The earliest traces of the three domains of life: evidence and challenges

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Deciphering the early record and evolution of life is crucial to characterize plausible and reliable biosignatures of microbial life and understand the evolution of the Earth biosphere. We can then address questions regarding the conditions for life to appear and develop on a planetary body (habitability), or the probability for an extraterrestrial biosphere to develop complex metabolism or complex life. This research is also critical to develop life detection strategies, instruments and missions applicable to other planets of the solar system and to atmospheres of rocky exoplanets, as space agencies have recently come to appreciate.

Possible isotopic, biosedimentary, molecular and morphological traces of life suggest the presence of microbial communities in diverse environments. However, these traces may in some cases also be produced by abiotic processes or later contamination, leaving a controversy surrounding the earliest record of life on Earth. Before a microstructure can be accepted as a microfossil, a series of approaches need to be employed to prove its endogenicity, syngenicity, and biological origin, as well as to falsify an abiotic explanation for the observed morphologies or chemistries. These micro- to nano-scale analyses complement the macro-scale characterisation of the geological context, as the environmental conditions will determine the plausibility of ancient habitats and the conditions of fossilisation. Similar approaches are also applicable to the search for life in situ beyond Earth, such as the ongoing and future Martian missions.

Interpreting the paleobiology of unambiguous traces may also be challenging. Considerable debates still exist regarding the origins of the three domains of life (Archaea, Bacteria, Eucarya), as well as the evolution of cellular life before LUCA, and the evolutionary steps in eukaryogenesis between FECA and LECA (first and last eukaryotic common ancestors). Molecular, isotopic and ultrastructural analyzes may provide insights on the evolution of crown groups of the 3 domains back to their respective last common ancestors, while the geological record may preserve both part of Earth and life history further back in time. Some of these early (Precambrian) biosignatures may be related to modern metabolisms or modern clades, but many cannot. However, regardless of taxonomy, the paleobiological record can provide direct evidence for extinct clades and/or for the minimum age of evolution of biological innovations. Traces of metabolisms similar to modern metabolisms of Bacteria and perhaps Archaea are identified since at least 3.4 Ga and 3.0-2.8 Ga, respectively, implying an older LACA (Last Archaea Common Ancestor) and an older LBCA (Last Bacteria Common Ancestor). Thus, LUCA (Last Universal Common Ancestor) appeared even earlier, and was preceded by the origin(s) of life, before 3.4 Ga and possibly as early as 4.3 Ga when Earth was habitable. The syntrophic association of an Asgard archaeon with bacteria gave birth to FECA (First Eukaryota Common Ancestor) and the domain EUKARYOTA. The timing, process and ecology of this event are unknown, but must be older than 1.65 Ga, the minimum age of the oldest eukaryotic microfossils. The age of LECA (Last Eukaryota Common Ancestor), the most recent ancestor of all modern eukaryotes, is also unknown, but must be older than 1.05 Ga, the minimum age of the oldest consensual crown group eukaryote (red algae), and perhaps older than 1.7 Ga as suggested by some molecular clocks and debated fossils.

Reassessing the evidence of early life is challenging but essential and timely for the quest of life's first traces and evolution, both on Earth and beyond.