Lecture 3: Earliest Evidence for Life on Earth

Aims of Lecture

(1) To summarise, and critically assess, the earliest evidence we have for life on our planet; and

(2) To briefly discuss the astrobiological implications of life's early appearance

Fig. 1. Artist's impression of the Archean (4.0-2.5 Gyr) Earth; note the stromatolites, hot springs, and volcanoes. (Courtesy of the Smithsonian Institution, painting by Peter Sawyer; http://ocean.si.edu/slideshow/ ocean-throughout-geologic-time-image-gallery).

Contents of Lecture

1. Introduction

Because the Earth is such a geologically active planet, few rocks dating from the first billion years of Earth's history have survived, and this greatly limits the number of places where we can look for evidence of early life. The earliest evidence we have for life on Earth dates from between about 3.8 and 3.4 billion years ago. Unfortunately, owing to the great age of the material, its generally altered state, and other difficulties of interpretation, much of the evidence is more ambiguous than we might wish. The locations of the most important Archaean (4.0-2.5 Gyr ago) outcrops containing evidence are shown in Fig. 2, below.

The evidence for early life on Earth consists of three main strands: fossilised micro-organisms (micro-fossils), stromatolites, and biologically altered isotope ratios. A recent review of evidence for ancient life has been provided by Emmanuelle Javaux: "Challenges in evidencing the earliest traces of life", *Nature,* vol. 572, pp. 451-460, 2019).

2. Microfossils

The oldest claimed evidence for fossilised micro-organisms comes from the 3.46 Gyr old Apex Chert, part of the Warrawoona Supergroup of Western Australia, and comparably old rocks from southern Africa (Fig. 2). However, all such claims require careful interpretation, especially if only based on morphology. For example, the first Apex Chert examples to be described consist of filamentary structures, a few microns wide and tens of microns long (Fig. 3). These were interpreted by their discoverer, J.W. Schopf of the University of California, Los Angeles, as filaments of photo-synthetic cyanobacteria.

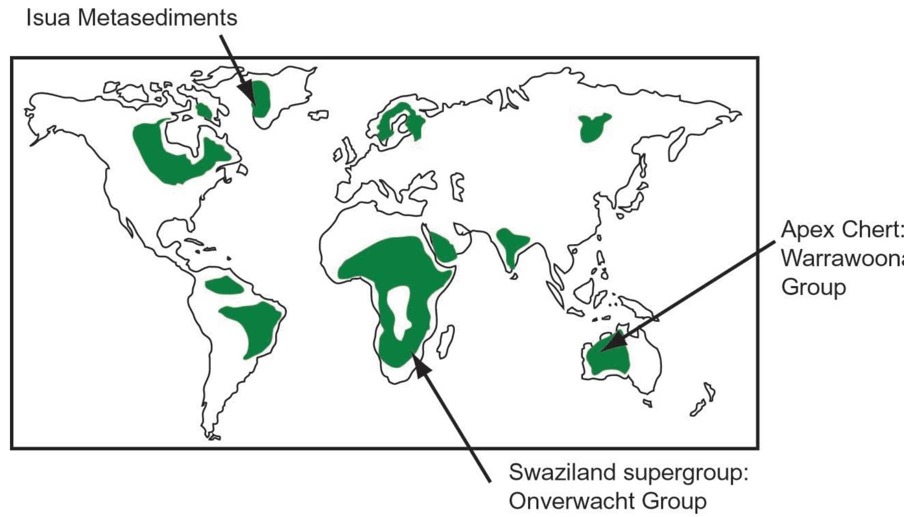


Fig. 2. The distribution of the main Archean (4.0-2.5 Gyr) rock outcrops around the world, showing those localities where the earliest evidence for life on Earth has been found.

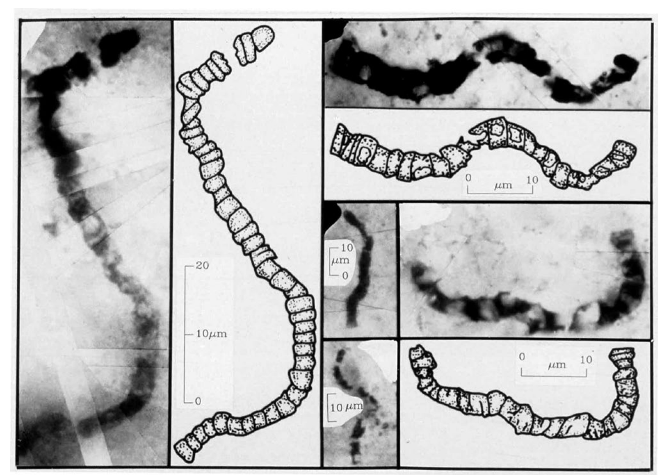


Fig. 3. Small (2-5 μm diameter) filaments discovered in the 3.46 Gyr old Apex Chert and interpreted by J.W. Schopf as the fossilised remains of cyanobacteria. (Image courtesy of J.W. Schopf).

Cyanobacteria (formally known as blue-green algae) often form filaments (Fig. 4), and Schopf interpreted the structures he found within the Apex Chert to be fossilised examples. However, since the original discovery (first published in 1993) doubt has been cast on this interpretation. There are several grounds for this:

- All we have are shapes reminiscent of species of modern cyanobacteria, but no other unambiguous evidence for a biological origin. Unfortunately, arguments based on morphology alone cannot prove a biological origin.
- Apparently similar structures found nearby, even on the same microscope slide, have different morphologies which are not consistent with fossilised bacteria.
- Recent work on the Apex Chert itself has suggested that it may have formed in a sub-surface hydrothermal system (Fig. 5), which would not support cyanobacteria but might be consistent with chemoautotrophic micro-organisms (Lecture 7).

It is therefore possible that these alleged 'fossils' may be abiological carbonaceous structures, produced by the chemical interaction of hot hydrothermal fluids with the surrounding rock. One the other hand, studies of carbon isotope ratios (see below) have been found to be consistent with a biological origin, so the biological status of these specimens remains unresolved.

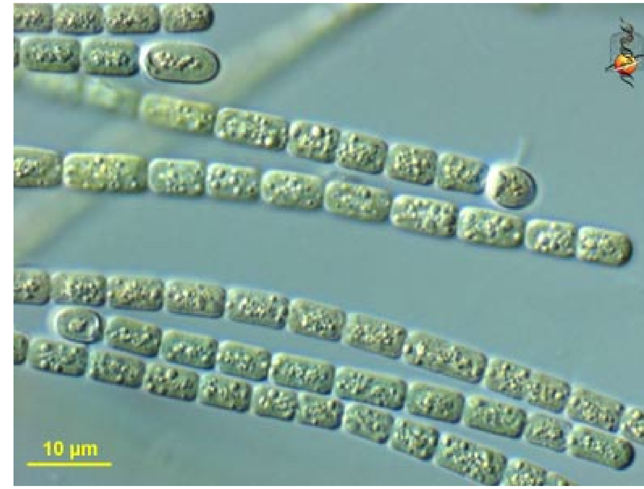


Fig. 4. Modern filamentary cyanobacteria, found in hot springs at Yellowstone National Park. Note scale bar. (Image courtesy of Woods Hole Marine Biological Laboratory, and the NASA Astrobiology Institute).

Fig.5. The Apex Chert outcrop sampled by William Schopf. Note hydrothermal dyke (photo: I.A. Crawford, 2015).

More recently, a number of better substantiated claims for ~3.5 Gyr old microfossils have appeared. These include evidence for a fossilized microbial mat from the Barberton Greenstone Belt (Onverwacht Group), South Africa, dated at 3.45 Gyr. In addition to the remains of a filamentous microbial mat (similar to stromatolites, see below), electron microscope images also reveal small (~2 μm long) rod-shaped structures interpreted as fossilized bacteria embedded in the mat (Fig 6). In this case also, the biogenic interpretation is supported by isotopic evidence (specifically a carbon isotope ratio of $\delta^{13}C = -27‰$; see below). The presence of evaporate minerals and desiccation cracks in the mat suggests that it formed in a near-surface environment.

In 2017, Matthew Dodd and Dominic Papineau from UCL published evidence for fossilised microorganisms in deposits attributed to an early Archean (4.28 to 3.77 Gyr) seafloor-hydrothermal vent deposit from Quebec (Fig. 7). This consists of fossilised hollow tubes ≥100 μm long and about 30 μm wide similar to those produced by filamentous iron-oxidising microorganisms in modern hydrothermal vent deposits. The rocks containing these structures also contain carbonaceous material depleted in ^{13}C ($\delta^{13}C = -19.7‰$ to $-25.7‰$), consistent with a biogenic origin (M. Dodd et al., *Nature*, 543, 60-64, 2017). This interpretation has proved controversial, but if correct would imply biological activity in submarine hydrothermal environments more than 3,770 million years ago, consistent with other evidence for life being present at that time.

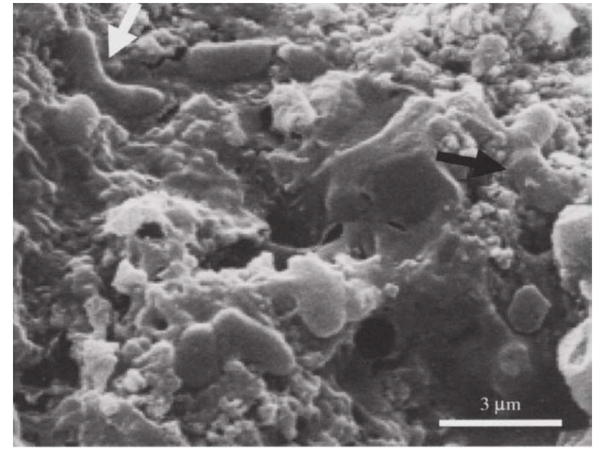


Fig. 6. Possible microfossils (arrows) within a 3.45 Gyr structure interpreted as a fossilised microbial mat from the Onverwacht Group from South Africa. Image courtesy Frances Westall (see also Westall et al., *Phil. Trans. Royal Society B*, 361, 1857, 2006).

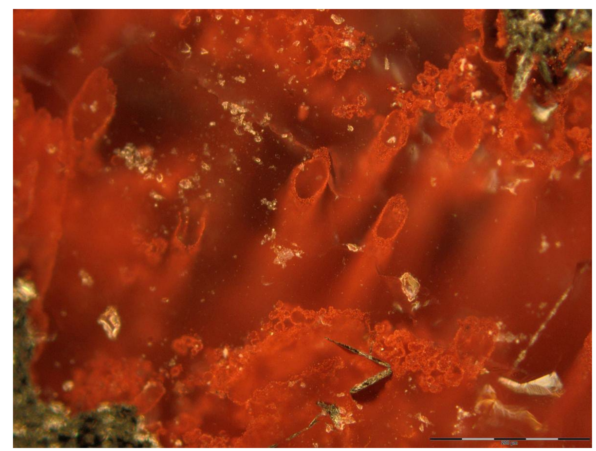


Fig. 7. Fossilised tubes identified in a 4.28-3.77 Ga hydrothermal deposit. Image courtesy of Matthew Dodd/Dominic Papineau/UCL

An exhaustive study of microfossil evidence for early life up to 2009 was provided by David Wacey (*Early Life on Earth*, Springer 2009). Wacey critically examined published claims of evidence for life older than 3.0 Gyr (including stromatolites, see below). Out of over sixty candidates, he identified 32 as ‘possible’ evidence for life (including that shown in Fig. 6) but which require further confirmation, and seven stronger candidates for which at present there were no known plausible abiological formation mechanisms. For a more recent review, see Emmanuelle Javaux: “Challenges in evidencing the earliest traces of life”.

3. Stromatolites

Stromatolites are bio-sedimentary structures built up by successive layers of microbial mats. Some contemporary stromatolites are shown in Fig. 8 (note that these famous examples above water are actually ‘relict’ stromatolites, stranded by falling sea level ~1000 years ago; active stromatolites are off-shore). In modern examples, the upper layer (the ‘growth surface’) is formed by photosynthetic cyanobacteria, below which is an ‘undermat’ populated by other micro-organisms living off the products of photosynthetic microbes above them (Fig. 9). The bacterial mats grow on sediments in shallow water. As the growth surface gets covered by sediment the cyanobacteria move upwards towards the light, leaving a layer of gelatinous material behind which traps the sediment. Some stromatolites are also partly constructed by micro-organisms precipitating micro-crystalline carbonates. Previous growth surfaces are then preserved as layers within the structure (Fig. 10).

Fig. 8. Contemporary stromatolites at Hamelin Pool, Shark Bay, Western Australia. (Photo: I. A. Crawford, 2015).

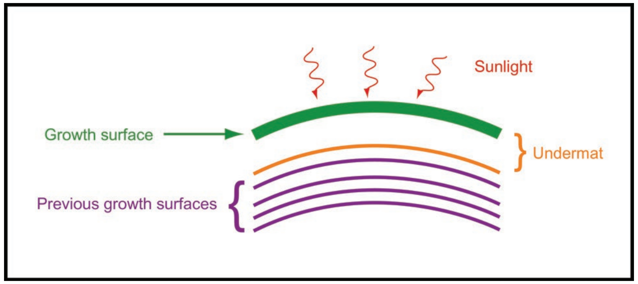
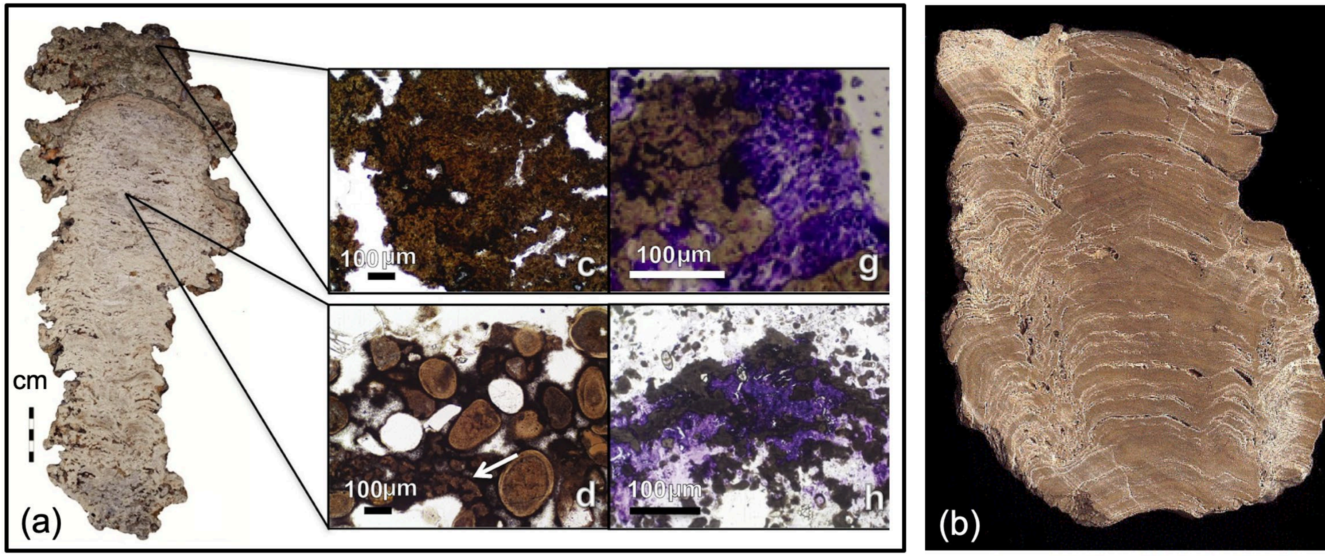


Fig. 9. Schematic illustration of the interior of a stromatolite (see text for details).

Fig. 10. Layering in stromatolites. **(a)** cross-section of a modern Shark Bay stromatolite; the insets show microcrystalline carbonate (brown) and organic material (blue) (for details see: Suosaari et al., *Scientific Reports*, 6: 20557, 2016; Open Access CC-BY-4.0). **(b)** Cross-section through a fossil stromatolite; note layers produced by successive growth surfaces.



The oldest recognized stromatolites are 3.4 -3.5 Gyr old, from W. Australia and S. Africa. Probably the most secure are those from the Strelley Pool Chert (Fig. 11) dating from 3.42-3.35 Gyr, where a range of geochemical evidence (including a 250-fold enrichment in rare earth elements characteristic of biosediments) and contextual studies support a biogenic origin. In her 2019 review article, Javaux identifies these stromatolites as “one of the strongest cases that has so far been documented for early traces of life.” Note that these structures may indicate the existence not only of life, but of photo-synthesis (but not necessarily oxygenic photosynthesis) ~3.4 Gyr ago.

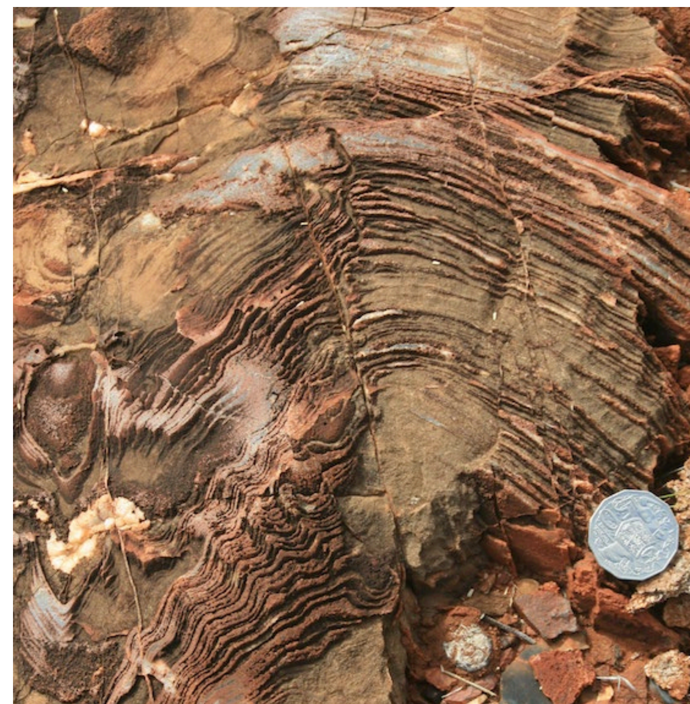


Fig. 11. Putative ~3.4 Gyr old stromatolite preserved in the Strelley Pool Chert, W. Australia (Photo: I. A. Crawford, 2015).

4. Isotope ratios

Many elements occur as different isotopes (i.e. while their atoms have the same number of protons in their nuclei, the number of neutrons differ). For example, carbon has two stable isotopes: ^{12}C, with six protons and six neutrons, and the heavier ^{13}C, with six protons and seven neutrons (carbon also has the much rarer radioactive isotope ^{14}C that is used in radiometric dating, but which does not concern us here).

On Earth, natural, inorganic substances have a ratio of $^{12}C/^{13}C = 89$. However, the various metabolic pathways that life uses to incorporate inorganic carbon (e.g. from CO_2 or CH_4) into living systems discriminate against the heavy isotope. Thus, living things are deficient in ^{13}C relative to ^{12}C. This is generally expressed by the $\delta^{13}C$ parameter, where:

$$\delta^{13}C = \left[\frac{(^{13}C/^{12}C)_{Sample}}{(^{13}C/^{12}C)_{Standard}} - 1\right] \times 1000$$

Note that $\delta^{13}C$ values are usually expressed in terms of parts per thousand, or 'per mil' (‰). As ^{13}C becomes more depleted, the $\delta^{13}C$ become more *negative*. Photosynthesis generally results in

$$\delta^{13}C = -26 \pm 7 ‰$$

and some other metabolic processes produce even more negative values. For example, methanotrophs (organisms which obtain their carbon from methane) can produce $\delta^{13}C$ values as low as −50‰.

Negative $\delta^{13}C$ values are commonly found in carbon associated with sedimentary rocks back to at least 3.5 Gyr ago (Fig. 12). This is generally taken to imply that life, and perhaps photosynthesis, existed at that time. This is consistent with the microfossil and stromatolite evidence discussed above (but note that non-biological processes can also discriminate against ^{13}C).

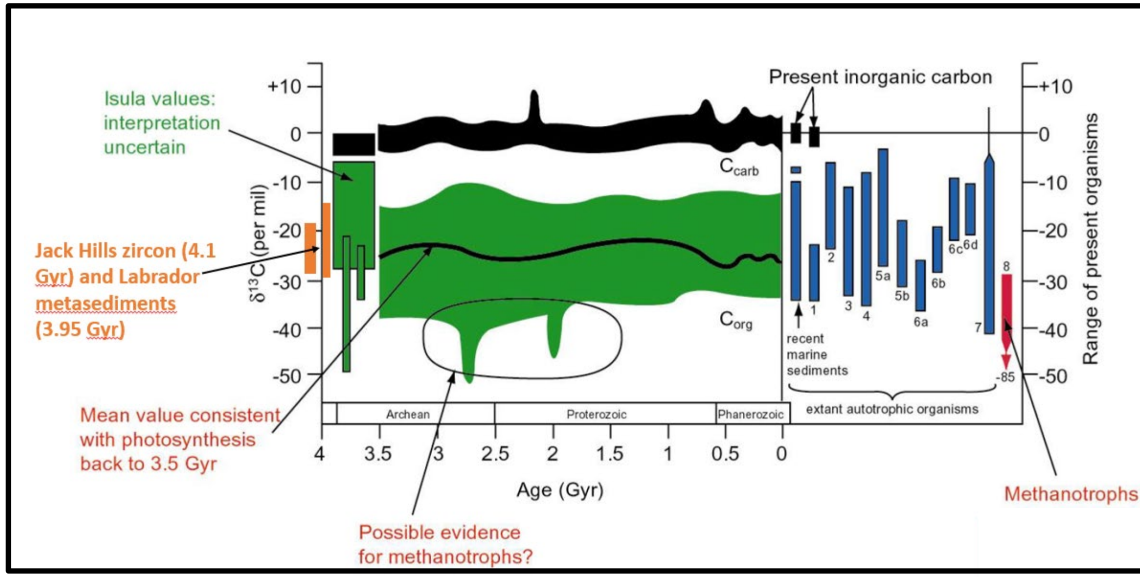


Fig. 12. Diagram showing how the $\delta^{13}C$ value of sedimentary material has varied through geological time. The range occupied by ancient organic material known prior to 2002 is shown in green (the black line traces the mean value); inorganic carbon is shown in black. The two orange bars show more recently (2015-17) published values in older samples (see text). The blue and red bars in the right-hand panel give the ranges occupied by extant autotrophs; the key for the numbers can be found in the chapter by M. Schidlowski in *Astrobiology: The Quest for the Conditions of Life*, ed. G. Horneck & C. B.-Khan (Springer, 2002), from which this figure is adapted.

Low $\delta^{13}C$ values are also found in 3.8 Gyr old metamorphosed sedimentary rocks from the Isua Peninsula in Greenland (Fig. 12). This is sometimes taken as the oldest evidence for life on Earth, but has been questioned because:

- Of the possibly non-sedimentary nature of the carbon-bearing material;
- The fact that, even if once sedimentary, the Isua rocks have since been severely metamorphosed, which may have affected the $\delta^{13}C$ values; and
- Some of the Isua $\delta^{13}C$ values are not as negative as those from 3.5 Gyr and younger deposits, and the gap between inorganic and alleged organic carbon is narrower (Fig. 12).

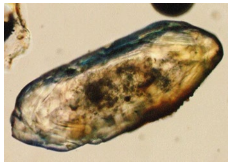
Note that simple thermal metamorphism should act to increase $\delta^{13}C$, so the original values would have been more negative (and therefore more consistent with life), but that other processes related to thermal decomposition of minerals and thermally-driven chemical reactions might reduce it (and therefore mimic a biological signature).

On the other hand, a recent geochemical study (T. Hassenkam et al., [*Nature*, 548, 78-81, 2017]) of carbonaceous compounds within the Isua metasediments has found evidence of carbon bonded to nitrogen and oxygen and phosphate, which supports a biological interpretation.

Moreover, another recent study T. Tashiro et al., [*Nature*, 549, 516-518, 2017]) has found $\delta^{13}C$ values in the range −22 ± 6‰ for graphite grains in 3.95 Gyr metamorphosed sedimentary rocks in Labrador (see Fig. 12). These are the oldest metasedimentary rocks yet studied. The authors have persuasively demonstrated that the graphite formed from carbon in sedimentary deposits prior to metamorphism and that, if anything, later metamorphic events will have made the observed $\delta^{13}C$ values less negative than the values originally present. The authors therefore argue that their data comprises the earliest evidence for autotrophs in the geological record.

Although the Isua and Labrador rocks represent the oldest known (metamorphosed) sedimentary rocks, older mineral grains are sometimes found incorporated into younger rocks. In particular, detrital zircon ($ZrSiO_4$) grains from Jack Hills in W. Australia (Fig. 13) are known with ages of up to almost 4.4 Gyr.

Fig. 13. The Jack Hills locality in Western Australia. Inset: a zircon ($ZrSiO_4$) crystal; length ~250 μm (Wikipedia Commons).



In 2015, Elizabeth Bell and colleagues (PNAS, vol. 112, pp. 14518-14521) identified graphite inclusions within a 4.1 Gyr-old zircon from Jack Hills (Fig. 13) with $\delta^{13}C = -24 \pm 5‰$, which they attribute to a biological origin. If correct, this would place the origin of life well within (or even before) the Late Heavy Bombardment. While the jury is still out on the meaning of the 4.1 Gyr Jack Hills zircon $\delta^{13}C$ values, the evidence for a biological influence on $\delta^{13}C$ values back to 3.8, or even 3.95 Gyr, now seems fairly secure.

Note that other isotope ratios may in principle act as biogenic signatures in ancient rocks. For example, work on sulphur isotopes in 3.5 Gyr old sulphate deposits in the Warrawoona Supergroup obtained negative $\delta^{34}S$ values. These have been interpreted as evidence for bacterial sulphate reduction at that time.

5. Conclusion and implications

Demonstrating a biological origin for morphological and/or chemical traces in rocks that are billions of years old is very challenging. The main conclusion of these studies is that in order to demonstrate biogenicity it is essential to have other evidence in addition to morphology (e.g. supporting geochemical evidence) and a clear understanding of the palaeo-environmental context in which the putative fossil evidence is found. Given this, it is salutatory to reflect on the difficulties we are likely to encounter when it comes to searching for evidence of ancient life on other planets!

Nevertheless, taking all the lines of evidence together (microfossils, stromatolites, and isotope ratios), it seems reasonably certain that life was established on *this* planet by at least 3.5 Gyr years ago, and possibly earlier. If life was established on Earth 3.8 to 3.5 Gyr ago, immediately after the end of the heavy bombardment (Lecture 2), it implies that our planet was inhabited almost as soon as it was habitable for microorganisms.

This in turn may imply that life arises naturally and easily in suitable environments, and thus might be common in the Universe. Indeed, this line of reasoning led the Nobel Prize-winning biochemist Christian de Duve (in his book Vital Dust: Life as a Cosmic Imperative, Basic Books, 1995) to conclude that:

> "Life is almost bound to arise … wherever physical conditions are similar to those that prevailed on our planet some four billion years ago. This conclusion seems to me inescapable."

Of course, we don't yet know that this is the correct conclusion to draw from the history of life on Earth. However, it can be tested by searching for evidence of life elsewhere, and in particular on the planet Mars (Fig. 14). We will return to this point in Lecture 8.

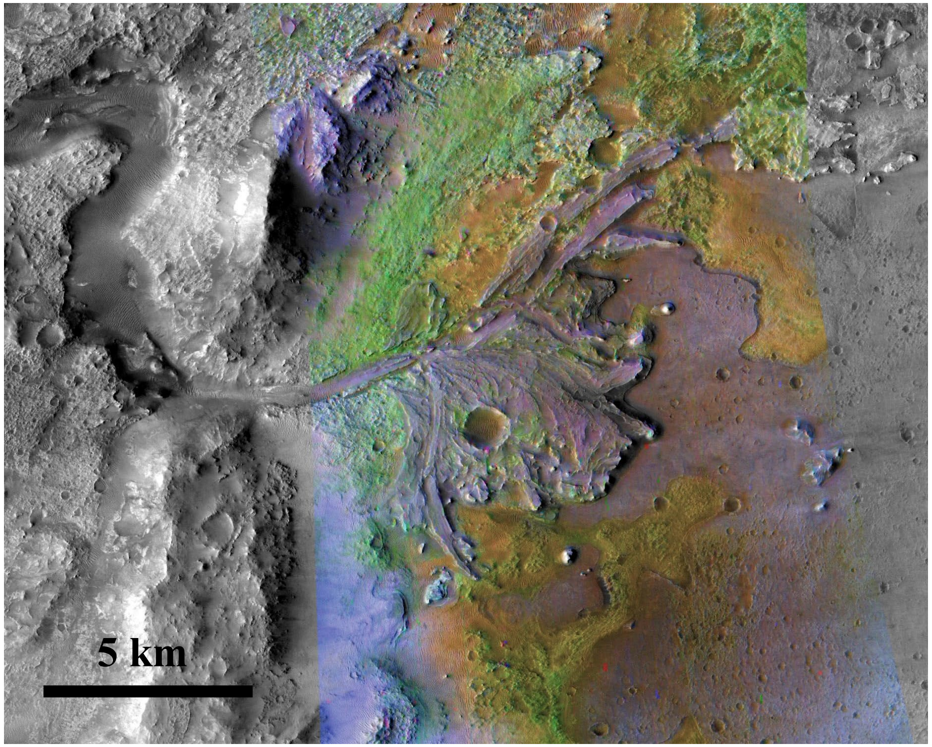


Fig. 14. Jezero crater and river delta on Mars. Abundant evidence for liquid water on early Mars implies an environment that may have been similar to that of the Earth at the same time, ~3.8 Gyr ago (Note false colours indicate surface mineralogy; B. Ehlmann et al./NASA).