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EDITORIAL

Special issue: Going Deep—Tracking life processes through time and space

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Ever since life arose, it has had a fundamental impact on environments on local and global scales. This means that understanding Earth—and possibly worlds beyond—requires understanding life and vice versa. However, our knowledge about life processes through time and space is still limited, and the extent of habitable environments remains poorly constrained. These problems are due to the enormous diversity of metabolisms, the huge complexity of biological communities, and the great variety of potential habitats. A further drawback is the unambiguous identification and interpretation of paleobiological fingerprints, particularly in Earth's oldest rocks. We launched this special issue to discuss such problems from a geobiological–paleontological perspective. We invited contributions exploring organisms and habitats through time and space, including progressive and provocative studies that combine classic approaches with innovative state-of-the-art techniques. For the special issue, 16 manuscripts were published. A brief account on the content is provided in the following.

The very early history of life on our planet is still hidden in the shadows of time. René Heller and co-workers used astrophysical modelling techniques and evidence from the rock record to evaluate the impact of tidal forces exerted by the much closer Moon on the early Precambrian Earth. They showed that the associated tidal heating played a significant role in the climatic stabilization of Earth's surface environments, on this way supporting the establishment of life on our Planet (Heller et al. 2021). Carolin Dreher and co-authors from the research group of Andreas Kappler provide a detailed overview about microbiological processes involved in the formation of Precambrian banded iron formations (BIFs). BIFs are considered to be of great significance to our understanding of some of the most profound environmental changes in Earth history, but the geobiological meaning of these deposits is still insufficiently understood (Dreher et al. 2021). Jan-Peter Duda and co-workers investigated molecular fossils from the bitumen and kerogen fractions of the ~ 1 Ga Lakhanda Lagerstätte (Siberia, Russia), which contains a wealth of exquisitely preserved fossils of early eukaryotic organisms. They show that the environment was dominated by anaerobic bacteria with no or very little

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inputs by eukaryotes, supporting the view that eukaryotes were present but not significant in Mesoproterozoic ecosystems (Duda et al. 2021).

Evolutionary developments during the Precambrian culminated in the rise and establishment of complex life forms such as animals in the terminal Neoproterozoic–Cambrian. The study by Zongjun Yin and co-authors focuses on the famous Weng'an phosphate deposit of the Doushantuo Formation in South China, which contains exquisitely preserved microfossils that partly resemble embryos of metazoans. However, the interpretation as animal embryos is still controversial and disputed. To shed new light on this question, the authors examine the Weng'an microfossil record by means of modern 3D imaging techniques (Sun et al. 2021). Alfred Uchmann and co-worker describe an Ediacaran fossil group with presumed systematic relationships to ascidians, adding to the growing body of knowledge on soft-bodied organisms from this critical time interval (Martyshyn and Uchman 2021). The third contribution on this topic is a comprehensive and excellent review by Xingliang Zhang and Degan Shu on the "*Cambrian explosion*" of animal life, illustrating that this development is deeply rooted in evolutionary developments during the Ediacaran (Zhang and Shu 2021).

Moving on in Earth's history, Ryan Wilson, Juergen Schieber and Cameron Stewart investigated trace fossils in Devonian black shales of North America. Both studies of the Schieber group illustrate the enormous impact of burrowing organisms on ecosystems and sediment formation in the deep sea. Furthermore, they demonstrate that organic-rich sedimentary rocks do not necessarily reflect persistently anoxic conditions in the overlying water column during deposition, which is commonly assumed in reconstructions of ancient environments. The described *Agrichnia*-traces exhibit morphological analogies with fossil possible keratose sponge skeleton remains and should be, therefore, discussed deeply, which interpretation is more convincing or not, this is due to the ongoing discussion of this topic from general importance (Wilson et al. 2021). Eberhard Gischler and colleagues studied a particular carbonate factory in the run-up to the terminal Devonian FrasnianFamennian crisis (or "Kellwasser Event"). They show that the putative Rübeland mud mound in the Harz Mountains is actually an extremely rare example of a cryptic reef-cave deposit that includes micritic carbonates and communities of deep-sea organisms (e.g., hexactinellid siliceous sponges) (Gischler et al. 2021).

It is widely accepted that ecological crises have affected biological evolution, but it is problematic (if possible at all) to access the significance of these events by means of taxonomic numbers. More detailed studies on ancient records are needed to gain a robust knowledge about the nature of such developments. Yu Pei and co-authors studied sedimentary sections in South China that cover the so-called Permian–Triassic boundary, illuminating the collapse and subsequent recovery of carbonate ecosystems during the ecological crisis (Pei et al. 2021). Hans Hagdorn contributed an excellent taxonomic, phylogenetic, and paleobiological study on Triassic crinoids, highlighting the enormous but unfortunately way too often underestimated potential of classical paleontological studies to understand past life (Hagdorn 2021).

Another set of contributions comprises taphonomic studies on fossil preservation in the spectacular Upper Pliocene Willershausen Lagerstätte (Lower Saxony, Germany). Klaus Wolkenstein and Gernot Arp investigated various colored angiosperm leaves from this Fossillagerstätte by means of UV-light-induced fluorescence. Through comparison with present-day senescing plants, the authors are able to show that fluorescence differences in fossil leaves are mainly caused by taxon-specific degeneration of organic compounds (Wolkenstein and Arp 2021). Tyede Schmidt-Schultz, Michael Schultz and Mike Reich report the presence of about 3 million years old extracellular bone matrix proteins in remains from the extinct proboscidean *Anancus* (Schmidt-Schultz et al. 2021)—a spectacular finding that highlights the enormous preservation potential of the Pliocene Willershausen Lagerstätte, stressing its meaning for paleo-reconstruction.

Geobiological studies on modern materials are important for the interpretation of ancient rock records. This is particularly true for the reconstruction of microbial processes through deep time. Michael Hoppert and co-authors studied *Rivularia* stromatolites, which provide an excellent model system to understand EPS-controlled carbonate mineralization in freshwater settings. The findings of this study are of direct significance to the interpretation of ancient microbialites. The paper by Pablo Suarez-Gonzalez and Joachim Reitner in contrast demonstrates the importance of EPS-controlled biomineralization in microbial mats from hypersaline ponds on the Pacific atoll of Kiritimati (Suarez-Gonzalez and Reitner 2021). Notably, these authors observed authigenic ooids within mineralizing studied microbial mats, which perhaps unravel the long-standing and still unsolved mystery of how these prominent carbonate components form. Luis Somoza and co-authors studied the spatial association of *Bathymodiolus* communities and methane seepage structures at deep-sea mud volcanoes in the Gulf of Cádiz, and elucidated the exact role of microbial symbionts in the bivalves (Somoza et al. 2021). A better understanding of these relationships is of uttermost importance, since such symbioses likely have had a lasting impact on the evolution of the involved organisms. A very intriguing contribution is also provided by Juergen Schieber and Ryan D. Wilson, showing how meioturbation affects rock fabrics especially in mudstones and black shales finding that clearly shows how poorly theimportance of meiobenthos in fine grained sediment is understood (Schieber and Wilson 2021).

Taken together, the special issue *Going Deep—Tracking life processes through time and space* comprises a fine selection of excellent contributions that cover a remarkably diverse range of topics (please note that one of the contribution will be published in the following issue of the *PalZ* due to technical problems during editing). All studies provide fascinating and valuable insights into state-of-the-art paleontological and geobiological research, thereby demonstrating the enormous potential of such study designs for unravelling the mysteries surrounding ancient worlds and for tackling the great questions about the co-evolution of life and Earth.

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