Origins and early evolution of the biospheres : insights from paleobiology

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Questions of origins and transitions are the most challenging and exciting questions in Science. Bridging biology, geology, chemistry and astrophysics is essential for untangling life's origins and early evolution, both on Earth and beyond. Deciphering the early record and evolution of life permits 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 early Earth 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. Whether or not we find traces of fossil life in Noachian clay-rich deposits, exploring the early geological record of Mars will inform on the missing Hadean record on Earth, when life probably originated.

Once the biogenicity is demonstrated, interpreting the paleobiology of a biosignature may also be challenging. Considerable debates still exist regarding the origins and relationships of the domains of life (Archaea, Bacteria, Eucarya), as well as the evolution of cellular life before LUCA, the Last Universal Common Ancestor. Molecular, isotopic and ultrastructural analyzes and experimental taphonomy may provide insights on the paleobiology and early evolution of microbial life through the Precambrian. 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. Isotopic or biosedimentary 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). This also provides minimum age constraints for LUCA, older than 3.4 Ga, and for the origin(s) of life, that happened before 3.4 Ga and possibly as early as 4.3 Ga when Earth became habitable, in agreement with recent molecular clocks.

The biological and fossil records also inform on one of the most radical transition in life evolution, the origin of complex cells or eukaryogenesis, the sequence of evolutionary events occurring between FECA and LECA (respectively the First and Last Eukaryotic Common Ancestors). The association of an Asgard archaeon with bacteria gave birth to FECA. However, the timing and relative order of evolution of cellular features characterizing LECA, such as the nucleus, endomembranes, cytoskeleton, and mitochondria, remain debated. Estimations for the age of LECA range from 1.9 Ga to 0.7 Ga depending on molecular clocks and interpretation of the fossil record. New microfossil assemblages from the Paleoproterozoic McArthur basin of Australia reveal an ecosystem with cyanobacterial mats, diverse unidentified vegetative cells and cysts, and ornamented protists. The morphological complexity of some of these fossils implies cytological sophistication for the synthesis of organic plates, external equatorial outgrowth, internal concentric ridges, and diverse protrusions and spines on large recalcitrant organic walls, which indirectly evidence the evolution of a complex cytoskeleton and endomembrane system before 1.78-1.73 Ga and pushes back the minimum age of eukaryotic fossils, previously reported at 1.65 Ga. These early protists thrived in anoxic-suboxic near-shore marine water, close to cyanobacterial mats providing low oxygen concentration undetectable by most geochemical proxies but sufficient for steroid synthesis and aerobe metabolism. They provide a minimum age for LECA, consistent with several molecular clocks, and push back FECA to the early Paleoproterozoic or Archean.

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