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Reviving the Primordial Earth – Geobiological Perspectives on the Origin of Life

Introduction

The Earth is truly a living planet: Ever since life began, our ~4.6 billion-years (Ga) old planet has been shaped by complex interactions between living and non-living matter. Seeking to understand how our modern world came into being, we need to develop a robust understanding of geobiological interactions across temporal and spatial scales. Much like historical research, geobiological quests into our planet's past rely on a variety of sources, and the only surviving archive that provides primary information about Earth's history is the geological record. Indeed, rocks encode a wealth of valuable information such as prevailing environmental conditions at the time of deposition and, in some cases, the presence and nature of ancient life. For this reason, geobiological research that is focused on the emergence of life examines Earth's most ancient rocks by means of field and laboratory based analytical approaches. This strand of research is complemented with parallel investigations of younger analogue systems and experimental work, both of which provide important means to test and refine rock-based explanatory models. In combination, these approaches allow geobiologists to illuminate the origins and evolution of life on our planet.

This contribution briefly highlights how we reconstruct primordial worlds by examining rocks from the juvenile Earth (>3.4 Ga), what we currently (think to) know about earliest life on our planet, and how this contributes to the ongoing quest for understanding the origins of life.

Approaching the origins of life

Why is the emergence of life a geobiological issue? Unfortunately it seems impossible to pinpoint the exact origin of life within the geological record because well-preserved materials from the early Earth are extremely rare (see below). Furthermore, information encoded in rocks is usually time-averaged to an extent that the temporal resolution needed to reconstruct abiogenesis will be lost. Nonetheless, geological archives are of unprecedented significance for understanding the origins of life. For instance, the earliest traces of life preserved in the rock record ("biosignatures") provide important age constraints on the transition from prebiotic to biotic chemistry. Additionally, we can reconstruct Earth's early environments and, in doing so, assess where life could have originated. In other words, the geological record allows us to establish a robust evolutionary time frame and provides a basis for constraining processes that might have driven the emergence of life.

What can we say about the birth and early evolution of Earth? The geological record of the first ~500 million years (Ma) of our planet's history has been irretrievably lost due to destructive processes such as meteorite impacts, plate tectonics, weathering and erosion. However, radiometric ages of lunar rocks and their geochemical similarity to rocks from Earth suggest that our planet collided with a Mars-sized protoplanet approximately 4.5 Ga ago. This extreme event resulted in the formation of the Moon [1], which played a crucial role in establishing and maintaining Earth's habitability [2]. Radiometric dating of lunar samples from the Apollo missions indicated that the early Earth–Moon system was perhaps still strongly affected by meteorite impacts in the aftermath of this event, peaking at ~3.9 Ga and tailing off thereafter. The existence and extent of this "late heavy bombardment" is still a controversial topic amongst scientists, especially in the context of when life emerged and how it would have survived these conditions.

But what is the earliest geological evidence for the Earth being capable of supporting life? The most ancient rocks on Earth occur in Canada and have radiometric ages of ~4.0 Ga [3]. Even older are some zircon minerals from Western Australia, which have been radiometrically dated at ~4.4 Ga [4]. Notably, the zircons derived from the breakdown of preexisting rocks and are now preserved as detritus in much younger deposits (~3 Ga). However, geochemical information encoded in the detrital zircon grains may indicate the presence of liquid water and supports the notion that oceans were present [4]. These lines of evidence ascertain the presence of a solid crust and liquid water on Earth's surface – two important requirements for life – at least as early as 4.4–4.0 Ga ago.

How can we reconstruct life's emergence? The most unambiguous and informative evidence of ancient life are the remains of organisms such as fossilized bones, shells, or wood. However, the earliest forms of life were microbial and had not yet evolved such hard parts. Interestingly, microbial cells can be preserved within rocks as fossils, which requires specific conditions to mineralize delicate cellular structures. It is important to note, however, that abiotic processes can also produce structures that can easily be mistaken for microbial fossils [5]. This is particularly relevant for Earth's most ancient rocks which ex-

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perienced high pressure–temperature conditions (“metamorphism”) during the billions of years after their initial formation. During metamorphism, the appearance and composition of rocks will be altered, thereby making any interpretation of their origin a challenge. Given the complexity of such alteration processes, it may not be surprising that the biogenicity of microstructures in >3.8 Ga rocks from Canada [6] is being debated and that purported microfossil-like structures in ~3.5 Ga rocks from Western Australia [7] are now widely regarded as abiotic artefacts [8].

Are there any other potential biosignatures available for tracking life in deep time? Since all known life is based on reduced carbon, carbonaceous matter preserved in Earth’s oldest materials is a candidate biosignature, especially, if it has a distinct stable carbon isotopic signature [9]. Carbon has two stable isotopes (^{12}C, ^{13}C) and the ratio between these two isotopes can be measured from any carbon-bearing material. Conventionally, $^{13}C/^{12}C$ ratios are compared to a standard (e.g., Vienna Pee Dee Belemnite, VPDB) and given as $\delta^{13}C$ in permille. Since autotrophic carbon fixation prefers ^{12}C over ^{13}C, biomass of primary producers will be isotopically depleted relative to the carbon source. In first approximation, heterotrophic organisms will take on the isotopic composition of their food with only minor variations. Therefore, biological organic matter typically exhibits $\delta^{13}C$ signatures between ~–20 and –30‰ VPDB. This means that ^{13}C-depleted carbonaceous matter preserved in rocks and minerals may be a valuable biosignature for tracking early life – provided that a post-depositional emplacement (e.g., through percolating fluids or modern endolithic organisms) can be excluded.

What is the earliest evidence for life on our planet then? One crack-free detrital zircon grain (~4.1 Ga) from Western Australia encapsulated isotopically depleted graphite (a crystalline form of elemental carbon) with a $\delta^{13}C$ signature of ~–24‰ VPDB, perhaps suggesting a primary and biological origin for this carbonaceous matter [10]. To date, only one of several hundreds zircons with ages >3.8 Ga is thought to contain graphite that is not associated with cracks; hence there is still skepticism as to whether these inclusions are of primary nature. Various types of organic carbon are also preserved in ~3.95–3.75 Ga rocks from different high latitude regions (see e.g. [9, 11] and references therein). Many of these materials exhibit $\delta^{13}C$ signatures below –20‰ to –25‰ VPDB, which may point to a biological origin. Problematically, however, some of these records also contain organic carbon with more positive $\delta^{13}C$ values. This is problematic because the host rock experienced high pressure–temperature conditions during which organic carbon may have formed abiotically (e.g., through thermal decomposition of carbonate minerals). Additionally, these conditions can allow for the isotopic re-equilibration of organic carbon with inorganic carbon phases within rocks (e.g., carbonates) and from percolating metamorphic fluids (e.g., CO_2, CH_4). In addition to these problems, syn-depositional contributions from abiotic sources (e.g., meteorites, Fischer-Tropsch-type processes on Earth) must be ruled out [12, 13]. It may not be astonishing that the origin of organic matter in such old rocks is commonly disputed, particularly, if it shows relatively heavy $\delta^{13}C$ signatures. Nonetheless, given the wealth of organic geochemical evidence consistent with biological processes, some of these records may indeed be vestiges of life.

Fig. 1: Ancient geological archives, such as ~3.5–3.4 Ga rocks exposed in the remote outback of Western Australia, are the only surviving historical records of the primordial Earth. Providing a rare primary source of information, these archives are of unprecedented significance for reconstructing how life began on our planet.

The first broad evidence for the presence of diverse microbial life on Earth comes from little metamorphosed ~3.5–3.4 Ga rocks in South Africa and Western Australia (Figure 1). The preserved evidence includes distinct deposits formed by the lithification of benthic microbial communities (“microbialites”), mineralogical and geochemical traits of rocks, as well as organic matter characteristics [13–16]. Notably, environments and microbial habitats were strongly influenced by hydrothermal processes and high-energy events such as tsunamis [13–17]. A particularly important discovery was the presence of primordial organic molecules and gases in primary fluid inclusions trapped in ~3.5 Ga rocks from Western Australia [15]. These rocks formed when hydrothermal fluids discharged into subaquatic environments where a distinct type of microbialite, originally consisting of iron sulfide minerals, developed. This suggests that some of the compounds delivered by hydrothermal fluids might have formed important substrates for benthic microbial communities, most likely consisting of ancestral sulfur and methanogenic metabolisms. Moreover, and perhaps even more importantly, the fluid inclusions contained stable building blocks of methyl thioacetate, a putative key agent in primordial energy metabolism and thus the emergence of life [15, 18, 19]. Therefore, this geological record provides a rare glimpse into a truly primeval and evolutionary ancestral system that was directly situated at the interface between prebiotic chemistry and biology.

Synthesis & implications for the origin of life

Geological archives are the only surviving historical records of our planet’s distant past. Information gleaned from these valuable archives indicate the presence of a solid crust and liquid surface water at ~4.4–4.0 Ga. At that point, the stage was set for life to emerge. Biosignatures preserved in Earth’s most ancient rock records indicate a possible existence of life as early as ~4.1 Ga and demonstrate the presence of diverse microbial communities around 3.5–3.4 Ga. Considering all other available evidence, it appears most plausible that life had been established not later than ~3.8 Ga ago. Taking the cataclysmic and life-sterilizing Moon-forming event ~4.5 Ga ago as maximum age

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constraint, we are left with a window of ~700 Ma for life to come into existence – an immense stretch of time. As a comparison, animals emerged between ~890–541 Ma whereas the first remains of our own species date back to only ~0.4–0.2 Ma. Spectacular new insights into the geobiology of the primordial Earth come from a recently discovered evolutionary ancestral system documented in ~3.5 Ga rocks. This record seems to provide a primary source of unprecedented information about primeval key-processes that might have been relevant to the origin of life. Furthermore, the study highlights that there are still many more exciting discoveries to come – our journey has just begun.

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I was born and raised in the wide-open spaces of the North German lowlands, a landscape which one might not initially associate with rocks or fossils. However, with enough gumption or luck, one can find vestiges of ancient life in this region. I still recall "that day" during my childhood when, while adventurously exploring the fields adjoining my parents' house, I luckily stumbled upon a fossil sea urchin sticking out from the wet clayey soil. Originally preserved in solid rocks from the time when giant dinosaurs roamed the Earth, this fellow was transported from elsewhere by melting ice shields some tens of thousands of years ago – what were the odds! Since that discovery my fascination with our planet was sparked and was further encouraged over the following years by a young, enthusiastic, and dedicated schoolteacher. Unfortunately, I somehow lost track of my fascination during the troubles and turmoils of adolescence, which perhaps some folks can relate to. The final three years of my education was completed at a school largely focused on economics and with minimal courses in the natural sciences. Needless to say, I was uninspired and left with no idea of what to do after graduation. It was a very dear friend of mine who, in a single conversation, re-opened my eyes to the obvious: My fascination for the deep and eventful history of life on our planet. I was back on track.

In summary: Thanks to an ancient sea urchin, a passionate schoolteacher, and a genuine friend, I decided to study geosciences. My studies at the University of Bremen (2004–2010) were very inspiring and led me to many fascinating places, including the Himalayas. Up there, in the dizzy heights of approximately 5,000 meters above sea level, I stepped over rocks consisting of the remains of organisms that once thrived in shallow seas – what a spectacular proof of the immense forces that shaped our planet's face! Thrilled by the complex interplay between organisms and environment through geological time, my focus shifted to one of the greatest mysteries of all – the dawn of life on Earth. Seeking a deeper understanding of how life emerged and co-evolved with our planet, I zigzagged between various renowned research institutions, letting my fascination be my guide. While the University of Göttingen (2010–2020) was my academic "home base", I conducted research at the Nanjing Institute of Geology and Palaeontology at the Chinese Academy of Sciences (2011) and the University of California Riverside (2018–2019). Since 2020, I have been privileged to lead my own research group at the University of Tübingen. With generous funding from the Deutsche Forschungsgemeinschaft (Emmy Noether Program and SPP 1833 "Building a Habitable Earth"), my team explores primordial environments from the distant past that may have been key for the emergence of life – the journey continues.

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