The search for the earliest life on Earth

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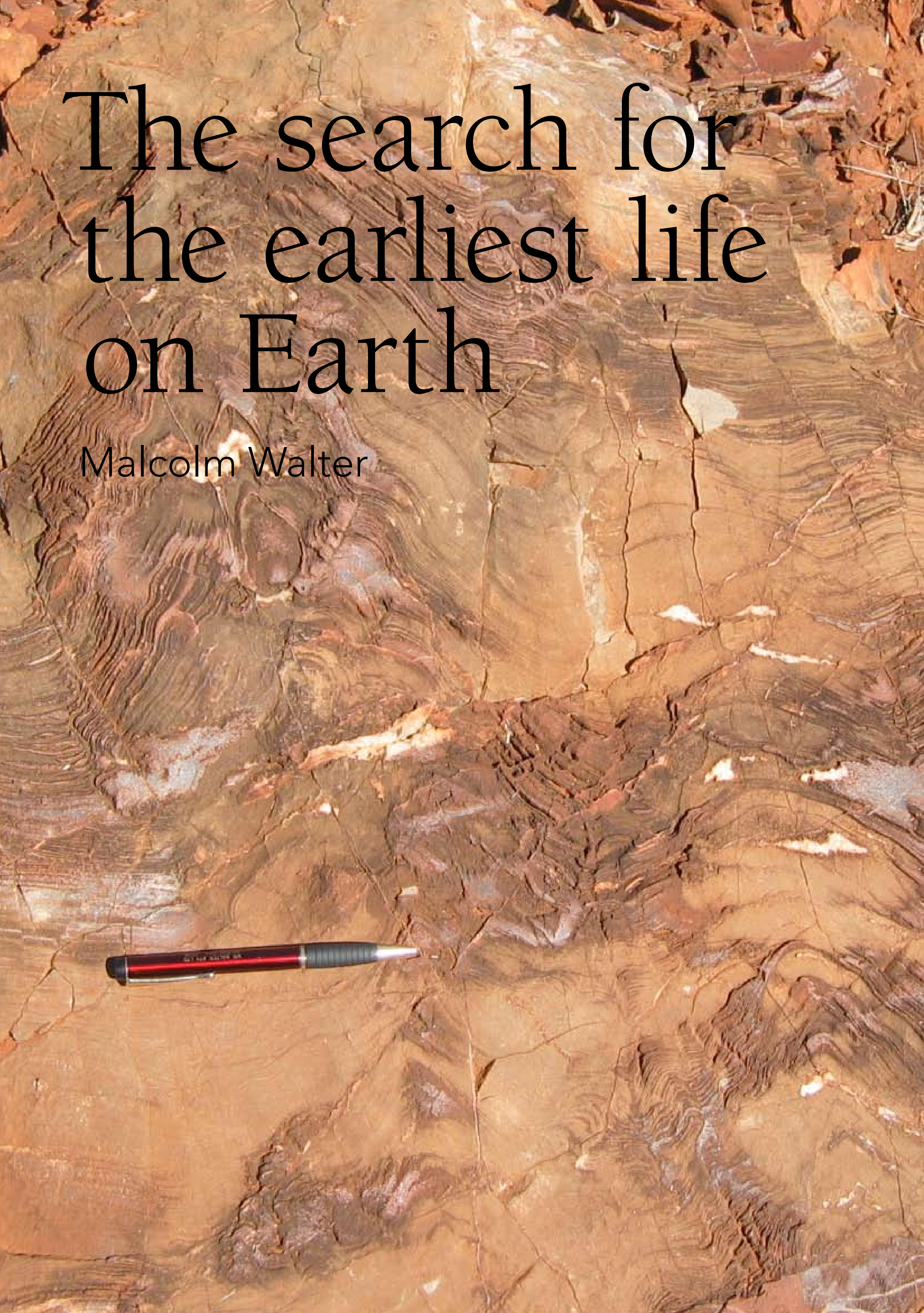

The record of life on Earth takes two forms: fossils and other evidence in the geological record, and what is encoded in the genomes of living organisms.

The rock record – limitations

What we can learn from rocks diminishes back through time. The further we go back in time, the fewer the rocks preserved. That is because of natural recycling processes: rocks weather, turn to sediment that is washed into seas and lakes, get buried by more sediment, and get "subducted" and melted during "tectonism" (continental drift). The result is there are no known well-preserved rocks older than 3.5 billion years (Ga) old. The Earth is 4.56 Ga old (Figure 1). So we don't know much about the first billion years of Earth history. Life arose during that time. We know that because we have fossils 3.5 Ga old from Western Australia.

Even at 3.5 Ga there are only two known regions of rock preserved, the Pilbara region of Western Australia, and the Barberton Mountainland of South Africa.

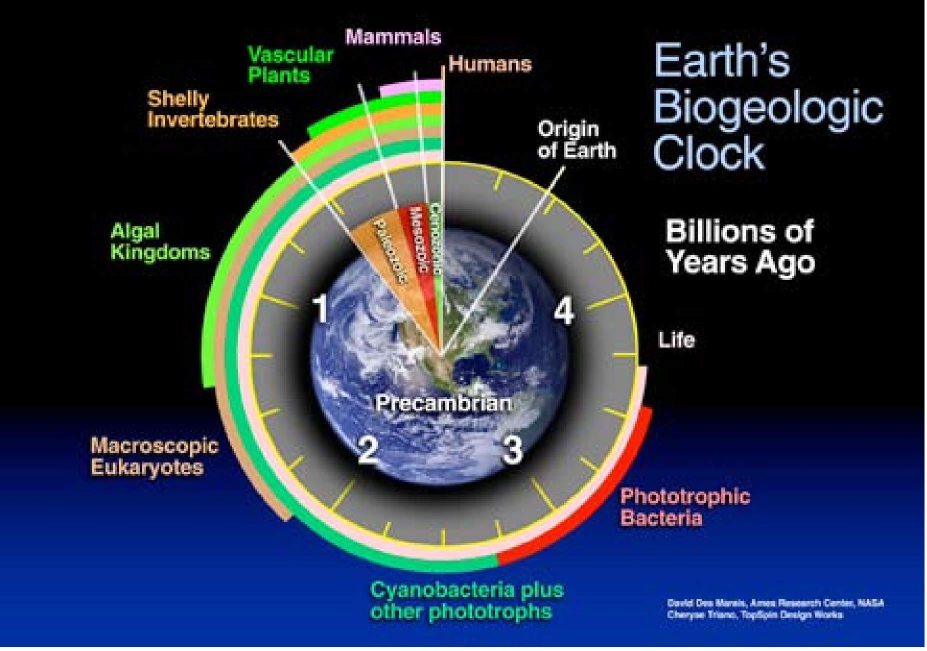

Figure 1: Geological time displayed as a clock, in billions of years. Major events in the evolution of life are indicated.

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From about 3 Ga onwards we have lots of rocks to examine for evidence of life, so we can be more confident about our interpretations.

Events in the history of life are dated mostly using the fact that some isotopes of elements are unstable and break down at known rates to form other isotopes and elements. The usual method of dating very ancient rocks uses uranium and lead isotopes bound in crystals of zircon, zirconium silicate.

Universal tree of life

There is a second way to uncover the earliest history of life. That history is encoded in the genes of living organisms. Using the subtle differences in the chemistry of the genetic molecules DNA and RNA "molecular biologists" have been able to work out the relationships of all current life on Earth. The result is a chart of relationships, one of the greatest achievements of science in the last 100 years.

Life clusters into three great "superkingdoms" or "domains", the Bacteria, Archaea and Eucarya (Figure 2). From this we can see that most life on Earth is microscopic. This is consistent with the geological record that shows us that until about 600 Ma almost all fossils are of microbes.

The universal tree also suggests that the most primitive organisms with living close relatives were hyperthermophiles, that is, they lived at high temperatures, more than 80°C. So in the ancient rock record we should be looking for the deposits of former hot springs to see what lived in them. We know how to find such deposits – they are often ores of gold, silver, copper, lead and zinc.

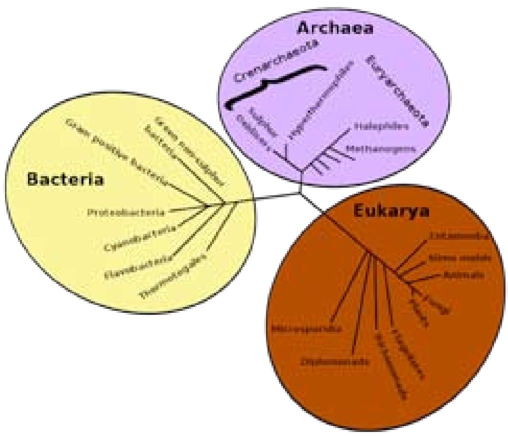

Figure 2: The Universal Tree of Life, a chart of the relationships of all extant life.

Source: Wikimedia Commons

Earth - The first billion years

Like the other planets, the Earth formed from a great cloud of dust and gas. Under the influence of gravity the cloud clumped into rocky and icy lumps that grew bigger and bigger. The volatile molecules were driven to the cooler further parts of the solar system as the Sun began to generate heat, forming the "gas giants", Jupiter, Saturn, Uranus and Neptune, the comets, and other objects such as Pluto. The small rocky planets, composed of less volatile material, Mercury, Venus, Earth and Mars, formed close to the Sun. By 4.56 Ga they were about their present size. However, for the next billion years the growth process, "accretion", continued and was very violent. Soon after 4.56 Ga an object the size of Mars smashed into the Earth with such energy as to melt and vaporise the surface of the planet, throwing a vast amount of material into orbit, which cooled to form the Moon. Frequent impacts from giant asteroids continued until about 3.9 Ga. Some of these would have vaporised the developing oceans, generating a "steam atmosphere". Life might have started in this violent period but have been extinguished. We do not know.

Imagine an Earth with thousands of volcanos, no continents but perhaps numerous islands that would later clump together to become continents, and a hot ocean. Somewhere life got started and managed to survive, proliferate and take over to generate the surface environment we now depend on for our existence. Faint evidence of the presence of life is found in highly altered 3.9 Ga rocks from Greenland. There are no conventional fossils, just suggestive patterns of carbon isotopes.

A snapshot at 3.5 Ga

We know from studying the rocks of the Pilbara region and the Barberton Mountainland that life was well established by 3.5 Ga. Despite occasional controversies, the evidence can be described as compelling because multiple lines of evidence reinforce and support each other.

Figure 3: Shark Bay stromatolites in the shallow subtidal environment.
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1. Stromatolites. These are macroscopic sedimentary structures resulting from the activities of "mats" of microbes living on the seafloor and in lakes. They still form in some modern environments such as Shark Bay in Western Australia (Figure 3), so we are able to observe how they form and use this information to help interpret the ancient forms.

In 3.43 Ga rocks in the Pilbara region, a wide range of different forms of stromatolites (Figure 4) formed all the way from a rocky coastline to offshore in several tens of metres of water. In 3.5 Ga rocks there are stromatolites at the vents of former hot springs.

2. Microfossils. These are fossilised microbes (Figure 5). Despite the fact that microbes have no hard parts they are sometimes fossilised when they become embedded in precipitated silica which then hardens to form a rock called chert. They can be found by using an optical microscope to examine slices of chert so thin that light can pass through them.

3. Carbon isotopes. Carbon has two stable isotopes, ^{12}C and ^{13}C. Some biochemical processes such as photosynthesis preferentially use compounds of "light" carbon, ^{12}C. This results in the cellular matter being enriched in ^{12}C, leaving the water in which the organisms grew enriched in ^{13}C. If calcium carbonate then precipitates out of the water to form limestone, and the microbes die and are fossilised in the

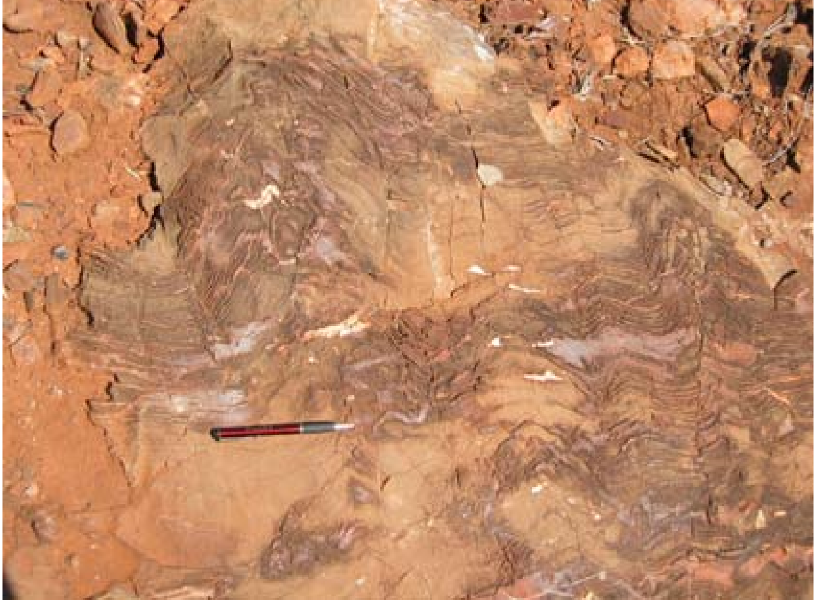

Figure 4: Stromatolites 3.43 billion years old west of Marble Bar in the Pilbara region of Western Australia.

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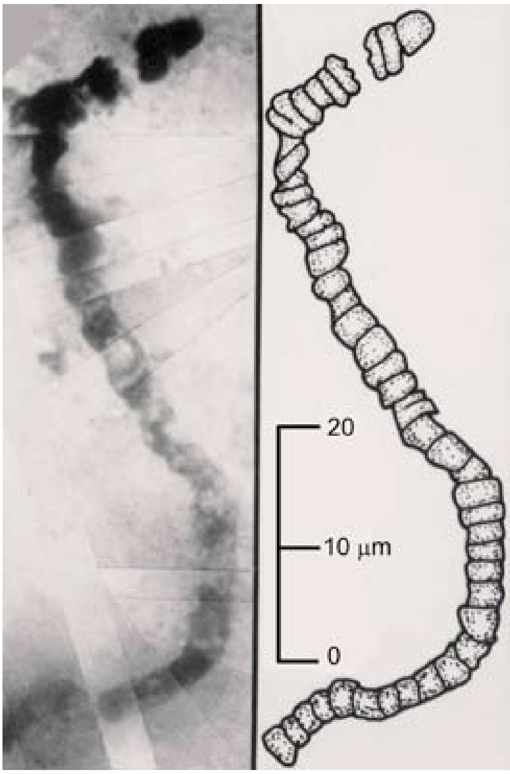

Figure 5: Filamentous microfossil 3.5 billion years old from near Marble Bar in the Pilbara region of Western Australia. The drawing on the right is a reconstruction.

Photographs courtesy of J. William Schopf and reproduced with permission.

limestone, the carbon isotope pattern is preserved. This pattern is found throughout Earth history back to 3.5 Ga and possibly to 3.8 Ga.

Complex life at 3.0 Ga?

Recently, large and relatively complex microfossils have been found in 3.0 Ga rocks in the Pilbara (Figure 6). These include spheroids up to 80µm wide, some with internal small spheroids, and discoidal structures with flanges, like classical pictures of "flying saucers". It is not known what sort of organisms these were, but their large size and relative complexity hint that they might be eukaryotes.

All the hard evolution over by 2.5 Ga

There are many well preserved rock successions at 2.5-2.8 Ga and abundant evidence of life. All life was still microscopic, as far as we know. All three domains are represented in the geological record. Some continents had formed and stromatolites were abundant in lakes and shallow seas. Though the evidence is not unequivocal it is likely that the main stromatolite-builders were cyanobacteria; this is deduced from the morphology of the stromatolites and some poorly preserved microfossils. The presence of cyanobacteria at this time is strongly indicated by another type of evidence: "biomarkers". These are hydrocarbon molecules that can be found in especially well preserved

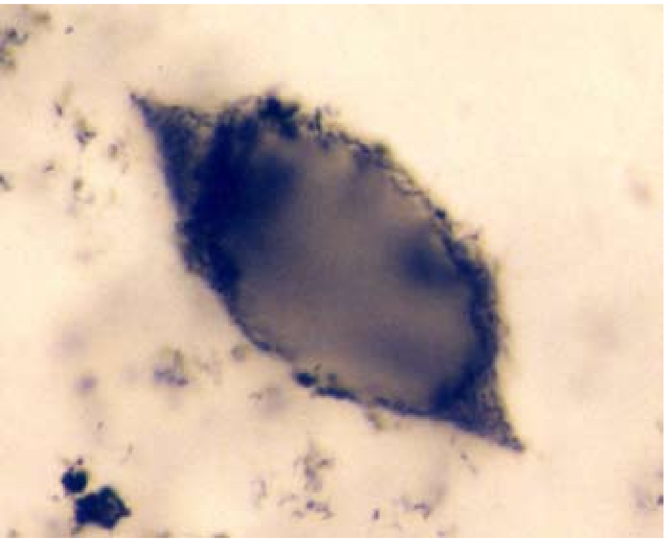

Figure 6: Spindle-shaped microfossil at least 3.0 billion years old from the Pilbara region of Western Australia. About 40 μm in maximum dimension.

Photograph courtesy of Kenichiro Sugitani and reproduced with permission.

sediments. Oil contains abundant biomarkers. After organisms die, decay and are buried in sediment some chemical components of their cells survive. Some of these organic compounds are characteristic of particular types of organisms, so when found in rocks they are markers for the former presence of these organisms. Compounds characteristic of cyanobacteria, and others characteristic of eukaryotes have been found in 2.7-2.8 Ga rocks in the Pilbara region and in South Africa. There is some controversy about this work as it is difficult to prove that these molecules are not later contaminants, but most of the evidence indicates that they are as old as the rocks in which they are found.

So we know that by 2.5 Ga, and probably much earlier, all three domains of life were flourishing on Earth. That means that most of the biochemical processes that characterise modern life had evolved by that time. All subsequent evolution has utilised those basic processes first established by microbes.

How did life start?

There is a simple answer to that question: no-one knows. However, there are ways to approach the problem, and a great deal has been learned in the last 50 years. A famous experiment was conducted in 1952 by Stanley Miller (then a university student in Chicago) and his supervisor Harold Urey. They filled a glass flask with a mixture of gases considered to represent the composition of the atmosphere on the early Earth – methane, ammonia, hydrogen, carbon monoxide and water. To represent lightning they created electrical sparks through the mixture of gases. The result was a brown liquid that when analysed was found to contain amino acids. These are the building blocks of protein molecules that are essential components of the cells of all living organisms. So they had demonstrated one possible step in the origin of life. Since then it has been discovered that there are many other ways that quite complex carbon compounds ("organic compounds") can form by natural chemical processes. This even happens in gas clouds in the universe (about 100 different carbon compounds have been identified in such clouds), and so would have been part of the cloud that condensed to form the solar system.

It is a long way from organic compounds to life and much is yet to be learned. For example, no-one has yet been able to synthesise a protein molecule, let alone the genetic molecules RNA and DNA. But there are comprehensive hypotheses about how life might have started and many of the necessary steps have been shown to be feasible. Perhaps viruses played a role before there were cells. A potentially very informative approach is to determine what essential components of cells are found in the most primitive forms of life known, and extrapolate back to predict what the earliest cells were probably like.