Estimates of the magnitude of the global NPP may improve as better knowledge of algal physiology and ecology is incorporated into the computations. In contrast, the spatial and temporal evolution of the ocean productivity is already described with a tremendous wealth of detail. The synergistic use of modeling and data from various sensors (for ocean color, temperature, clouds, wind, surface height) is the recipe for future progress. An international strategy for the implementation of a global-scale, internally consistent, temporally uninterrupted set of such data is imperative (19).

References and Notes

PERSPECTIVES: ORIGIN OF LIFE

Some Like It Hot, But Not the First Biomolecules

Jeffrey L. Bada and Antonio Lazcano

The inventory of organic compounds on the early Earth may thus have been derived from a number of sources: Earth-based syntheses, asteroid and comet impacts, and the accretion of meteorites and interplanetary dust particles. These abiotic, monomeric organic compounds would have accumulated in the early oceans, providing the raw material for subsequent reactions. Eventually these reactions would have led to life as we know it: membrane-enclosed systems of polymers such as nucleic acids and proteins, the core molecules involved in the central biological functions of replication and catalysis.

For monomers in the early oceans to undergo polymerization, a thermodynamically unfavorable process, concentration of the soup constituents, would have been required. Experimental evidence suggests that clays, metal cations, and imidazole derivatives, among others, may have catalyzed prebiotic reactions, including polymerization. Selective absorption of molecules onto mineral surfaces has been shown to promote concentration and polymerization of various activated monomers in the laboratory (3). Because absorption involves the formation of weak noncovalent bonds, mineral-based concentration would have been most efficient at low temperatures (4). Other processes such as evaporation of tidal lagoons and eutectic freezing of dilute aqueous solutions may also have assisted concentration. The latter process is particularly effective in the nonenzymatic synthesis of oligonucleotides (5). As polymerized molecules became larger and more complex, some of them began to fold into configurations that could bind and interact with other molecules, expanding the list of primitive catalysts that could promote nonenzymatic reactions. Some of these catalytic reactions, especially those involving hydrogen-bond formation, may have assisted in making polymerization more efficient. As the variety of polymeric combinations increased, some polymers may have developed the ability to catalyze their own imperfect self-replication and that of their molecular counterparts.

How did life emerge? Various steps thought to be involved in the origin of life on Earth. The shaded area represents the contribution from the metabolist theory to the overall scheme.
kin. This would have marked the appearance of the first molecular entities capable of multiplication, heredity, and variation, and thus the origin of both life and evolution.

This scheme is necessarily speculative but has an intrinsic heuristic value: Experimental models can be developed to construct a coherent narrative of this evolutionary sequence. The chemical nature of the polymers used by the first self-replicating entities remains uncertain, but threose-based RNA analogs and peptide nucleic acid molecules are possible contenders (6–8). It is generally thought that the first living molecular entities evolved into the RNA world, which was in turn a stepping stone to the DNA/protein world of modern biochemistry.

Low temperatures are the most favorable for the long-term survival of organic compounds (9), especially those carrying genetic information, and for the stability of catalytic polymer configurations. Studies of fossils have shown that ancient DNA is preserved for ~100,000 years in cool, high-latitude environments, compared with only 1000 to 10,000 years in warmer, lower latitude environments (10, 11). RNA is much more fragile (12). Although the survival of nucleic acids may be extended by encapsulation into hydrocarbons, such as amberlike resins (10), it is unknown whether this would have been important in enhancing the stability of genetic molecules in early biotic systems.

The prebiotic soup scenario thus suggests that the first living entities appeared, and evolved through the RNA world to DNA/protein biochemistry, when Earth was cool rather than boiling hot. Because of the reduced luminosity of the young Sun, Earth may indeed have been completely covered with ice during its early history (13). The first self-replicating molecular entities may have developed under these conditions from the prebiotic organic ingredients.

In the last decade, the validity of the prebiotic soup theory has been questioned, particularly with respect to the robustness of polymer synthesis. An alternative “metabolist” theory has been proposed (14–16), although it is not a new idea (17). According to this theory, the first living system on Earth was a primitive metabolic life characterized by a series of self-sustaining reactions based on monomeric organic compounds made directly from simple constituents (CO₂, CO) in the presence of metal sulfide catalysts. A primitive type of reductive citric acid cycle is often cited as a model. According to this theory, life in its beginning was nothing more than a self-sustaining chain of chemical reactions associated with mineral surfaces, with no requirement for genetic information. Metabolic life is thus rightfully referred to as “life as we don’t know it” (18).

**References and Notes**

2. It has also been proposed that life began elsewhere and was transported to Earth, but this only shifts the problem of the origin of life to a different location.
21. A relevant example is petroleum formation. Petroleum is produced from sedimentary organic matter by a series of geochemical reactions that take place at temperatures of 50°C to 175°C over time scales of several million years. At hydrothermal vent temperatures of 300°C to 350°C, these reactions are much more rapid, and petroleum may be produced in periods as short as 100 years. On a global scale, however, the amount of hydrothermal petroleum is small compared with that generated at lower geologic temperatures.