The Origin and Evolution of Life

by *David J. W. Moriarty*

Part 1: Prebiotic Organic Chemical Synthesis

Introduction

As 2011 is the International Year of Chemistry, it is appropriate to discuss the origin of life on Earth from a chemical and biochemical perspective. In 1996, McKay and colleagues at NASA published a paper describing probable fossilised bacteria in the meteorite ALH84001 from Mars. There was considerable controversy then; however, more data have been published recently indicating that some of the material in the meteorite is indeed likely to have had a biological origin. How likely is it that bacteria evolved on Mars as well as on Earth soon after the planets formed? (http://www.nasa.gov/centers/johnson/home/mars_meteorite.html).

The question of whether it is likely that there could be life on other planets or moons in our solar system, or elsewhere in the galaxy, could be answered from studies into the origin of life here. If there is life elsewhere, then from our knowledge of chemistry, we would expect it to be similar to that on Earth. This was a topic for discussion recently at the Royal Society in London, where Christian de Duve argued that life was a cosmic imperative: -To the extent that chemistry was involved, the processes leading to the origin of life may be viewed as occurring obligatorily under the prevailing physical – chemical conditions and imposed by those conditions. Chemistry deals with strictly deterministic, reproducible events. Let even a tiny element of chance affect chemical events, and there could not be any chemical laboratories or industries.‖ (Phil. Trans. R. Soc. A (2011) 369, 620–623).

The chemistry of when and how life may have started on Earth is now a large area of research in the field of astrobiology. From the viewpoint of chemistry, some of the questions we ask are: what was the chemical state of the Earth soon after it formed from the protosolar nebula (i.e. in the Hadean) and what organic molecules that are important for life were present before life began and what was their origin? How did the first bacteria feed themselves?

All life is organic, i.e. it is based on the chemistry of carbon and its interactions with oxygen, nitrogen, hydrogen, sulfur and phosphorus, which are the major elements required for life. (Note for astronomers: these elements are NOT metals!). However, some metals are very important for life, in particular: iron and some of the other transition metals. The Periodic Table is the way chemists classify the elements; see: http://en.wikipedia.org/wiki/Periodic_table.) An important property of transition metals for supporting life is that they readily lose 1 or more electrons to form cations (i.e. with a positive charge) and form stable bonds with non-metals, e.g. oxygen or sulfur. Conversely, non-metals such as oxygen readily accept electrons to make stable orbits around their nuclei.

Biochemistry

Several chemical processes are essential for the origin and continuation of life i.e. for biochemistry:

1. the presence of organic molecules, i.e. molecules based on carbon together with hydrogen, oxygen and nitrogen;
2. the generation of energy for cellular processes, which requires a membrane to separate negative electric charges (electrons) and positive charges (protons: H^+);
3. the development of RNA and DNA — molecules that are sufficiently complex to:
    a. store and transmit genetic information,
    b. provide variability in structure, and thus stored information, upon which environmental selection processes could operate to permit evolutionary development.

In this article, I discuss the first of these processes. There is much discussion about which of these came first, but in fact each was necessary before the first living cell could be formed. Furthermore, an environment that was conducive to the beginnings of life had to be present — water and protection from intense UV radiation. If the conditions were right for the development of life on Mars more than 3.5 billion years ago, or on Europa under its ice, we could expect to find bacteria or their fossils. The electrons orbiting the nuclei of carbon, oxygen, nitrogen and phosphorus follow strict physical laws in their interactions with other atoms and thus form molecules that are the same everywhere, and therefore, wherever life originates, it will not be fundamentally different from that on Earth.

On Earth there is a huge range in the environments in which microbes live and the ways in which they obtain energy for growth. Molecules that are essential for life occur in galactic dust clouds — e.g. oxygen, water, amino acids and for wine lovers: ethanol. They were present in the protosolar nebula from which the sun and planets were formed and are found now in meteorites and comets. It seems unlikely that much organic matter would have survived the accretion processes during the formation of the Earth. Therefore, we have to consider whether chemical processes on the early Earth would have produced sufficient amounts of appropriate organic molecules from which the first bacteria — life — evolved.

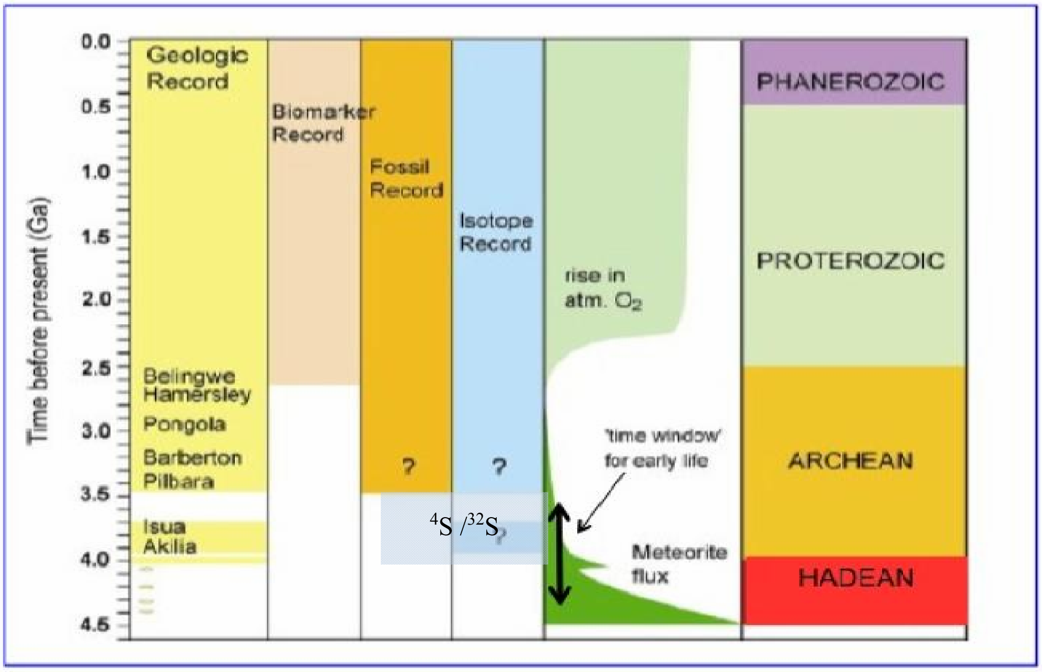

Figure 1. Record of life over time. There was no free oxygen in the atmosphere before about 2.6 Ga. The earliest probable bacterial fossils date from about 3.5 Ga; older rocks have been transformed so much by heat and pressure that fossils have not survived. Instead geochemists use chemical signatures of stable isotope fractions as signs of processes mediated by bacteria. Bacteria prefer the lighter ^{32}S isotope instead of the ^{34}S, so sulfides in very old rocks in Greenland and Western Australia with a low proportion of ^{34}S indicate microbial activity.

Prebiotic Synthesis of Molecules Essential for Life

When did the first living organisms evolve? Until recently, it seemed unlikely that the first microbes could have formed in the Hadean due to the high temperatures at the surface of the early Earth, and even if life had evolved then, the Earth would have been sterilised during the Late Heavy Bombardment (LHB). at 3.9 Ga. Therefore, it was proposed that life arose very rapidly in the early Achaean as there is chemical and geological evidence of life in rocks dating from 3.8 Ga. Now, however, some scientists argue that it is probable that the Earth was indeed potentially habitable soon after its formation. Studies on zircons dating from 4.4 to 4 Ga embedded in rocks in the Pilbara (WA) indicate that there were oceans and tectonic plate activity on the Earth in the Hadean. Modelling studies of heat distribution during the LHB indicate that only about 10% of the Earth‘s crust was heated to very high temperatures, and therefore the Earth would not have been sterilised then. Thus there was a period of about 700 million years during the Hadean and early Archaean for living organisms to evolve.

As there is geochemical evidence for the presence of bacteria at the beginning of the Archean Period, the abiotic synthesis of organic nitrogenous molecules— amino acids and nucleotides — as precursors for life was necessary in the Hadean. Hydrogen cyanide (HCN) is a major reagent for the synthesis of the organic nitrogenous molecules essential for life, and is formed in subduction zones at the margins of tectonic plates. Carbon dioxide on the subducting plate is reduced to carbon monoxide and methane. As the plate descends, it is heated and dehydrated, allowing the adsorbed CO and CH_4 to react with ammonium to form HCN and hydrogen (H_2). Furthermore, alkaline hydrothermal systems in the subduction zones are the sites for abiotic synthesis of sugars such as ribose, a constituent of RNA.

Mafic rocks, which have a high proportion of minerals with iron in its reduced state, e.g. olivine, were formed by crystallization of mantle-derived magmas on the planet‘s surface after the Earth‘s formation. On modern Earth, mafic rocks are found when the Earth‘s mantle is exposed along slow-spreading ridges. They are converted into serpentinites when they come into contact with water, as happens at the mid-ocean ridges and subduction zones. The oxidation of the ferrous (reduced) iron in olivine to ferric compounds is coupled to the reduction of water and the liberation of hydrogen. Iron and nickel, which are also released as native metals during the serpentinization process, catalyse the reduction of N_2, NO_3^- and NO_2^- to NH_4^+ (ammonium). Hydrogen, released from water during the serpentinization process, is a major energy source for anaerobic bacteria in the hydrothermal zones now and probably also on the early Earth when bacteria first evolved.

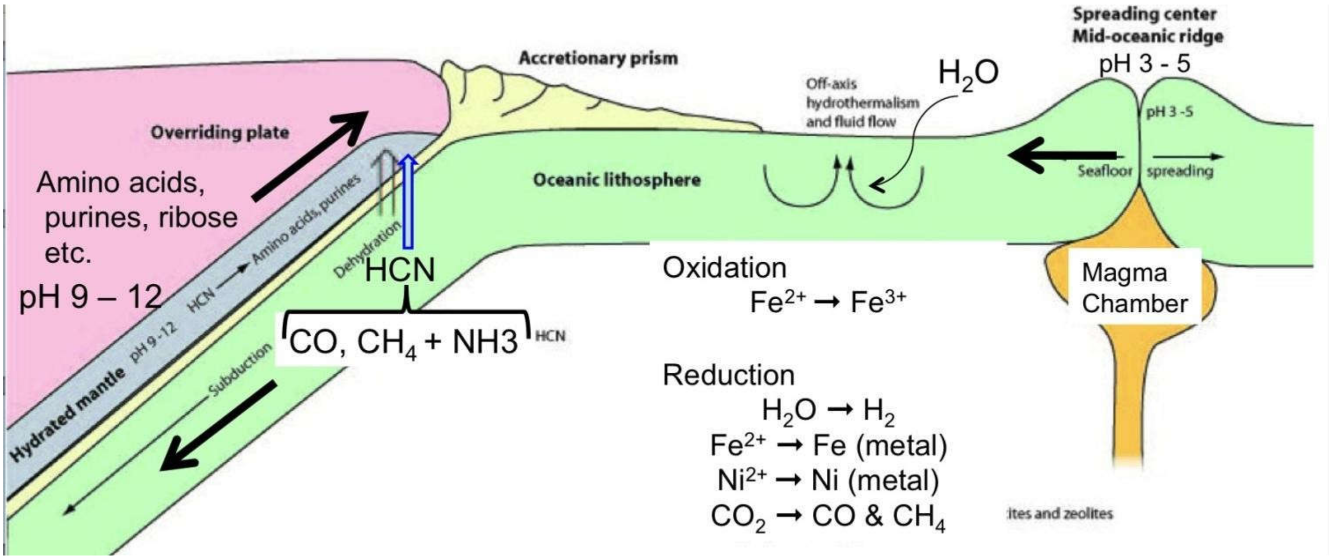

Figure 2. Hydrothermal flow away from the spreading centre in the oceanic lithosphere results in the abiotic oxidation of iron and the reduction of water to hydrogen. Hydrogen cyanide, formed from the reactions of carbon monoxide and ammonia, rises into the hydrated mantle rocks where the pH is alkaline and there condenses into larger molecules, including purines and amino acids.

[References will be supplied on request]

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Part 2: *Energy Sources for the Early Bacteria*

Introduction

In the previous section, I discussed the proposed origin of life around oceanic hydrothermal and subduction zones, where abiotic synthesis of essential organic molecules occurs via chemical processes. In these zones, inorganic chemicals that provide the basis for chemical energy are also formed, including hydrogen, methane and various sulfur compounds, as well as organic molecules.

Life before Oxygenic Photosynthesis: Chemoautotrophy

Amongst research workers studying how life may have originated and evolved, there is debate about whether the first organisms were chemoautotrophs or heterotrophs utilising organic carbon molecules that had accumulated from abiotic chemical processes on Earth and possibly also delivered by meteorites or formed during meteoric impacts. Chemoautotrophs feed themselves by using chemical energy to reduce carbon dioxide to synthesise organic compounds, in contrast to photoautotrophs, which use sunlight as their source of energy. There are other bacteria that live heterotrophically (i.e. obtain their organic carbon compounds from external sources or other organisms) and generate energy by transferring electrons from the organic compounds to ferric iron and therefore reduce it to the ferrous form.

Electron transfer processes of oxidation and reduction are very important in providing energy for the chemical processes that maintain life. Molecules vary in their tendency to give up or accept electrons; i.e. they vary in their redox potential. When electrons move from a molecule with a low reduction potential to one at a higher (more oxidised) potential, energy is released. Before photosynthetic organisms evolved, the earlier microbes are likely to have derived energy from the redox reactions of hydrogen, iron and sulfur.

Anaerobic microorganisms use hydrogen to reduce CO_2 to organic C; methanogens produce methane and acetogens produce acetic acid.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$
$$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O$$

Bacteria prefer the lighter ^{32}S of isotope over the ^{34}S, so where pyrite (iron sulfide) is found with a lower proportion of ^{34}S than natural abundance it is a sign of their activity. Sulfur dioxide, is released by volcanoes, can be split into sulfur and sulfide, which have a low redox potential, and sulfate, which has a higher redox potential than sulfur dioxide.

$$4SO_3^{2-} + 2H^+ \rightarrow H_2S + 3SO_4^{2-}$$
$$4S^0 + 4H_2O \rightarrow 3H_2S + SO_4^{2-} + 2H^+$$

Microbes can oxidise the reduced forms of sulfur to obtain energy. Indisputable evidence of bacterial fossils in 3.4 billion-year-old rocks from the Pilbara in Western Australia was reported by David Wacey and colleagues Nature Geoscience in August this year. The sulfur and carbon isotopic ratios associated with the fossils indicate that they were indeed of biological and not geochemical origin. Their work confirms indications from other researchers that microbial ecosystems depending on chemical energy from sulfur, as well as hydrogen and light, were abundant in the early Archean. As most rocks from that period have been drastically metamorphosed, fossil microstructures mostly have not survived.

Atomic iron (Fe) readily loses 2 electrons to form a ferrous cation (Fe^{2+}) or 3 electrons to form a ferric cation (Fe^{3+}). The anoxygenic purple non-sulfur bacteria can use it as a reductant together with light energy to reduce CO_2 to organic compounds.

$$4FeCO_3 + 7H_2O \rightarrow CH_2O + 4Fe(OH)_3 + 3CO_2$$

Iron within basaltic and other volcanic rocks is tightly bound in silicates and not available to bacteria, and therefore, could not support a high productivity of organisms. At the edges of tectonic plates, however, ferrous iron is released and oxidised with water as the oxidant, liberating hydrogen (*see Figure 2 in the first section, Part 1 last month*).

In order to trap and use energy from oxidation of reduced compounds, bacteria (and indeed all cells) need to separate charges across a membrane and use the electrical gradient to synthesise chemicals that can transfer the energy. Organic compounds with phosphate (ATP) or iron (Ferridoxin) have major roles for energy transfer in cells, however, we do not know how the first cells harnessed energy for metabolism.

Analysis of DNA base composition in eubacteria (true bacteria) and archaebacteria indicates that the earliest organisms were probably mesophilic or moderately thermophilic, not hyperthermophilic, and thus could have evolved in hydrothermal sites with temperatures of around 25 - 80°C. The Lost City hydrothermal field 15 km away from the axis of the Mid Atlantic ocean ridge is a modern example of an ecosystem based on autotrophic microbes utilising hydrogen and methane as their energy sources.

The first organisms were anaerobes, i.e. they did not derive energy for metabolism by respiring oxygen. Oxygen comprises about 50% of the Earth‘s crust by mass; it is a very reactive element and so is found combined with many other elements as oxides, e.g. with hydrogen (water), with iron (rust), with silicon as silicates in many different minerals and with carbon to form carbon dioxide and many carbonate minerals, e.g. limestone with calcium. On the early Earth — in the Hadean and Archaean periods — oxygen was not present in the atmosphere as a free element. It has occurred in the free state in the atmosphere and oceans since the start of the Proterozoic about 2.4 – 2.5 Ga (billion years ago) due to the biochemical activity of oxygenic photosynthetic microbes: the cyanobacteria.

Oxygen was probably first produced by cyanobacteria about 3.8 Ga, but did not exist in a high enough concentration to support heterotrophs until about 2.3 Ga. It took a very long time for the large amounts of reduced iron in the oceans, and the other chemical sinks for oxygen, to be oxidised and thus allow oxygen produced by the microorganisms to remain free in the water and atmosphere. Roger Buick said at a Royal Society meeting in 2008: ―If all of these lines of evidence turn out to be correct, then the history of oxygenic photosynthesis before oxygen started accumulating in the atmosphere was very long indeed, almost as long as the geological record itself. This would imply that the history of life goes much deeper in time, and that the most recent 85% of Earth‘s and life‘s evolution has merely been an adjustment to more oxygen.‖

Most heterotrophic bacteria and multicellular organisms are aerobic: they obtain energy by oxidising reduced organic compounds and transferring the electrons thus liberated to oxygen. Complex multicellular organisms require large amounts of energy for life. Aerobic respiration is far more efficient than anaerobic respiration; it provides much more energy for metabolism. For the existence of highly intelligent animals — ourselves — and indeed for most animals and plants, oxygen in the atmosphere is essential. If it were detected in the atmosphere of another planet, that would be an indicator of the possible existence of intelligent life. There are many types of bacteria and archaea that live without oxygen, and it is within these groups that we might find living organisms on other planets and where we should look to try and discover how life evolved.

[References will be supplied on request]