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EDITORIAL

Geobiology: Deep Time Perspectives

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What is Geobiology?

Integrating paleontological data with biological, geochemical, and stratigraphic information is not new. The idea that life shaped the environment throughout geologic time emerged in 1926 by the Russian scientist Vladimir Vernadsky. The Dutch microbiologist Lourens Baas-Becking introduced the term *Geobiology* in 1934 for organisms and the environment at the chemical level (Knoll et al., 2012). Although many paleontological studies fall in the broad category of geobiology, a better-informed understanding of the subject has arrived in the past three decades. The advancements in analytical techniques, development of the Paleobiology Database, and CHRONOS System for the geoinformatics needs of paleobiology have energized interest in this discipline. A research consortium called Sedimentary Geochemistry and Paleoenvironments Project initiated to create a relational database tailored to the deep-time sedimentary geochemical research (Farrell et al., 2021) appears to have potential geobiological use. Geobiology, as understood today, consider Earth as a system and life as part of it. Life influences Earth's development, and the changing environments on the Earth impact life (Noffke, 2005). Paleobiology and biogeochemistry are at the core of geobiology, but revealing the interaction between organisms and their chemical and physical environments transcends the boundary of all sciences. Microbe-mineral interaction, biomarkers, and molecular genetics are some of the other tools of the study that make geobiology a genuinely holistic science. Considering the importance of the discipline, a journal titled *Geobiology* was launched in 2003 to explore the relationship between life and the Earth's physical and chemical environment.

Microbes as Agents of Geobiological Processes

Environment impacts all lifeforms to certain degrees, and every organism plays some role in the environmental process. Microbes have possibly provided the most information about the Earth-life interactions among the various lifeforms. Geobiologists have actively examined the mineral formation and elemental cycling by microbes. Microbes precipitate many minerals; some are biologically induced while others are biologically controlled. Bacteria precipitate minerals passively as an incidental consequence of interaction with the environment. Banded iron formation and stromatolites are good examples of bacterial involvement in mineral precipitation. They also indicate the enormity of the process. The Precambrian era was ruled by bacterial geobiology. In biologically controlled mineralization, the microbes participate actively in the precipitation of minerals. The microbes modulate the fluid composition, and the precipitated mineral serves as their skeletal structures. The eukaryotic planktons, comprising coccolithophores, foraminifera, radiolaria, and diatoms, secrete their shells by this process and are prolific biomineralizers in the modern oceans. Their counterparts in sedimentary records are a vital source of geobiological information in the Phanerozoic. In the global calcium carbonate budget, the calcareous shells of planktons alone contribute >1.6 Gt primary inorganic carbon (PIC) yr^{-1}. Although a substantial part of it is dissolved while the dead planktons sink through the water column or settle on the seafloor and ultimately, 0.1 Gt of PIC is buried in the deep-sea (Berelson et al., 2007). Both phyto- and zoo-planktons are vital components of the ocean carbon pump.

The eukaryotes have been mineralizing skeletal structures for nearly 750 million years. The microfossils belonging to foraminifera, coccolithophores, diatoms, and radiolaria are the proven archives of the evolutionary history of the ocean. They are tracers of paleoenvironmental changes. Many geochemical proxies are developed to extract information about ocean chemistry, seawater temperatures, and atmospheric pCO_2 from the tiny shells of the microfossils. Their global distribution and an almost uninterrupted record in the deep-sea have made them indispensable in geobiological research.

Time Scales of Geobiological Observations

The geobiological studies span the complete spectrum of time from investigating modern processes in field and laboratory to deep geological time as archived in sedimentary records. A basic understanding of geobiologic processes is achieved in the living world. However, beyond this, the context is geological. Life history and ecology are studied in the field. The organism is cultured in the laboratory to investigate calcification and silicification (in skeletal formation). The cultured specimens are also used to calibrate isotope or trace element data with environmental variables while developing a proxy.

Life has evolved through time, and so have the environments. The present-day biological processes may not have existed in the past, and the past biosphere may not have modern analogs. The oxygen-poor environment 2 billion years ago contrasts with the oxygen-rich surface environments of the modern day Earth. The evolving life and environment complicate the linkage between biological and geological processes. Therefore, observations have to be made at different temporal and spatial scales to understand the complexity of interactions between life and Earth. The laboratory experiments and field observations in modern settings have unquestionably provided important information in geobiology, but it only captures short-term processes. It visualizes some aspects of geobiological processes in a frozen time. However, it is grossly inadequate, and may even fail, to explain the dynamic and inter-dependent evolution of life and Earth. The limitations of the uniformitarian approach are evident in understanding how life responds to extreme climates (for example, in the Cretaceous and early Paleogene) or how it recovers after the impact of extra-terrestrial bodies (Cretaceous/Paleogene boundary). The answers lie in the geological records. Moreover, the development of Earth's ecosystem is a long-term process beyond the human lifetime observation. The modern ecosystems developed through 7 million years after global cooling in the late Miocene when the terrestrial plant and animal communities restructured in response to a cool and dry climate with enhanced seasonality (Herbert et al., 2016). A deep-time perspective in geobiological research is essential; else, it will remain of interest only to biology or chemistry.

Issues in Geobiology

A wealth of micropaleontologic data is retrieved from the deep-sea records. These are possibly the best paleobiological records from the statistics and reproducibility viewpoint. The question of diversity, abundance, and evolutionary innovations in these groups are addressed or are being addressed at local to regional scales. Exploring the global scale data for questions of paleobiological importance will have a potential interest. There are also associated geochemical records (mainly the oxygen and carbon isotopes) for understanding the biogeochemical cycles of the past. The instinctive question is, how did biodiversity changes and evolutionary innovations impact the biogeochemical cycles? The evolution of diatoms (siliceous), coccolithophore (calcareous), and planktic foraminifera (calcareous) in the Mesozoic had a crucial impact on oceanic biogeochemical cycles. Two distinct geobiological processes regulated ocean chemistry and the marine biological community in the Cenozoic. The availability of silica in the world's oceans was greatly limited by the diversification of diatoms in the Cenozoic. As a result, silica secreting organisms, including the sponges, radiolarians, and diatoms themselves, utilized less silica in their skeletal formation. Against the biologically-driven depletion in silica saturation, the growth of carbonate-secreting organisms was impacted by the change in marine chemistry (Mg/Ca ratio of seawater). The prolific growth of coccolithophores in the late Cretaceous is attributed to the low Mg/Ca ratio and high Ca concentration in the ambient environment. However, the high Mg/Ca ratio and low Ca concentration in the modern seawater have constrained the growth of many coccolithophore species (Stanley, 2006). The organic matters remove atmospheric CO_2, and calcification releases CO_2 into the atmosphere. The relative roles of the two processes are not fully resolved in long-term carbon cycle models.

The evolution and diversification of siliceous and calcareous microbes also impacted sediment distribution. Was it due to the

Fig. 1. Favorable warm climate of the Eocene promoted the growth of heavily calcified larger foraminifera along the Tethys. The photograph shows an extensive development of carbonate rocks formed by these foraminifera in Kutch. In the inset is close-up view of the same showing foraminifera as the main constituent.

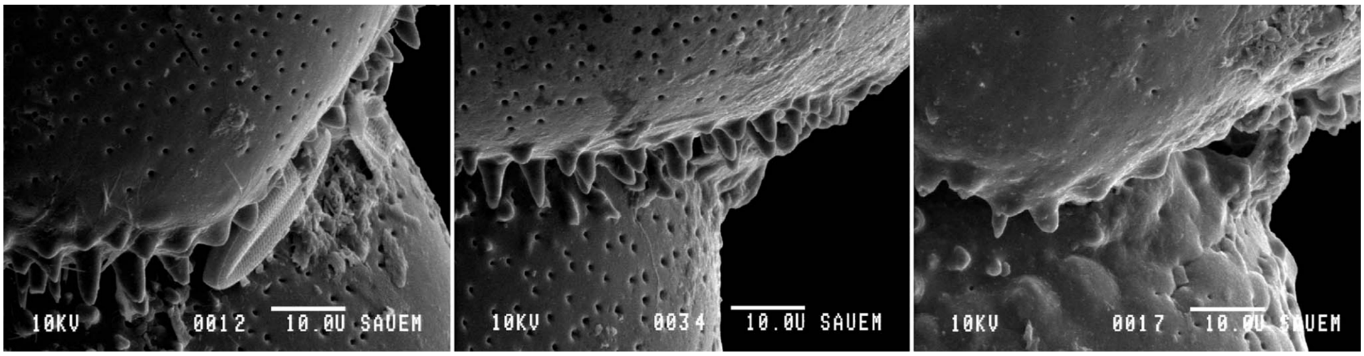

Fig. 2. Scanning electron micrographs of *Haynesina germanica* exposed to different CO_2 treatments in the laboratory. Note the presence of tubercles and teeth in the apertural region at 380 ppm (left) and 750 ppm (middle), and their almost absence at 1000 ppm of CO_2 (right). (after, Khanna et al. 2013; reproduced under Creative Commons Attribution CC BY License).

response of the biosphere to climate change? If so, did ecology play a vital role in the distribution of sediments? During the warmer climate of the early Paleogene larger benthic foraminifera diversified rapidly and contributed significantly to shallow-marine carbonates (Fig.1). Diatom diversity decreases in warmer climates. It is likely to impact silica distribution in the event of future global warming. In this context, studying the response of sediment-producing microbes to climate change becomes essential. More focused research on biodiversity and innovative changes in the Cretaceous and early Paleogene greenhouse needs to be carried out. It will give an insight into how these organisms braved the global warming and possible ocean acidification. Further, these studies can gain insight into the consequences of the ongoing anthropogenic changes.

Interesting laboratory results are found on the effect of elevated CO_2 on eukaryotes. The benthic foraminifer *Haynesina germanica* was cultured at atmospheric CO_2 concentrations of 380, 750, and 1000 ppm, respectively (the present-day CO_2 is ~418 ppm). Specimens incubated at high CO_2 levels displayed shell dissolution and a significant reduction and deformation of ornamentation associated with feeding (Fig. 2; Khanna et al., 2013). Similar laboratory experiments indicate that ocean acidification is likely to compromise many foraminifera's growth and life function. However, coccolithophore *Emiliania huxleyi* significantly increased calcification and net primary production with increasing CO_2 partial pressures from 280 ppmv to 750 ppmv (Iglesias-Rodriguez et al., 2008). Some results indicate that warm water species are expanding their biogeographic ranges in response to global warming. Time series data suggest rapid southwestward progression of foraminifer *Amphistegina* on the eastern coast of Africa at ~8 km/yr. By the year 2050, it is projected that many species will expand their biogeographic range by 1 to 2.5^o latitudes north- and southward (Weinmann et al., 2013). Both coccolithophores and foraminifera contribute majorly to the carbonate and carbon cycles of the ocean. Their varying response to modern climate change suggests the complexity of the ecosystem inherent in geobiological problems.

One of the most debated questions in geobiology has been the role of oxygen in shaping animal evolution, and there are fiercely opposing views (Planavsky and Konhauser, 2020). The benthic microbes in the oxygen minimum zones and anoxic environments can provide some answers to this question. The benthic foraminifera adopts different life strategies to survive dysoxic and anoxic environments. How did the planktic and benthic microbes respond to the multiple anoxic events of the Aptian-Turonian? The studies indicate that planktic foraminifera decreased size, morphological diversity, and complexity at the Aptian/Albian boundary anoxic event. Such observations are few and sketchy at present.

Re-evaluation of the existing proxies and development of new proxies will remain an active area of research in the foreseeable future. The critical question is, what is the fidelity of the proxy? How truly does it measure the environmental variable? The problems of 'vital effect' in isotopic and trace element signatures are long-recognized. Also, there is no way to determine 'vital effect' or its magnitude in fossil taxa. The observations in modern-day taxa and in-depth studies on calcification are trying to open this black box. It is essential to decouple 'vital effect' from environmental signatures in isotope and trace element proxies.

The advanced analytical tools and relational databases give new insights into geobiological processes. It has energized interest in the environment-life relationship, promoting geobiology as a distinct discipline. However, the complex response of the organisms to environmental change needs to be fully appreciated in modeling marine ecosystems and biogeochemical cycles. A coordinated approach of micro-paleontology, (paleo)oceanography, sediment geochemistry, and climatology will be key to the success of research in this area of geobiology.

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