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Mineral surfaces and the prebiotic selection and organization of biomolecules

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ABSTRACT

One of the most enigmatic steps in Earth’s ancient transition from a lifeless planet to a living world was the process or processes by which prebiotic organic molecules were selected, concentrated, and organized into the essential macromolecules of life. More than a half-century of theory and experiment points to the critical roles of mineral surfaces in the assembly of proteins, lipid bilayers, and genetic polymers. This review considers three aspects of this problem: (1) the self-assembly of lipids, which may be enhanced in the presence of minerals; (2) the role of minerals in polymerization of amino acids and nucleic acids; and (3) the selective adsorption of organic species, including chiral molecules, onto mineral surfaces.

Keywords: Surface studies, calcite, quartz, feldspar, new technique, microarray, origin of life

INTRODUCTION

The origin of life approximately four billion years ago was a geochemical event, dependent on reactions among the Archean oceans, a primitive atmosphere, and rocks and minerals. This hypothesis of “chemical evolution,” like any valid scientific model, leads to numerous testable predictions: Life must have emerged as a sequence of chemical steps of increasing complexity, and each of these chemical steps must be subject to confirmation in reproducible laboratory experiments.

This naturalistic view of life’s origin, though widely accepted within the scientific community, can evoke as much public controversy as any topic in science. In particular, intelligent design (ID) represents a highly publicized and intensely criticized rival hypothesis to chemical evolution (Scott 2004; Forrest and Gross 2004). According to supporters of the ID model, life is too complex to have arisen by natural chemical processes (Behe 1996; Dembski 1999). Life requires hundreds or thousands of interconnected chemical reactions; consequently, ID supporters find it difficult to imagine a step-wise process from simplicity to complexity. Indeed, according to this view, life is “irreducibly complex.” The logical conclusion, according to ID proponents, is that a supernatural designer—either an alien or God—must have engineered life on Earth. In this view, life arose by some combination of natural and supernatural events.

Most philosophers of science argue that intelligent design does not rise to the standards of an acceptable scientific hypothesis, because it relies on supernatural processes to explain the natural world. This dependence on miracles not only invalidates ID as science, but it also represents suspect theology (Miller 1999; Pennock 1999; Fry 2000; Hazen 2005a, 2005b; Bertka 2006). ID relies on the discredited “God in the gaps” argument, by which one resorts to supernatural explanations if a natural phenomenon is seemingly too complex to understand as a lawful process.

Supporters of ID point to the origin of life as the quintessential example of irreducible complexity. Ultimately, the most powerful response to any God in the gaps argument is to fill in the gaps, in this case by a research program that demonstrates a natural transition from the chemical simplicity of the Hadean Earth to the emergent complexity of the first living cell. If such biological complexity can be shown to arise spontaneously as the result of lawful, natural processes, then the central tenet of ID regarding life’s supposed miraculous origin is invalidated.

The objective of this Presidential Address is to outline such a scenario for the origin of life on Earth based on the hypothesis that life’s genesis is an example of the more general natural phenomenon of emergent complexity (Holland 1995, 1998; Morowitz 2002; Hazen 2005a). In this summary I place special emphasis on one of the most significant gaps in our present understanding of life’s origin—the selection, concentration, and organization of biomolecules into life’s essential macromolecules. In particular, I elaborate some of the processes by which mineral surfaces may have facilitated this key emergent step in the ancient transition from geochemistry to biochemistry.

THE EMERGENCE OF LIFE

The origin of life on Earth can be modeled as a sequence of emergent steps, each of which added chemical complexity to the geochemical world (Hazen 2001a, 2005a). Emergent complexity commonly arises in systems of numerous interacting particles, or “agents,” as energy flows through the system (Prigogine 1980; Holland 1998; Morowitz 2002). Numerous examples include the shapes of sand dunes and ripples (Bagnold 1941, 1988; Hansen et al. 2001), the formation of galactic spiral structures (Bertin 1980; Carlberg and Freedman 1985), and the behavior of myriad biological systems such as slime mold, ant colonies, and the conscious brain (Solé and Goodwin 2000; Camazine et al. 2001). The emergence of life required at least four such steps: (1) the emergence of biomolecules, (2) the emergence of