An adaptive model of marine biogeochemistry in the Archaean

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Here we describe ongoing work that applies adaptive modelling techniques from artificial life to open questions in Earth system science. Understanding the Earth system in terms of global chemical cycling is of critical importance for the interpretation of Earth history and the prediction of climate change. Many of the key chemical reactions that facilitate biogeochemical cycling occur during the metabolism of organisms. The range of metabolic reactions present in the biota has changed significantly over evolutionary timescales, often with dramatic effects on the Earth system. Yet models of biogeochemistry have traditionally only included static representations of the biotic components of the major nutrient cycles. More recently, some models have begun to include a number of functional types of organism, each with different prescribed biogeochemical properties. However, none of these models address the dynamic adaptation of the biota over time, which can change the way in which different species interact and alter their effects on biogeochemical cycling. Here we present a new adaptive individual-based model of the marine ecosystem in the Archaean period of Earth history. We use a simplified version of the major physical chemical processes and metabolic functions that are known to have existed at this time; the marine ecosystem during the Archaean is in any case simpler than the modern ecosystem, being solely based on microbial life. We specifiy a number of microbial guilds containing species that have similar metabolic reactions and biogeochemical functions, e.g., photosynthesisers, chemoheterotrophs, etc. Within each guild, multiple species may coexist and compete on the basis of various physiological traits. Individual microbes each have a genotype that specifies various metabolic traits and thus determines their growth rate as a function of their environment. We consider each model individual to represent an aggregation of many genetically similar real world individuals; this assumption allows us to study phenomena on a global scale. Successful microbes (i.e., those that are well suited to their environment) grow and reproduce, while unsuccessful microbes starve and die. Mutation can occur during reproduction, allowing the creation of new species. Competition for nutrients drives ongoing adaptation that dynamically changes the chemical environment in a coevolutionary loop of interaction. Our model considers a vertical column separated into three compartments representing the deep and surface ocean layers and the atmosphere. We find that diverse self-sustaining ecosystems emerge over time without being prescribed, and that the distribution of nutrients and organisms between the three compartments is qualitatively similar to that believed of the Archaean. In particular, photosynthesisers tend to dominate the sunlit surface ocean, fixing inorganic carbon (CO_2) into organic forms that support other populations, while the deep ocean ecology is dominated by methanogens, which are able to survive in the dark and anoxic deep ocean conditions. Adaptation of nutrient uptake and light sensitivity traits creates species within each guild that are optimally suited to their environment. Recent work has looked at evolutionary trade-offs and the possibility of a biological trigger for the Great Oxidation event. This work represents the first step in a greater program of study that will seek to model evolutionary adaptation in marine biogeochemistry.