Lecture 5: Pre-Biological Chemical Evolution and the Origin of Life

Aims of Lecture

(1) To examine the possibilities for the pre-biological synthesis of organic molecules;

(2) To discuss theories for the origin of life, and in particular the concept of an ‘RNA world’

(3) To discuss possible locations for the origin of life

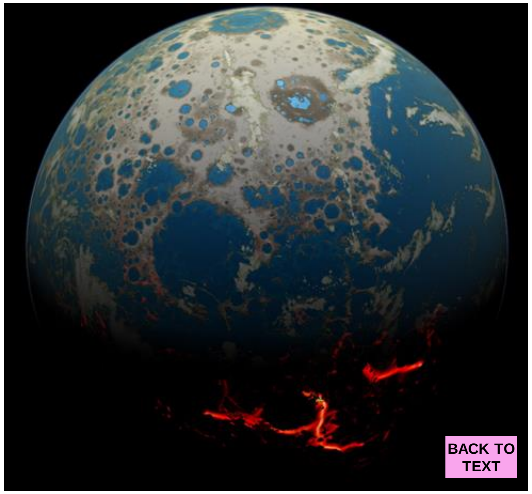

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Fig. 1. Artist’s conception of the Earth ~4 Gyr ago (image: Simone Marchi/SwRI/NASA).

1. Introduction

Assuming life to be indigenous to Earth, sometime around 4.0±0.5 Gyr ago complex biochemistry, including self-replicating molecules and autocatalytic reaction networks, arose from geochemistry. This must have occurred in conditions appropriate to the early Earth: i.e., a planet with liquid water on its surface, a CO_2 –dominated atmosphere with no free oxygen, lots of volcanic heat (including likely submarine hydrothermal vents), and frequent meteorite impacts (Fig. 1). We can refer to this transition as the ‘origin of life’, but presumably it was a protracted evolutionary *process* rather than a single event.

If life didn't originate on Earth (discussed Lecture 9) then the geochemical-biochemical transition would have occurred in some other environment and at an earlier time, with life then being transported to the early Earth.

Unfortunately, there is no universally agreed definition of life. However, Gerald Joyce, a leading researcher into life's origins, has offered the following working definition that NASA has adopted and that may be helpful:

"Life is a self-sustaining chemical system capable of undergoing Darwinian evolution"

The central problem of understanding the origin of life is to identify chemical systems capable of satisfying these criteria and which could plausibly evolve into the DNA/protein-based life we have today.

2. Pre-biological synthesis of organic molecules

Life today either recycles the organic molecules on which it depends (by eating other life) or manufactures them through complicated metabolic processes (such as photosynthesis or chemosynthesis (discussed in Lecture 7). The earliest lifeforms would not have had these options – rather they somehow evolved out of a pre-existing mixture of organic molecules (sometimes called the 'primordial soup').

It follows that non-biological processes on the early Earth (or wherever else life has evolved) must have produced sufficient quantities of organic raw materials to permit this to occur. There appear broadly to be three possibilities (or some combination of them):

- Synthesis of organics at or near the Earth's surface
- Synthesis of organics at hydrothermal vents
- Delivery of organics to the early Earth by comets or asteroids

2.1 Pre-biotic synthesis at the Earth's surface: the Urey-Miller Experiment

The first experiment to try and determine whether the early environment of the Earth could produce organic molecules abiotically was performed in 1953 by Stanley Miller and Harold Urey at the University of Chicago, who produced an experimental apparatus (Fig. 2) which tried to recreate what were then thought to be the chemical conditions on the early Earth. A flask of water represented the oceans, above which was another flask containing strongly reducing gases such as CH_4, NH_3 and H_2. An electrical discharge (i.e. a spark) was used to simulate lightning, and the water vapour in the 'atmosphere' was condensed and collected in a U-tube at the bottom of the apparatus.

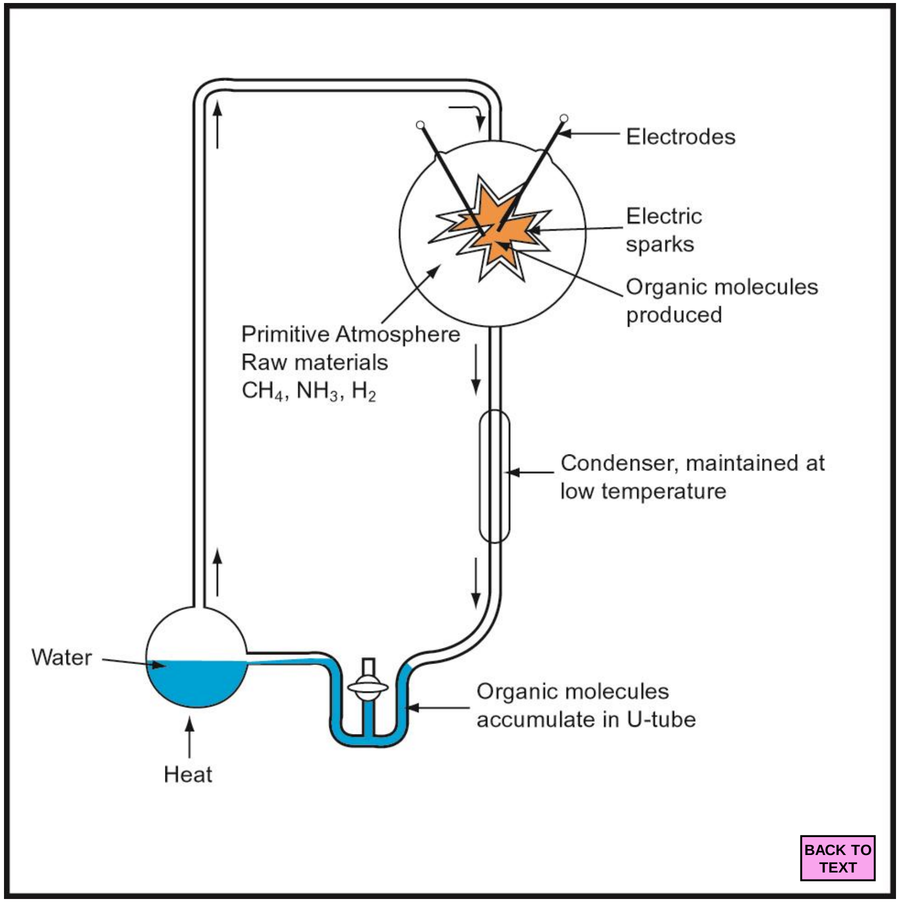

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Fig.2. Schematic diagram of the Urey-Miller experiment (see text for details).

After a few days, the contents of this were examined to see if organic molecules had been produced. The results were very encouraging. In the initial experiments about 16% of the original carbon was converted into organic molecules, including amino acids – glycine alone accounted for 2% of the original carbon. Later experiments have produced most (at least 17) of the 20 amino acids used by life on Earth, several complex lipids and sugars (including ribose), and all five of the DNA/RNA bases.

However, since the time of the original experiments, we have come to realise that the Earth's early atmosphere was probably much more oxidising than assumed by Urey and Miller in 1953. Specifically, it now seems much more likely that most of the carbon would have been in the form of CO_2 rather than CH_4, and most of the nitrogen in N_2 rather than NH_3 , with very little free H_2. Under these conditions, Urey-Miller experiments produce much smaller yields of organic molecules – more than a thousand times less in the absence of H_2 (Fig. 3). Thus, unless local sources of H_2 were available (which they may have been around volcanic vents), significant prebiotic synthesis of organic molecules may not, after all, have occurred at the surface of the early Earth.

2.2 Hydrothermal vents

At mid-ocean ridges geothermally heated water is injected into the base of the ocean at temperatures as high as 450°C. The water cools rapidly, and minerals that have been dissolved in it at high temperature precipitate out to form the famous 'black smokers' (Fig. 4). Among the substances dissolved in the hydrothermal fluids are CO_2, derived ultimately from the mantle, and H_2, produced by water-mineral ('serpentinization') reactions (discussed in Lecture 7).

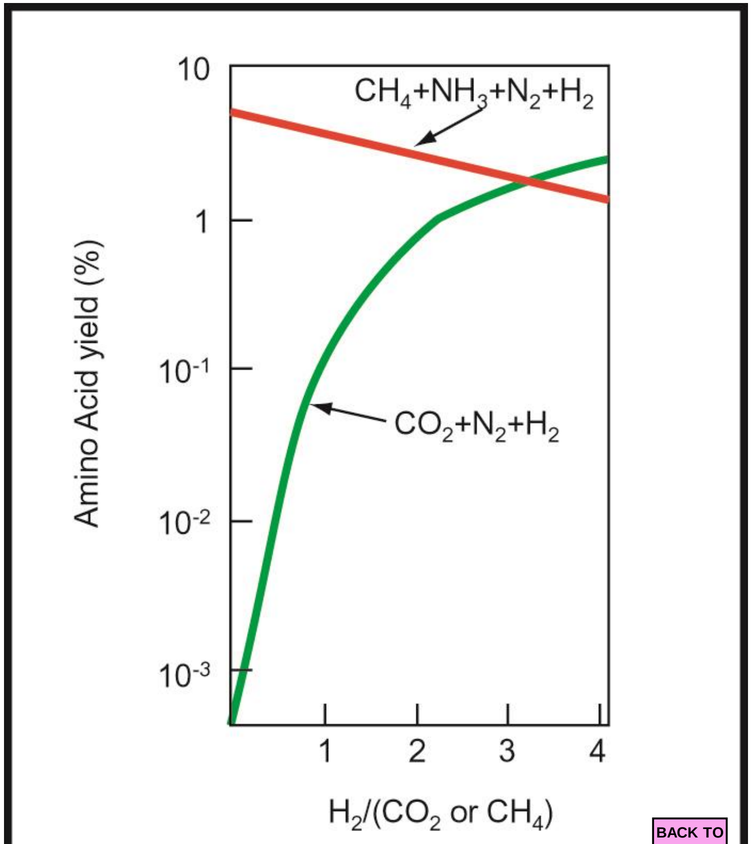

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Fig.3. Graph showing the amino acid yield (i.e. percentage of carbon incorporated into amino acid molecules) for Urey-Miller experiments conducted with different gaseous mixtures. The red line shows the case for a reducing atmosphere containing methane and ammonia, while the green line shows the results for an oxidising atmosphere containing carbon dioxide and nitrogen. The effect of adding hydrogen to both mixtures is also shown (the x-axis gives the H_2/CH_4 and H_2/CO_2 ratios for the red and green lines, respectively).

Under these conditions, some of the carbon in CO_2 can be converted into organic molecules similar to those produced by the Urey-Miller experiment. Thus, hydrothermal vents are a possible source of organic molecules at the ocean floor, albeit in localised areas. This may support other evidence (see Lecture 6) that life may have arisen in a hydrothermal environment. At least it shows that a source of organic molecules would have been available in such an environment.

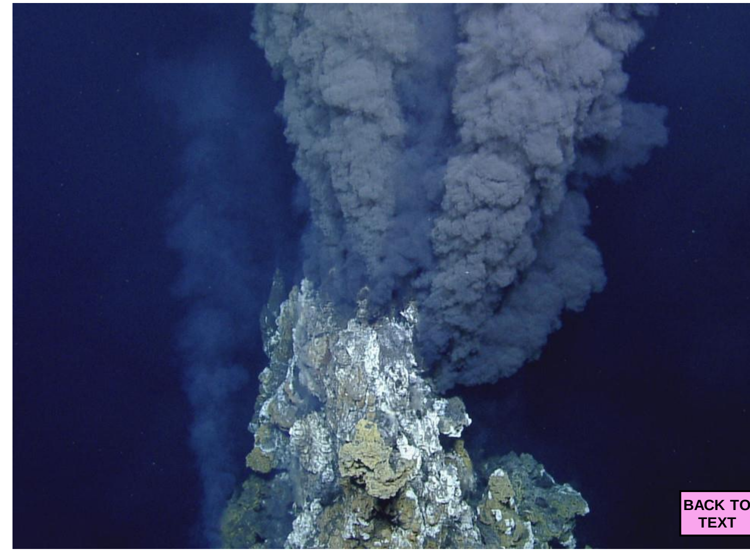


Fig.4. A ‘black smoker’ at hydrothermal vent on the ocean floor. These environments are capable of synthesising organic molecules, similar to those produced in Urey- Miller experiments (Public domain).

2.3 Cosmic delivery

We saw in Lecture 1 that interstellar chemistry, and chemistry in the protoplanetary disk itself, may also have produced a wide range of organic molecules. These organics will likely have become incorporated into comets and meteorites. This expectation is supported by astronomical and spacecraft studies of comets (Fig. 5), which reveal them to be rich in organic molecules, and by the fact that many organic molecules, including amino acids, are found in carbonaceous chondrite meteorites (Fig. 6). Impacts of comets and meteorites with the Earth may therefore introduce externally synthesised organic material into the terrestrial environment.

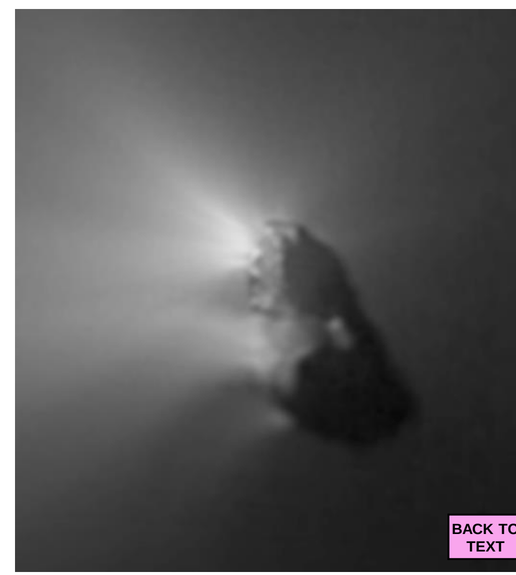
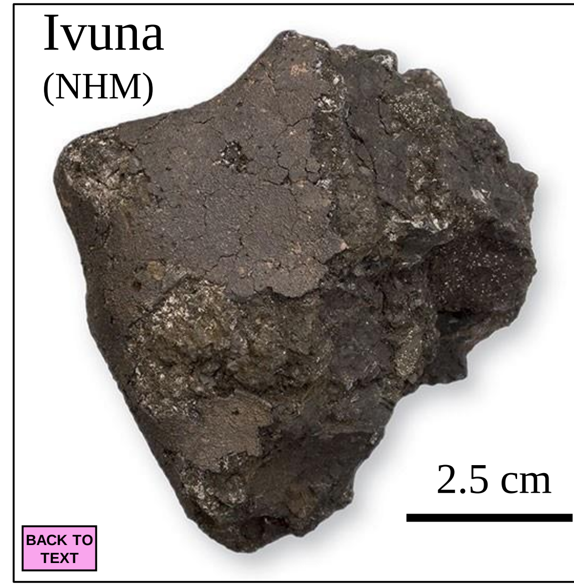


Fig.5. The nucleus of Comet Halley (~15 km long) imaged by the Giotto spacecraft in 1986 (ESA).

Fig.6. A sample of the Ivuna carbonaceous chondrite in the Natural History Museum, London. Such meteorites contain hydrated minerals (~ 10% water by mass) and ~2-4% carbon, much of it in organic molecules including amino acids. The fact that such meteorites survive landing on Earth intact indicates that they must have introduced volatiles and organic molecules to the Earth's surface in the past (credit: NHM).



2.4 Summary of prebiotic synthesis

There are two points to take away from this discussion of the prebiotic synthesis of organic compounds:

- The three processes discussed are not mutually exclusive – all three may have been important on the early Earth; and
- The relative ease of producing organic molecules in a wide range of natural environments (from interstellar space to hydrothermal vents) shows that they are likely to be common in the Universe – a shortage of raw materials is not, in itself, likely to be an impediment to the origin of life.

Given a source of suitable organic raw material, we still have to ask how this collection of chemicals made the transition to Joyce's "self sustaining chemical system." No one knows how this happened, but, as we saw in Lecture 3, it does seem to have occurred very rapidly after the end of the heavy bombardment, and perhaps even before.

3. The RNA World and its limitations

3.1 The RNA World concept

As we have seen, modern cells use DNA as a repository of information, and proteins (specifically enzymes) to catalyse chemical reactions. Between the two, RNA plays crucial and multiple roles (e.g. mRNA, tRNA, rRNA), and this may suggest that the first 'living' systems were based on RNA: the so-called 'RNA World'. There are four main lines of evidence for the RNA world hypothesis:

- The vital, multiple roles of RNA in today's cells, which may be a left-over, a 'memory', of a time when RNA was even more important (recall Fig. 13 in Lecture 4).
- RNA, like DNA, can record genetic information as its bases are complementary to those of DNA (e.g. mRNA).
- Like enzymes, RNA is able to catalyse chemical reactions (as so-called ribozymes). This is possible because, as a single strand, RNA is able to fold into complex, enzyme-like shapes.
- Under certain (laboratory) conditions, RNA has been shown to be capable of catalysing its own replication (see, e.g., Tracey Lincoln and Gerald Joyce, "Self-sustained replication of an RNA enzyme", *Science*, vol. 323, pp. 1229-1232, 2009).

A chemical system like this, consisting of interacting RNA molecules, which are both carriers of genetic information and catalysts of their own replication, could be considered 'alive' by Joyce's definition.

Note that, in order to keep all the reactants together, they must have some how become enclosed within a membrane of some kind. Whether this resembled the present phospholipid-type membrane, or some simpler arrangement, can only be speculated about at present.

Once a self-replicating chemical system arises, natural selection would favour those ‘RNA species’ that are best able to reproduce themselves. This in turn may have led to the evolution of a more robust information carrier (double-stranded DNA rather than single-stranded RNA), and more efficient molecular catalysts (i.e. specialised protein-based enzymes rather than ribozymes).

Although in many ways the RNA world is an attractive bridge between prebiotic chemistry and DNA/protein-based life, when examined closely it is found to suffer from a number of difficulties. The main problems are as follows:

- While the components of RNA nucleotides (ribose, phosphates, bases) are all produced by Urey-Miller type experiments, getting them to assemble into actual nucleotides under prebiotic conditions has not yet been achieved.

- Although the components of RNA can be produced under abiotic conditions, they are actually only a minority of all the molecules produced in Urey-Miller-type syntheses. For example, although Urey-Miller experiments do produce ribose, they also produce many other sugars that are of no biological significance, and which interfere with attempts to synthesise RNA itself. As Gerald Joyce has himself put it in a review of the RNA world concept (*Nature*, vol. 418, p. 214, 2002):

  “***The main difficulty is overcoming the clutter of pre-biotic chemistry*.**”

- Nucleotides are chiral molecules (i.e. left- and right-handed mirror images exist). Modern life uses right-handed sugars in DNA and RNA, whereas prebiotic syntheses produce a 50:50 mixture of left- and right-handed molecules (such a mixture is said to be ‘racemic’). However, a racemic mixture of nucleotides further inhibits the growth of strands of RNA. Somehow, nature has managed to select only right-handed molecules from a racemic mixture.

3.2 A Pre-RNA world?

These difficulties suggest that, if there ever was a RNA world, it must have been preceded by an earlier stage as sketched below:

Pre-biotic Chemistry → Pre-RNA World → RNA World → DNA/Protein World

A pre-RNA world would have involved simpler self-replicating molecules that were easier to synthesise, yet able eventually to direct RNA synthesis. Plausible suggestions include:

(a) ‘Peptide nucleic acid’ (PNA): a simpler peptide chain with RNA bases attached (Fig. 7).

(b) Trapping of biomolecules between the layers of phyllosilicate minerals (e.g. clays), where the charges on the mineral surfaces might hold them in place to catalyse polymerization (Fig. 8).

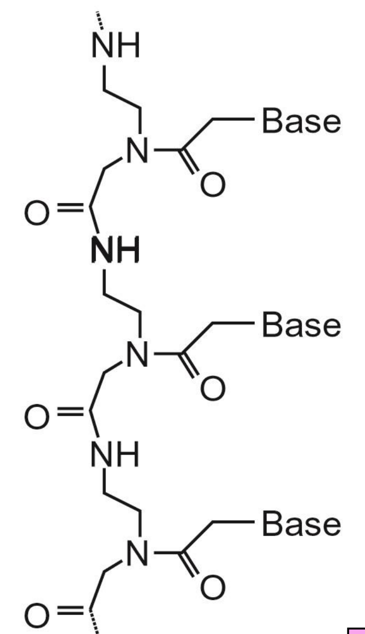


Fig. 7. Protein nucleic acid (PNA), a relatively simple molecule that may have acted as a possible intermediary between pre-biotic chemistry and the RNA world.

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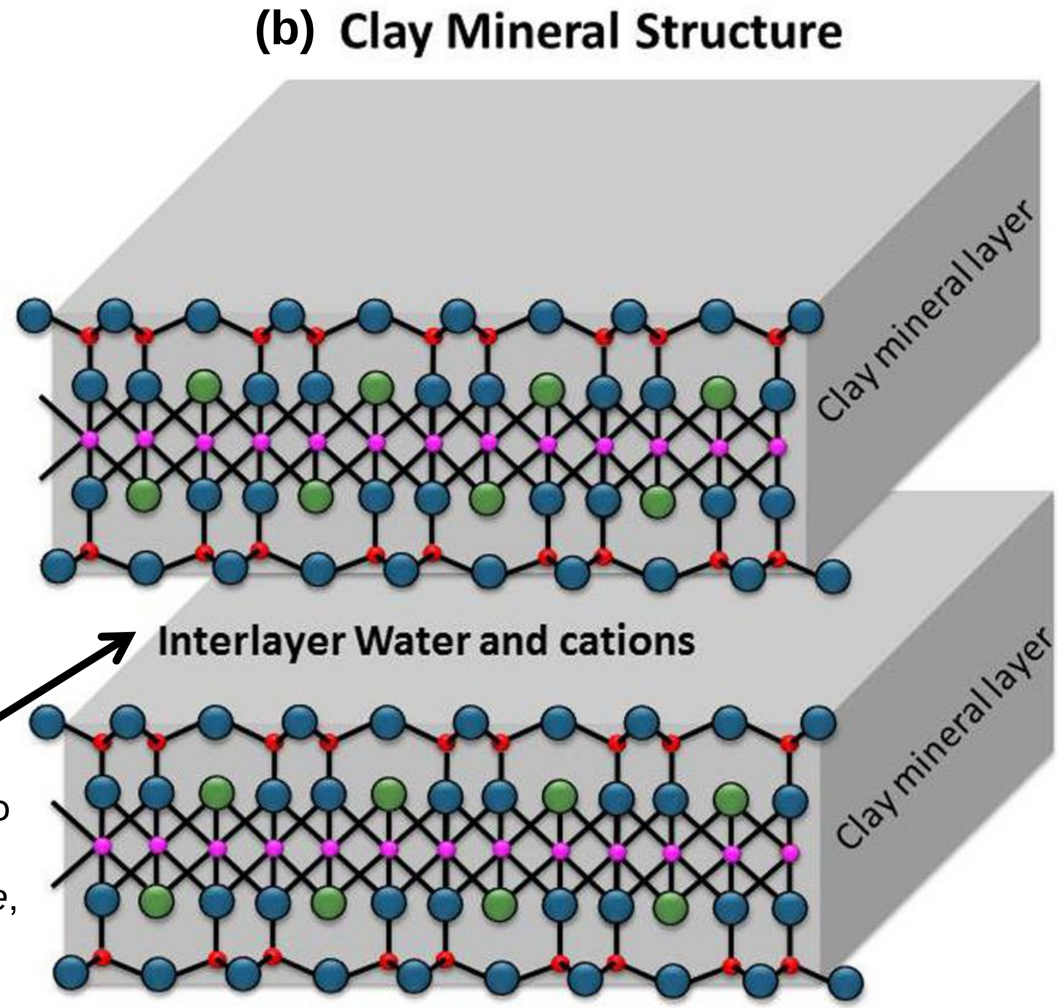

Biomolecules such as RNA trapped between phyllosilicate layers may undergo polymerization (e.g., Graham Cairns-Smith, *Clay Minerals and the Origin of Life*, CUP, 1986; see also D. Yang et al., *Science Reports*, 3, 3165, 2013).

Fig. 8. (a) Clay minerals excavated from a rock in Gale Crater on Mars by the Curiosity rover; note that clays will be ubiquitous on wet planets with basaltic rocks. (b) Schematic illustration of the molecular structure of clay minerals (images courtesy of NASA).

4. Location(s) for the Origin of Life

It is not yet known where ‘abiogenesis’ (i.e. the origin of life from non-life) occurred, but obtaining an answer to this question is crucial for understanding the planetary environments where life may *originate* rather than merely exist. An excellent recent review from an astrobiological perspective has been given by Alex Longo and Bruce Damer (*Life*, Vol. 10, Article #52, 2020). Possibilities include:

- Charles Darwin famously hypothesised a “warm little pond”:

  “*But if (& oh what a big if) we could conceive in some warm little pond with all sorts of ammonia & phosphoric salts,—light, heat, electricity &c present, that a protein compound was chemically formed, ready to undergo still more complex changes….*” (Letter to Joseph Hooker, 1 February 1871; see Fig. 9).

- Tidal pools (or other transient bodies of water) have been suggested, because repeated cycles of wetting and drying may aid in the polymerization of organic molecules (possibly assisted by clay minerals)

- Hydrothermal vents, especially alkaline vents like *Lost City* in the Atlantic (Fig. 10), have been suggested because conditions may mimic pH gradients found across cell membranes and are less extreme than at hot deep sea hydrothermal vents (e.g. Nick Lane, *The Vital Question*, 2015)

- Or possibly life did not originate on Earth at all (i.e. the theory of ‘panspermia’; Lecture 9), although this only postpones the problem…

Fig. 9. A hydrothermal pool on the flanks of the Kverkfjoll volcano in Iceland – the kind of environment that Darwin had in mind for the origin of life? (Photo: I.A. Crawford).

Fig. 10. The *Lost City* alkaline hydrothermal field may also represent the kind of environment where life arose (NASA).