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Water-rock interaction and life

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Abstract

Water-rock interactions play a critical role in the origin, existence, and prospects of life. Minerals are sources of energy and nutrients. Life uses aqueous chemical gradients to access and use minerals. Chemical disequilibrium, therefore, represents one type of biotic signature. Life also controls other types of disequilibrium, including isotopic disequilibrium and morphology. Water is a fundamental contributor to all of these biosignatures, acting as a medium for mass transfer and a reservoir for components. Distinguishing biosignatures from abiotic signatures challenges instrumental capabilities. Finally, the ubiquity and heterogenous distribution of life on Earth challenges the ability to interpret different types of disequilibria as evidence for life, or absence thereof.

Keywords: astrobiology, geochemistry, detection of life.

1. Introduction to Signatures of Life

One of the most profound questions is that of whether life existed, exists, or could develop elsewhere in the universe. At present, Earth is our only example of life (N=1). Despite its proximity, gaps remain in the record of life on Earth, particularly for the most ancient examples. Insight from modern life and its environments, communities and processes serves to fill some of those gaps, but research is limited by the ubiquitous occurrence of life on Earth. Natural examples of abiotic environments capable of hosting life are not found on Earth; though organisms may be scarce, they have been found in terrestrial environments characterized by extremes in temperature, pressure, depth, nutrient-availability, and humidity (e.g., [1-3]). Abiotic conditions are only achieved in laboratories and even then may be subject to questions of sterility.

The one thing that is known, however, is that life on Earth requires water, energy, carbon, and other nutrients. These ingredients (except for light as a source of energy) ultimately come from inorganic sources: rock or atmosphere. Water-rock interaction is critical for providing carbon, nutrients, and, at

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least for primitive life forms, energy. Life, then, could be expected to impart some type of chemical or physical signatures as it uses these ingredients, changing them into other forms and consuming the products of water-rock interaction. This paper examines the role of water-rock interaction in the search for signatures of life on Earth and, by extrapolation, to other systems.

1.1. Disequilibrium

Disequilibrium, the departure of system components from their thermodynamically stable phase, is a fundamental characteristic of geological systems as well as biological systems. For the former, disequilibrium derives from physical gradients that, presumably with mixing, can be eliminated over time. Even after 4.6 Ga, the Earth is not homogenous and is not geochemically partitioned according to thermodynamic principles. In many near-surface and surface environments, the latter represents a concerted effort by life to prevent mixing in order to maintain gradients for the purpose of extracting energy and nutrients from the environment. This can be achieved internally by transporting materials across a membrane and externally through the release of reactive substances. Such activities generate disequilibrium in several key, detectable systems, including chemistry, mineralogy, and morphology.

Oxidation-reduction (redox) potential, isotopic distribution and chemical composition are three examples of chemical disequilibrium that life induces in its environment. Redox potential is manipulated by life to extract energy from the environment. This leads to gradients of concentrations of redox pairs, including the energy-rich, unstable redox pair – O_2/H_2O. Evidence for changes in the concentration of O_2 in Earth's atmosphere is found in modern and ancient rocks as differences in the values of S^{2-}/SO_4^{2-} and Fe^{2+}/Fe^{3+} redox pairs as indicated by the presence or absence of minerals, such as pyrite or hematite. Life selects for light isotopes of C along with several other elements. As a consequence, organic carbon tends to have negative $\delta^{12}C/^{13}C$, leaving the remaining inorganic carbon with a heavier isotopic signature.

The presence of organic carbon itself is not necessarily evidence of life because organic compounds are found in many meteorites [4], but isotopic fractionation requires selectivity and energy input, which on Earth is provided by life. Nevertheless, organic compounds are constructed from a restricted group of subunits in living systems, more so than in extraterrestrial materials (e.g., [4-10]). Hence, high concentrations of organic carbon with relatively restricted types of organic structures provide a signature of terrestrial life, at a minimum.

In addition to effects on chemical signatures, disequilibria in morphological and mineralogical signatures provide evidence for terrestrial life. Stromatolites are examples of biogenic structures (Fig. 1); stromatolites are laminated rocks in which the laminae differ mineralogically and chemically as a direct consequence of microbial activities. Ancient stromatolites document the expansion of life to many environments (e.g., [11]) while modern stromatolites are restricted to extreme environments (e.g., [12]). Such morphological structures can be signatures of life if their formation is strictly biologically mediated (e.g., [11, 13]); biota use energy to control otherwise entropic depositional processes. Life also provides templates for mineral formation that are unique; biogenic minerals and mineraloids have characteristics that cannot be replicated in abiotic systems [14]. For example, echinoderms and diatoms use organic templates to dictate deposition of optically monocrystalline calcite and amorphous opal, respectively; disorder would dominate in a thermodynamically driven system with some exceptions [15].