/0301-9268\(88\)90061-7](http://dx.doi.org/10.1016/0301-9268(88)90061-7)
- [39] J. R. Eggleston and W. E. Dean, “Fresh Water Stromatolitic Bioherms in Green Lake, New York,” In: M. R. Walter, Ed., *Stromatolites. Developments in Sedimentology*, Vol. 20, Elsevier, Amsterdam, 1976, pp. 479-488.
- [40] M. R. Walter, “Geyserite of Yellowstone National Park: an Example of Abiogenic ‘Stromatolites’,” In: M. R. Walter, Ed., *Stromatolites. Developments in Sedimentology*, Vol. 20, 1976, pp. 87-112.
[http://dx.doi.org/10.1016/S0070-4571\(08\)71131-2](http://dx.doi.org/10.1016/S0070-4571(08)71131-2)
- [41] R. Buick, “When did Oxygenic Photosynthesis Evolve?” *Philosophical Transactions of the Royal Society B*, Vol. 363, No. 1504, 2008, pp. 2731-2743.
<http://dx.doi.org/10.1098/rstb.2008.0041>
- [42] A. D. Czaja, C. M. Johnson, B. L. Beard, E. E. Roden, W. Li and S. Moorbath, “Biological Fe Oxidation Controlled Deposition of Banded Iron Formation in the ca. 3770 Ma Isua Supracrustal Belt (West Greenland),” *Earth and Planetary Science Letters*, Vol. 363, 2013, pp. 192-203.
<http://dx.doi.org/10.1016/j.epsl.2012.12.025>
- [43] P. S. Braterman, A. G. Cairns-Smith and R. W. Sloper, “Photo-Oxidation of Hydrated Fe²⁺—Significance for Banded Iron Formations,” *Nature*, Vol. 303, 1983, pp. 163-164.
<http://dx.doi.org/10.1038/303163a0>
- [44] A. G. Cairns-Smith, “Precambrian Solution Photochemistry, Inverse Segregation, and Banded Iron Formation,” *Nature*, Vol. 276, 1978, pp. 807-808.
<http://dx.doi.org/10.1038/276807a0>
- [45] K. O. Konhauser, L. Amskold, S. V. Lalonde, N. R. Posth, A. Kappler and A. Anbar, “Decoupling Photochemical Fe (II) Oxidation from Shallow-Water BIF Deposition,” *Earth and Planetary Science Letters*, Vol. 258, No. 1-2, 2007,

- pp. 87-100. <http://dx.doi.org/10.1016/j.epsl.2007.03.026>
- [46] A. Kappler, C. Pasquero and K. O. Konhauser, "Deposition of Banded Iron Formations by Anoxygenic Phototrophic Fe(II)-Oxidizing Bacteria," *Geology*, Vol. 33, No. 11, 2005, pp. 865-868. <http://dx.doi.org/10.1130/G21658.1>
- [47] A. F. Trendall, "Varve Cycles in the Weeli Wolli Formation of the Precambrian Hamersley Group, Western Australia," *Economic Geology*, Vol. 68, No. 7, 1973, pp. 1089-1097. <http://dx.doi.org/10.2113/gsecongeo.68.7.1089>
- [48] C. J. Bjerrum and D. E. Canfield, "Ocean Productivity before about 1.9 Ga ago Limited by Phosphorous Adsorption onto Iron Oxides," *Nature*, Vol. 417, 2002, pp. 159-162. <http://dx.doi.org/10.1038/417159a>
- [49] F. Robert and M. Chaussidon, "A Palaeotemperature Curve for the Precambrian Oceans Based on Silicon Isotopes in Cherts," *Nature*, 443, , 2006, pp. 969-972. <http://dx.doi.org/10.1038/nature05239>
- [50] E. A. Gaucher, S. Govindarajan and O. K. Ganesh, "Palaeotemperature Trend for Precambrian Life Inferred from Resurrected Proteins," *Nature*, Vol. 451, 2008, pp. 704-707. <http://dx.doi.org/10.1038/nature06510>
- [51] T. D. Brock, "Environmental Microbiology of Living Stromatolites," In: M. R. Walter, Ed., *Stromatolites. Developments in Sedimentology*, Vol. 20, Elsevier, Amsterdam, 1976, pp. 141-148.
- [52] Geology.com, "Lightening map by NASA," 2005-2011. <http://geology.com/articles/lightening-map.shtml>
- [53] N. Lane, "Chances or Necessity? Bioenergetics and the Probability of Life," *Journal of Cosmology*, Vol. 10, 2010, pp. 3286-3304.
- [54] C. S. Cockell, "Biological Effect of Highultraviolet Radiation on Early Earth – A Theoretical Evaluation," *Journal of Theoretical Biology*, Vol. 198, No. 4, 1998, pp. 717-729. <http://dx.doi.org/10.1006/jtbi.1998.0738>
- [55] E. G. Nisbet and N. H. Sleep, "The Habitat and Nature of Early Life," *Nature*, Vol. 409, 2001, pp. 1083-1091. <http://dx.doi.org/10.1038/35059210>
- [56] N. Lane, "The Cradle of Life," *New Scientist*, Vol. 17, No. 2730, 2009, pp. 38-42. [http://dx.doi.org/10.1016/S0262-4079\(09\)62756-1](http://dx.doi.org/10.1016/S0262-4079(09)62756-1)
- [57] J. H. McClendon, "The Origin of Life," *Earth Science Reviews*, Vol. 47, No. 1-2, 1999, pp. 71-93. [http://dx.doi.org/10.1016/S0012-8252\(99\)00015-X](http://dx.doi.org/10.1016/S0012-8252(99)00015-X)
- [58] N. Noffke, K. E. Eriksson, R. M. Hazen and E. L. Simpson, "A New Window into Early Archaean Life: Microbial Mats in Earth's Oldest Siliciclastic Tidal Deposits (3.2 Ga Moodies Group, South Africa)," *Geology*, Vol. 34, No. 4, 2006, pp. 253-256. <http://dx.doi.org/10.1130/G22246.1>
- [59] M. T. Rosing and R. Frei, "U-rich Archaean Sea-Floor Sediments from Greenland: Indications of >3700 Ma Oxygenic Photosynthesis," *Earth and Planetary Science Letters*, Vol. 217, No. 3-4, 2004, 237-244. [http://dx.doi.org/10.1016/S0012-821X\(03\)00609-5](http://dx.doi.org/10.1016/S0012-821X(03)00609-5)
- [60] J. F. Allen and W. F. Vermaas, "Evolution of Photosynthesis," *Encyclopedia of Life Sciences*, John Wiley & Sons, Chichester, 2010, pp. 1-11. <http://dx.doi.org/10.1002/9780470015902.a0002034.pub2>
- [61] R. E. Blankenship, "Early Evolution of Photosynthesis," *Plant Physiology*, Vol. 154, No. 2, 2010, pp. 434-438. <http://dx.doi.org/10.1104/pp.110.161687>
- [62] F. U. Battistuzzi, A. Feijao and S. B. Hedges, "A Genomic Timescale of Prokaryote Evolution: Insights into the Origin of Metanogenesis, Phototrophy, and the Colonization of Land," *BMC Evolutionary Biology*, Vol. 4, 2004, p. 44. <http://dx.doi.org/10.1186/1471-2148-4-44>
- [63] B. E. Schirrmeyer, J. M. de Vos, A. Antonelli and H. C. Bagheri, "Evolution of Multicellularity Coincided with Increased Diversification of Cyanobacteria and the Great Oxidation Event," *PNAS*, Vol. 110, 2013, pp. 1791-1796. doi:10.1073/pnas.120992711/-/DCSupplemental
- [64] A. Bekker, H. D. Holland, P. L. Wang, D. Rumble III, H. Stein, J. L. Hannah, L. L. Coetsee and N. J. Beukes, "Dating the Rise of Atmospheric Oxygen," *Nature*, Vol. 427, 2004, pp. 117-120. <http://dx.doi.org/10.1038/nature02260>
- [65] A. H. Knoll, E. J. Javaux, D. Hewitt and P. Cohen, "Eukaryotic Organisms in Proterozoic Oceans," *Philosophical Transactions of the Royal Society B*, Vol. 361, No. 1470, 2006, pp. 1023-1038. <http://dx.doi.org/10.1098/rstb.2006.1843>
- [66] B. Rasmussen, I. R. Fletcher, J. J. Brocks and M. Kilburn, "Reassessing the First Appearance of Eukaryotes and Cyanobacteria," *Nature*, Vol. 455, No. 7216, 2008, pp. 1101-1104. <http://dx.doi.org/10.1038/nature07381>
- [67] E. J. Javaux, C. P. Marshall and A. Bekker, "Organic-Walled Microfossils in 3.2-Billion-Years-Old Shallow-Marine Siliciclastic Deposits," *Nature*, Vol. 463, No. 7283, 2010, pp. 934-938. <http://dx.doi.org/10.1038/nature08793>