PALAIOS

An International Journal of SEPM
(Society for Sedimentary Geology)

VOL. 17, NO. 6 **DECEMBER, 2002**

ONLINE

The Concept of Geobiological Studies: the Example of Bacterially Generated Structures in Physical Sedimentary Systems

Geobiology is an interdisciplinary approach to investigating the interactions between biological and geological processes. The term reflects the application of biology to the reconstruction of ancient worlds. Hence, geobiology follows earlier fruitful combinations of geology with other scientific disciplines including chemistry (geochemistry), mathematics (geomathematics), or physics (geophysics).

The two 'parent disciplines' of geobiology—biology and geology—are both basic research fields. The integration of their subdisciplines (e.g., microbiology, botany, biochemistry, or paleontology, sedimentology, and mineralogy) results in a synthesized application. In geobiology the parent disciplines inspire each other, and frame any hypothesis. As a consequence, they are connected. To verify a hypothesis, methods of all subdisciplines serve as independent tools. They may vary with subdiscipline or group of subdisciplines. By using the investigatory methods of biology and geology, new aspects are expanded for both basic research fields. Therefore, geobiology is not a new term for geomicrobiology, biogeochemistry, or paleobiology, and others, as often understood (compare discussion on geobiology as research agenda for paleontologists in Olszewski, 2001, and references therein). Indeed, both parental research fields and their subdisciplines continue to exist, and, even more important, become sources of elementary knowledge and interdisciplinary arguments for geobiology. Thus, the basic research disciplines are supported from a new methodological approach, and one might regard geobiology as an applied science that reflects developing technological possibilities with respect to methods of investigation.

The objective of geobiology is twofold: to document (1) geobiological processes, and (2) resulting structures, fossils, or minerals in consolidated lithologies. That is, on the one hand, geobiology defines biological and geological parameters as elements in coupled processes, and quantifies the influences of both sets of parameters. On the other hand, geobiology serves to detect lithological features, to decipher their genesis in the context of past environmental conditions, and to reconstruct the taphonomic path and diagenetic alterations that took place during consolidation of the sediment.

The specifically dual nature of the objective requires a twofold methodological approach. First, to investigate processes, an understanding of the actualistic principle is important and can be accomplished through the measurement and quantification of geobiological processes, through laboratory experimentation or by studies conducted in modern environments. Hence, processes can be explained by direct methods. Second, in contrast, only indirect methods (including comparative description) can serve to investigate structures, fossils, or minerals in the consolidated rock. Direct data may be derived only rarely, for example, from geochemical analyses. That is, it is fundamental within any geobiological study that direct and indirect methods are used in tandem to approach both processes and resulting lithological phenomena. Hence, if the original investigation is focused on an actualistic and direct approach, then comparative studies of rocks with indirect methods should be undertaken, and vice versa. This dualism in objective and methodological approach is core to geobiology, mirroring its parentage.

Recently, more and more attention has been paid to the signficance of biological processes within sedimentary geology, and geobiology provides valuable concepts for the interpretation of modern and ancient depositional environments. An array of current studies were presented at the Pardee Keynote Session 'Geobiology: its Application to Sedimentary Geology' during the 2001 GSA Meeting in Boston. Symposium contributions ranged from the rise of trace fossils created by macrobenthos within the early Cambrian to

Nora Noffke is a new assistant professor at Old Dominion University, Norfolk, Virginia, where she is developing a research program for geobiology and biosedimentology. Her research interests range from actualistic experiments on the influence of epibenthic bacteria on physical sedimentary dynamics to studies on fossil 'Microbially Induced Sedimentary Structures' in ancient environments, from the Archean to the Quaternary.
Already as a child, Nora roamed through outcrops in southern Germany, and over the years built up a huge collection of fossils. She studied geology and paleontology at the Eberhardt-Carls-University in Tuebingen, Germany. As a student of Adolf Seilacher and Hannsmartin Huessner, she made her diploma thesis on trace fossils in siliciclastic sediments.
For her PhD, she joined the working group 'Geomicrobiology' of Gisela Gerdes and Wolfgang E. Krumbein at Carl-von-Ossietzky-University Oldenburg, Germany. The focus of her research in Oldenburg was the bacterial interaction with sediment-dynamic processes in evaporitic and siliciclastic tidal systems. After a year as a consulting geologist at an environmental company in Germany, Nora returned to academia as a guest researcher in Andy Knoll's lab at Harvard University where she focused on geobiological aspects of the Proterozoic record.
Nora finally decided to move to Virginia. She is a horse lover and, of course, 'Puschel' had to move from Germany to the US with her.

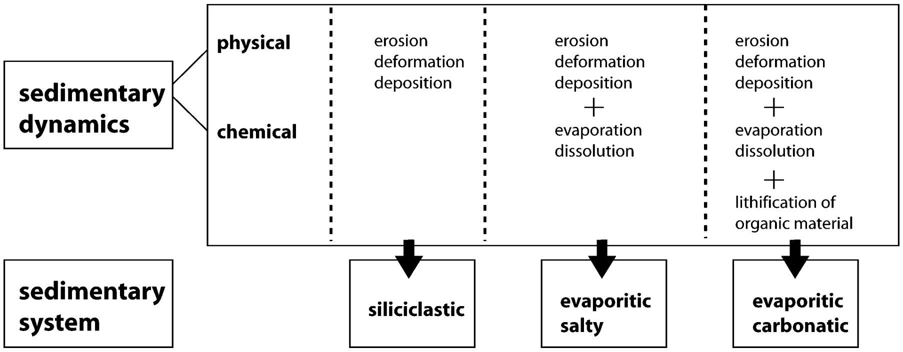

FIGURE 1—Main types of sedimentary systems defined by their specific physical or chemical dynamics.

the microbial impact on sedimentary processes in siliciclastic or carbonatic depositional areas; from biomarker investigations to isotope dating both proving the appearance of earliest bacteria; and from evolution of life on Earth to potential existence of life on Mars.

From a geological perspective, the interaction of organisms with their depositional environment is very important, because this interaction defines distinct and preservable sedimentary signatures. The signatures provide clear evidence for biological activities, whereas other data on potential influences on atmospheric composition, global temperature, or ocean-water chemistry often remain interpretative. This is especially true for the interpretation of extraterrestrial environments or rocks, but also for Archean worlds that appear more strange to us than the more familiar nature recorded of Earth's history since the Proterozoic.

Trace fossils are typical sedimentary signatures of biogenic activity commonly understood as having been produced by grazing, resting, or burrowing organisms. Not only macroorganisms can produce trace fossils, but bacteria also modify the sedimentary environment and produce discernible structures. Of the latter, stromatolites are the most well known, and innumerable studies have been conducted on their modes of formation. A precondition for stromatolite build up is *in situ* mineral precipitation, which is induced mainly by the metabolic activities of benthic bacteria that change their chemical microenvironment. Mineral precipitation is characteristic of chemical sedimentary systems, and commonly is associated with evaporitic carbonate environments. In these environments, geobiologists in the past have examined the biogeochemical processes that result in the precipitation and accumulation of carbonates. In contrast, far less work has been conducted in physical sedimentary systems that are governed by erosion, deposition or deformation, and where either there is a minimum or an absence of mineral precipitation (Fig. 1). Physical sedimentary systems comprise siliciclastic environments. The reason for the disinterest of many geobiologists in such systems, modern and ancient, may be the absence of bacterially generated sedimentary structures that are as striking as stromatolites. Exploratory studies on microbial phenomena in siliciclastic rocks were described in the volume by Hagadorn et al. (1999).

Recent research has revised the picture of 'dead' sandy sediments, especially in cool climates that seemed to stand in contrast to carbonate deposits of humid-tropical climates, where microbial life thrives. It is now known that a great variety of bacteria also colonize siliciclastic deposits. Of those, benthic cyanobacteria play a dominant role in modifying sediment as they do in precipitating environments, even if the biotic-sedimentary interaction is different. Cyanobacteria are photoautotrophic microbes that have been termed 'blue-green algae' because of their relative large sizes. Benthic species construct biofilms that effectively influence sedimentary processes. Most significant biofilms are thick, leathery microbial mats that can cover km^2 of depositional surfaces. Investigations in modern and ancient environments have revealed a great variety of microbial mat-related influences on sedimentary dynamics in siliciclastic depositional areas (compare overviews by Gerdes et al., 2000; Noffke et al., 2001). Direct measurements conducted in flume chambers and field experiments have provided quantitative data for bacterial activities including "baffling, trapping and binding", "biostabilization", or "imprinting." These bacterial activities shape sedimentary surfaces and give rise to true 'traces' that can become preserved as 'trace fossils' in the consolidated rock. Bacterial traces have been identified as their own category—Microbially Induced Sedimentary Structures (MISS)—and have been placed into the Classification of Primary Sedimentary Structures (Noffke et al., 2001). MISS are regarded as the counterpart to stromatolites (Noffke et al., in prep.), and are distributed widely in the stratigraphic record. The understanding of their formational modes provides information that is critical to reconstruct paleoenvironmental conditions.

One key microbial feature found within siliciclastic rocks are 'wrinkle structures' (Hagadorn and Bottjer, 1997). In the contribution of Noffke et al. 2002 (this volume), wrinkle structures are regarded as trace fossils of ancient microbial mats. Both (1) ecological parameters that control microbial mat development, and (2) taphonomic parameters that result in microbial mat preservation as wrinkle structures, are elucidated. By geological mapping of rock successions, the pattern of substrate-related distribution of wrinkle structures could be reconstructed. The distribution reflects the complex interaction between sedimentary parameters and microbial mat occurrences. Sedimentary parameters function as controlling parameters that define the 'ecological window' of cyanobacterial mat development in physical sedimentary areas, which has been proved by direct studies in modern siliciclastic environments or in flume chamber experiments (Noffke et al., 2001). By geological mapping of the rock successions, the specific taphonomic path that lead to microbial mat preservation also could be revealed. Such processes can be deduced only indirectly from the rock record. Because taphonomy is selective, this 'taphonomic window' must be considered in a paleoecological reconstruction.The example of microbially induced sedimentary structures in siliciclastic deposits documents that the interdisciplinary concept of geobiology serves to better provide an understanding of microbial mat development and preservation and paleoenvironmental conditions. In conclusion, a strict ecological interpretation from the rock record alone can be misleading. Vice versa, biological investigations of modern environments without knowledge of ancient life conditions, sedimentary processes, taphonomy, or diagenesis can deliver poor insight into past worlds. To bridge the gap, geobiology is the tool of choice.

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