The origin of life as seen by a geologist who loves astronomy

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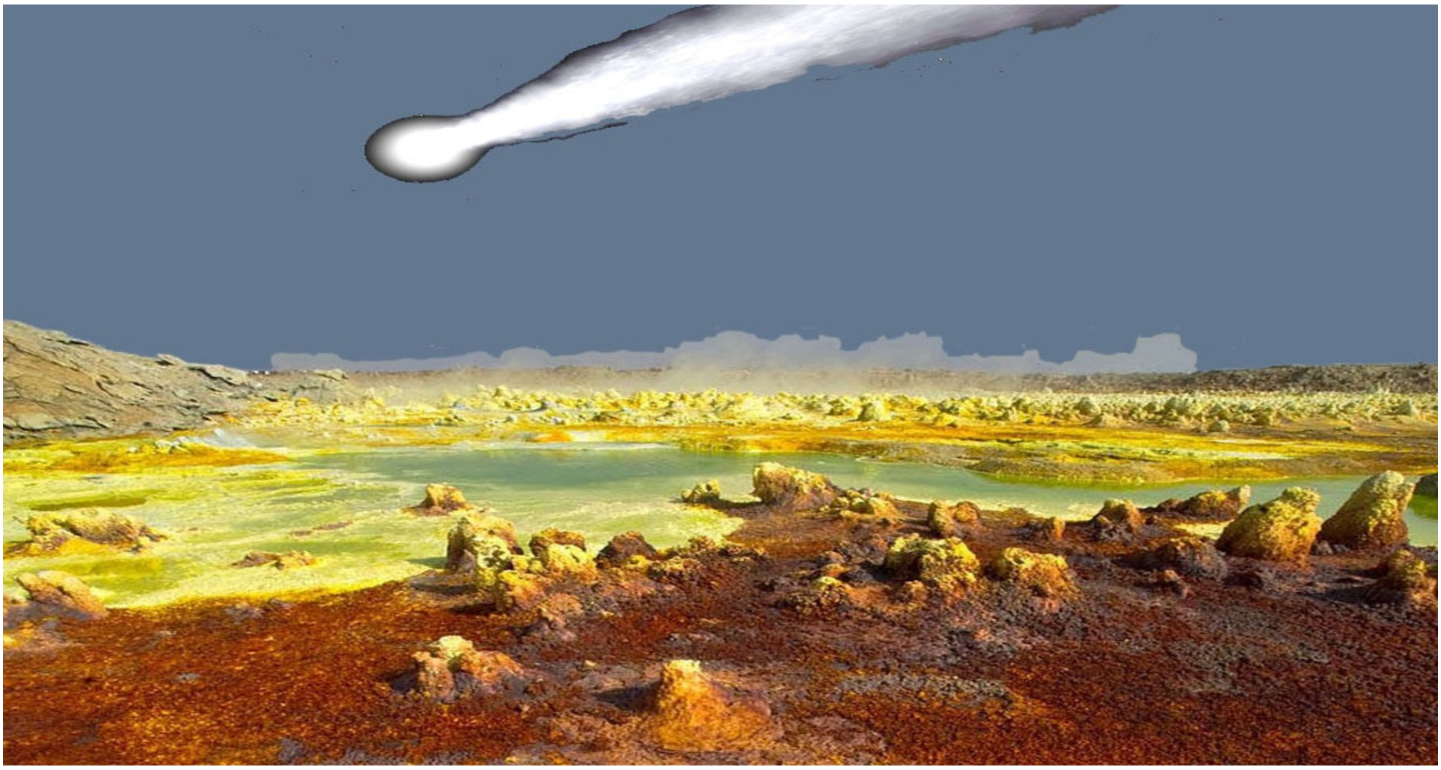

Life on Earth was born about four billion years ago, shortly after the formation of our planet, 4.54 billion years ago. While the transition from complex macromolecules to the simplest cells is still poorly understood, their origin poses far fewer problems. Their basic constituents are naturally synthesized on the surface of the dust grains that have produced comets and meteorites and in the Earth's surface crust (the lithosphere), where hot water is in contact with iron-rich silicates. However, many meteorites and comets fell to earth around -4 billion years ago, and minerals rich in silica (silicates) and iron abounded on and below the Earth's surface.

1. The origin of life: a story of a cell

Until the middle of the 19th century, the origin of life did not pose any problems: life was the work of a Creator. For atheists or critical believers, the theory of spontaneous generation solved the problem: life (at least simple organisms) appeared spontaneously from mineral substances when the environment was suitable. When, in the 1860s, Pasteur demonstrated that this spontaneous appearance of living organisms did not occur under natural conditions and durations compatible with laboratory experiments, the problem became crucial. One hundred and fifty years later, how can we summarize the problem? Life is above all a story of a **cell** (see Origin of the first cells...). To make a cell is "conceptually" quite easy. This requires 3 steps that can be described by going back in time. The most recent step is the formation of the cell itself. This requires complex **organic macromolecules**, polymers such as **proteins**, **nucleic acids**..., if possible with properties of auto-replication{ind-text}Action of copying or reproducing oneself{end-tooltip} and catalytic properties{ind-text} the ability of a molecule (e.g. enzyme) to perform chemical reactions{end-tooltip}. These macromolecules, present in solution or suspended in water, must also group together, create **membranes** that are more or less permeable, and associate into entities that isolate an internal environment from an external environment. Before this 3rd step, a 2nd step is needed, which corresponds to the manufacture of these macromolecules by **polymerization** of simpler but already quite complex carbon molecules such as **amino acids**, **nitrogenous bases**, simple **sugars**... And before this 2nd step, a 1st step is needed, i.e. to manufacture those already complex molecules that will polymerize. This first stage in the history of life, the oldest, therefore consists in synthesizing amino acids, nitrogenous bases... from simple and omnipresent molecules (carbon dioxide, CO_2; water, H_2O; ammonia, NH_3; hydrogen cyanide, CNH...) containing the main components of life: carbon (C), hydrogen (H), oxygen (O) and nitrogen (N).

2. Fossil evidence of primitive life on Earth

Figure 1. Example of a morphological marker proving the existence of an ancient life: beautifully sized stromatolites (here in South Africa) dating back about -3 billion years [Source : photo Pierre Thomas]

Are there any witnesses to the origin of life? To know where to look for it, you must first try to identify the environment, conditions and time in which these three stages took place. The oldest morphological traces of life forming consensus in 2016 date back -3.5 billion years. These are indirect traces found in Australian or South African **sedimentary rocks** showing the existence of bacterial veils {ind-text} Also called biofilms. Microbial communities marked by the secretion of an adhesive and protective matrix. Usually formed in water or in an aqueous medium. Biofilms were probably the first colonies of living organisms {end-tooltip} and stromatolites{ind-text} Often calcareous structures that develop in shallow aquatic, marine or freshwater environments. They are both sedimentary and biogenic in origin (built by cyanobacterial communities). The stromatolite as a structure is not alive, only the cyanobacteria that build it are. Stromatolites already existed 3.5 billion years ago; they are found on all continents.{end-tooltip} that have a morphology quite similar to their current equivalents (Figure 1) (see The biosphere, a major geological actor). Remnants of bacterial cells are also identifiable, but their origin is still the subject of debate. In these sedimentary rocks, there is also organic matter, enriched in ^{12}C, the light (and major) isotope{ind-text} Special form of a chemical element. Isotopes of the same element different from each other by the number of neutrons but they have the same number of protons and electrons.{end-tooltip} of carbon. However, the synthesis of organic molecules by enzymatic processes (such as the **Benson and Calvin cycle**) enriches organic matter to ^{12}C in the same proportions as found in these old rocks. No morphological life index older than 3.5 billion years is known. But we know of metamorphic rocks{ind-text} Rocks that have undergone mineralogical and structural transformation following a rise in temperature and pressure.{end-tooltip} showing an enrichment in ^{12}C. We know a lot about them in Greenland where they date back to -3.8 billion years ago. The oldest rocks (in fact minerals) with such anomalies in ^{12}C have been found in Australia; they date back -4.1 billion years, suggesting that a biosphere already existed at that time. Life would have appeared on Earth at a time when the atmosphere and ocean were devoid of **oxygen** (O_2), when the Earth was still bombarded by countless comets and meteorites, when **volcanism** was more abundant than today... It is in such a context that the 3 main stages that are at the origin of life had to take place.

3. The three stages of the origin of life

3.1. Forming a cell from organic macromolecules...

The geologist is not the best equipped to understand step 3: i.e. making cells from polymers and other organic macromolecules. This step left no fossil record. It can only relate to the work of chemists and biochemists, which is far from having been completed in 2016. Since the beginning of the 20th century, experiments (and more recently modelling) have indicated possible paths and suggested what could have happened: grouping polymers into films, transforming films into globules, existence of RNA{ind-text}Ribonucleic acid, a molecule consisting of a sequence of ribonucleotides (adenine, cytosine, guanine, uracil) and performing many functions within the cell.{end-tooltip} having both catalytic properties, the ability to perform reduction reactions{ind-text}Chemical reactions based on the transfer of electrons between a molecule that oxidizes (loses an electron) and another that is reduced (gains an electron).{end-tooltip} and the ability to transmit information necessary for their replication...

3.2. Manufacturing organic macromolecules by polymerization

The geologist is much more concerned with the 2nd stage of the origin of life: i.e. manufacturing these macromolecules by polymerization of simpler organic monomers such as amino acids, nitrogenous bases... Indeed, this polymerization is greatly facilitated by catalysts, and geology provides such catalysts: they are sulphides such as **pyrite** (FeS_2) and phyllosilicates.{ind-text} or lamellar silicates, minerals from the group of silicates built by stacking tetrahedral layers.{end-tooltip} The main ones are **clays** and **serpentines**. The surface of these minerals has the property of adsorbing monomers such as amino acids, concentrating them and greatly promoting their polymerization. Sulphides are common in volcanic regions, and clays and serpentines are abundant when water comes into contact with silicate rocks, particularly basalt{ind-text}Dark volcanic rock from rapidly cooled magma.{end-tooltip} and periodotites{ind-text}Magmatic rock, of an ultrabasic nature, which constitutes the major part of the Earth's upper mantle.{end-tooltip}, rocks constituting the lithosphere{ind-text}Surface part of the earth consisting of two superposed terrestrial layers: the crust (oceanic or continental) and the rigid upper mantle. It is between 60 and 70 km thick under the oceans and 100 km under the continents.{end-tooltip}. If, therefore, we have an aqueous medium "rich" in amino acid molecules and other organic molecules (sometimes referred to as " **primitive soup**"), phyllosilicates and/or sulphides, these steps 2 and 3 can then "spontaneously" give rise to proto-cells{ind-text}Cell prototypes, rudimentary cells.{end-tooltip} which will become the first living organisms.

3.3. Making the "molecules of life"

Which source(s) of amino acids, nitrogenous bases and other monomers{in-text}Basic constituents of complex molecules have been the source(s)? Thus amino acids form proteins, oses form complex sugars, nucleotides form nucleic acids {end-tooltip} (sometimes called "elementary building blocks of life"), an essential first step in the development of complex polymers such as proteins, nucleic acids and other macromolecules? Scientists studying Earth and the Solar System propose three mechanisms at the origin of this first step, three not incompatible origins.

The atmospheric origin. The first origin (chronologically speaking) was proposed in 1953: these are Miller's famous experiments [1]. At the time, it was thought that the Earth's atmosphere around -4 billion years ago was mainly composed of methane (CH_4), ammonia (NH_3), hydrogen (H_2) and water (H_2O). An external energy supply (electric discharge, UV photons...) is sufficient to generate more complex molecules, such as **amino acids** (read Once upon a time there was life...). But it is now believed that the Earth's primitive atmosphere did not include H_2, and that its carbon was mainly in the form of CO_2 and not CH_4. With such an atmosphere, the syntheses are not the same, and discharges and UV form almost exclusively compounds that are too oxidized. Miller's experiments would therefore not concern the Earth. However, it is far from being ruled out that in particular sites, in an atmosphere rich in volcanic compounds for example, such syntheses may be possible. The search continues.

The alien origin. Comets and meteorites are the second possible source of the origin of life's molecules (Figure 2). We know since 1864 with the fall of the meteorite of Pride (Tarn et Garonne) that some meteorites (the chondrites carbonaceous{ind-text}Type of meteorites considered as the most primitive meteorites of the solar system (their elementary composition is very close to that of the sun). They are characterized by their richness in carbon, water and volatile gases (especially rare gases). {end-tooltip}) contain these famous "**elementary building blocks of life**". It was proven in the 1960s that these organic molecules were intrinsic to the meteorite and did not come from land-based pollution, contrary to what was mentioned (or even invoked) as soon as the Pride meteorite fell. One ton of this meteorite class contains 60 grams of amino acids, the mass of a hen's egg, and 1.3 grams of nitrogenous bases.

Figure 2. Comet and meteorite. On the left, a sample of carbonaceous chondrite. Such meteorites contain up to 5% carbon, including 60 ppm amino acids (sample/photo Pierre Thomas). On the right, image of comet 67P-CG (known as Churyumov-Gerasimenko, or Chury) photographed on 26 September 2014 by the European probe Rosetta. [Source : Photo © Esa, Rosetta, NavCam. The analyses (still preliminary) show that this comet is rich in organic molecules]

Simple organic molecules are detectable (by spectral analysis) in the tail of comets. *In situ* analyses by the *Giotto* probe (1986) and the *Rosetta-Philae* mission (2014-2016) confirmed the presence of organic molecules in comets. What a pity that the *Philae* lander could not carry out its analyses of the soil of comet 67P-CG (called *Churiumov-Guerassimenko* or simply Churi). But just by analyzing the volatile compounds escaping from this soil, *Philae* has identified 16 carbonaceous molecules, some of which are precursors to amino acid synthesis (see How to study the organic Molecules of Comets). And one of the cometary grains brought back to Earth in 2006 by the American *Stardust* probe contained glycine, the simplest of amino acids. Wisteria has also been detected in the tail of the comet Tchouri thanks to the *Rosina* instrument, installed on the *Rosetta* probe. When meteorites or cometary fragments and dust arrive on Earth, the majority are burned by crossing the atmosphere; however, a significant portion arrive intact at the surface. Based on the current flow of meteorites and that of the past (deduced from lunar studies), and depending on the organic carbon content of these objects, we have estimated that 10^{15} to 10^{16} kg of organic molecules arrived on Earth without being destroyed between -4.5 and -4 billion years ago. These extraterrestrial organic molecules are believed to date much of the origin of the solar system. The external dusts of the pre-solar nebula (those that gathered to become comets and carbonaceous chondrites) must have been rich in H_2O ice and other small molecules (CO, CO_2, CH_4, NH_3, CH_3O...). And when such a mixture of ice is irradiated with UV photons or cosmic rays, more complex molecules are formed, including our famous elementary bricks.

The geological origin. The ocean floor and/or subsoil of the continents are the 3rd possible source of the origin of life in the form of organic molecules. We know how to make organic molecules with H_2 and CO_2 at high or medium temperature in the presence of suitable catalysts:

$CO_2 + 4\ H_2 \rightarrow CH_4$ (and other more complex molecules) + $2\ H_2O$ (*Fischer-Tropsch* reaction)

In the presence of NH_3 (ammonia) or HCN (hydrogen cyanide), amino acids and nitrogen bases may be synthesized (*Strecker* reaction). However, when water that is not too cold (T ≥ 80°C) comes into contact with silicates containing iron in the Fe^{2+} form (olivine, pyroxene, etc.), a reaction occurs whose type can be summarized by the following equation:

Olivine + $H_2O \rightarrow$ serpentine + brucite + magnetite + H_2

Figure 3. Flaming release of a mixture of methane, ethane, propane and dihydrogen from serpentine soil in southern Turkey. This site, named "la Chimère" proves the reality of organosynthesis reactions such as Ficher-Tropsch, since they take place nowadays in the Turkish subsoil [Source : photo Pierre Thomas]

H_2 can therefore be synthesized as soon as water (seawater, groundwater, etc.) comes into contact with hot olivine-rich rocks such as peridotite (Figure 3). This reaction produces magnetite (Fe_3O_4) and serpentine. However, magnetite is a catalyst that promotes Ficher-Tropsch-type reactions. In addition, brucite ($Mg[OH]_2$) maintains a basic environment that promotes Strecker-type reactions. And it turns out that serpentine is a very good catalyst for the polymerization of organic monomers. These sites where water is in contact with hot olivines therefore had "everything it takes" for life to appear: typical amino acid monomers, and a catalyst to polymerize them. The other two proposed mechanisms (monomers brought by meteorites or comets, or synthesized in the atmosphere and then dropped to the ground) require another condition: that they have arrived in a geographical area rich in phyllosilicates. But there is no shortage of phyllosilicates.

4. Conclusion and perspectives of the origin of life

All of the above strongly suggests that the origin of life is a spontaneous phenomenon that is "quite easy" to achieve because it does not require any exceptional conditions; the "speed" with which life appeared on Earth reinforces this impression. The terms "easy" and "fast" must obviously be understood in a geological sense. "Fast" means that life took less than 400 million years to appear, or less than 8% of the Earth's history. And "easy" must be understood in the sense that a puzzle is "easy" when it is done "quickly". All this also suggests that life could have appeared wherever there was liquid water, meteorite and comet arrivals and/or water in contact with olivine or pyroxenes. Such sites are not lacking in the solar system, particularly Mars, Europe (Jupiter satellite), Enceladus (Saturn satellite), not to mention countless extrasolar planets. Future research will tell us what's going on! As for Mars, Europe and Enceladus, it is "just" a matter of time to go and see them on site, as they are accessible from Earth using space probes. For extra-solar planets, which cannot be studied *in situ* in the foreseeable future, it will be necessary to make do with spectral studies of their atmosphere and surface. One of the easiest avenues to explore, although still outside our instrumental reach in 2016, will be to look in the atmosphere of an exoplanet for the coexistence of spectral lines of highly oxidizing (such as O_2) and highly reducing (such as CH_4) compounds. This coexistence will prove that there is a strong chemical imbalance in this atmosphere. But life is a tremendous source of chemical imbalance!

References and notes

[1] Miller SL & Urey HC (1959) *Organic Compound Synthesis on the Primitive Earth,* Science, 130, pp. 245-251.

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