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Editorial: Advances in bioerosion in the 21st century: new challenges

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Editorial on the Research Topic
Advances in bioerosion in the 21st century: new challenges

Introduction

Bioerosion, i.e., the breakdown of hard substrates by organisms, is a major structuring force that modifies past and present ecological communities and ecosystem functions. It acts at various scales and is performed by a multitude of organisms encompassing chemical and/or mechanical means during superficial grazing, attachment, or internal micro- and macrobioerosion.

Research, that crosses many disciplines among the sciences, has explored the mechanisms and effects of bioerosion. Since the term "bioerosion" was established by Neumann already 55 years ago (Neumann, 1966), a wide variety of bioerosion research has been conducted and various papers have been published focusing on topics from micro (e.g., Calcinai et al., 2008; Golubic et al., 2016; Wisshak et al., 2018; Heřmanová et al., 2023) to macro bioerosion organisms (e.g., Santos et al., 2003; Garilli et al., 2022), from many different marine (e.g., Akpan, 1990; Calcinai et al., 2011; Santos et al., 2015) and non-marine environments (e.g., Bolotov et al., 2018; Mayoral et al., 2020; Mikuláš et al., 2020) to different climatic zones (e.g., Aitken and Risk, 1988; Tribollet, 2008; Cerrano et al., 2010; Wisshak et al., 2011; Wizemann et al., 2018; Patterson et al., 2020; Wisshak et al., 2021; Meyer et al., 2022).

More recently, with increased accessibility to and elaboration upon advanced analytic techniques, new methods and perspectives in the study of bioerosion are emerging including the application for sophisticated analysis techniques such as micro-CT to the study of bioerosion impact on cultural heritage. With all these improvements, we now know that bioerosion is a fundamental and global ecological process that can affect habitat structure, biodiversity and biogeochemical cycling. There are shared aspects in the mechanisms of bioerosion that suggest similarities in the forces that drive bioerosion and its ecological outcomes. Recent research has shown that bioerosion intensity increases in response to modern climate change and human-induced impacts, e.g., increased temperature, alkalinity, eutrophication and sea level rise (e.g., Tribollet et al., 2009; Wisshak et al., 2013; Silbiger et al., 2016; Chazottes et al., 2017; Prouty et al., 2017).

In a changing world, bioerosion is rapidly responding to anthropogenic changes in multiple and complex forms, with significant and far-reaching effects on all systems. Emerging data further underscores the significance of bioerosion and the need to mitigate its impacts. In this context, the magnitude and interdisciplinary nature of challenges presented by bioerosion to society are evident. A cross-disciplinary approach is needed to understand better how future changes will affect the dynamics of bioerosion throughout ecosystems and taxa. However, the biological and geological systems of the past should not be forgotten, as they may hold the key to many of our future research questions. In this context, further research across disciplines is urgently required to expand our knowledge of bioerosion and to predict its multiple impacts, especially under fast-changing worldwide conditions.

This Research Topic is dedicated to evaluating bioerosion effects across ecosystems during the past and present in a context of global change. This is devoted to a multi-disciplinary perspective of how bioerosional processes affect the huge variety of biological and geological systems, both past and present, and focuses on new questions that will come during the 21st century with climate change issues. The diverse spectrum manuscripts submitted to this Research Topic ranged from the Palaeozoic to the Recent.

Contributions to this topic

The underwater marine environment hosts impressive historical documentation that archaeologists are trying to unveil and describe. Archaeological remains are an important part of the worldwide cultural heritage and are of high historical value. Moreover, they provide information on ancient technologies, and exchanges of goods and resources, contributing to the reconstruction of the origins of important historical vents; for this reason, their conservation has been promoted through the UNESCO Convention on the Protection of the Underwater Cultural Heritage (UCH). Bioerosion affects any submerged substrata made of carbonates including underwater archaeological remains. This Research Topic was addressed by the review on the impact of bioerosion on submerged archaeological artefacts in the Mediterranean Sea (Sacco Perasso et al.); the paper summarized studies on bioerosion impact on statues, remains of submerged cities and shipwrecks and included the first list of archaeological sites in the Mediterranean Sea where bioerosion has been studied. The review revealed that despite the huge diversity of boring organisms affecting marine archaeological remains and the severity of the damage caused by them to heritage artifacts little information is still available, compromising the design of effective conservation measures. In the paper, a discussion of the available strategies proposed for the *in-situ* protection and conservation of Underwater Cultural Heritage was provided; all boring organisms affecting submerged artefacts (algae, fungi, cyanobacteria, sponges, bivalves, polychaetes, sipunculids, and echinoids) were described, and their role in the structuring of endolithic assemblages was addressed. The paper deals also with the experimental techniques employed to analyse bioerosion traces and to identify species.

One of these novel techniques is micro-CT. Turicchia et al. investigated with this technique both bioconstruction and bioerosion processes in travertine limestone tiles that have been deployed in the North Adriatic Sea (Mediterranean Sea) for 12 years. The results lead to hypothesize that in the northern Adriatic coralligenous reefs a steady state, resulting from the net balance between bioconstruction and bioerosion, exists. The paper confirms how in the northern Adriatic coralligenous reefs, Porifera represents the main taxon responsible for bioerosion as the most effective borers were sponges of the genus *Cliona*.

With a similar approach using micro-CT, Mikuláš et al. studied domichnial borings in Cretaceous serpulid tube walls from France and Czechia. Authors were able to identify that the tracemakers of these borings adapted to the small size of their substrates by necessarily staying very small by themselves but living to adulthood as a functioning population.

Following the path of emerging technologies, the work by Alaguarda et al. focus on the study of microbioerosion on a living coral skeleton sections over the last five decades from Myotte (Western Indian Ocean) based on an innovative machine learning approach. The nature and global importance of corals and the rapid destructive impact of Global Climate Change call for extensive and fast indexing and monitoring. Due to their susceptibility to natural and anthropogenic threats currently, reefs are suffering remarkable changes and are in danger. Alaguarda et al. applying artificial intelligence (AI) to solve the time-consuming, observer biases of the main types of microbioerosion and proxy determination of their abundance based on thousands of SEM images. Machine learning approach has the potential of solving this problem efficiently, and by far exceeds in terms of reliability and accuracy human microbioerosion reef documentation and monitoring in a few hours with an accuracy of 93% (Alaguarda et al.). Although only three types of traces were determined, authors were able to identify the main common trace makers colonizing live coral skeletons (i.e., *Ostreobium quekettii*, *Plectonema* sp). To determine the possible abiotic and biotic factors influencing the variability of microborers abundance over the last decades, authors also measured the main coral skeleton parameters (vertical extension and bulk density) along the core and collected Sea Surface Temperature (SST), Sea Surface Temperature Anomalies (SSTA), precipitation, instantaneous maximum wind speed, and the cumulative insolation duration over the last 54 years from available databases. This new methodology provided for the first time the opportunity to highlight a major shift in the microboring assemblage composition and an unprecedented decrease in microborers abundance over the life span of a slow-growing massive coral *Diploastrea* sp. According to Alaguarda et al. possible explanatory factors could be linked to ocean warming (both SST and SSTA), wind stress, precipitations, and cumulative insolation more or less combined, as well the bulk density of the coral host. However, the direct or indirect effects of those factors in microboring communities need to be explored, especially that of global warming.

To improve projections of coral reef evolution, it is important to better understand dynamics of bioerosion processes. In light of this, and to better understand the conditions of production of alkalinity in seawater by boring microflora and its possible effects on reef resilience, Tribollet et al. conducted a series of experiments with natural rubble (*Porites lobata*, *P. compressa*, *Pocillopora meandrina*, *Montipora capitata*) maintained under natural or artificial light, and various saturation states of aragonite. Based on the data obtained, Tribollet et al. confirmed the abundance of the phototrophic eukaryote *Ostreobium* sp. within the natural microboring communities studied. These are the main drivers of reef dead coral dissolution observed under a large range of saturation states in seawater (at least between 2 and 6.4). Authors report for the first time $CaCO_3$ biogenic dissolution under natural daylight conditions, simultaneously with significant rates of net photosynthesis (13–25 mmol $C.m^{-2}.h^{-1}$). Also, net $CaCO_3$ biogenic dissolution rate and net photosynthesis increased with time in the three outdoor incubations (up to ΩArag <6.4), suggesting that constant brushing, combined with some environmental factors such as nutrient availability and temperature, certainly stimulated microborer growth (in depth and/or by branching) over the duration of the experiment.

The relevant importance of Porifera (i.e., sponges) in bioerosion activity on reefs is underlined by the paper of Pohler et al. The authors analyzed in several locations, in southwest and central Fiji, Kiribati, and Solomon Islands (Pacific Ocean) the levels of infestation in random sampled reef rubbles; the study reveals four styles of sponge bioerosion mainly due to sponges of the genus *Cliona*. High levels of sponge infestation can be linked to the abundance of free substrate available for the settlement of boring sponge larvae, while coral rubbles completely covered by algal plaques are not a good substrate for boring sponges. The relatively more isolated locations showed an impoverished sponge fauna, probably endemic.

Concerning the study of macro bioerosion structures from Miocene-Pliocene deposits from Canary Islands, a new ichnotaxon is introduced to the literature by Verde et al. The new trace fossil *Santichnus mayorali* is attributed to vermetid gastropods and share a close relationship with the ichnotaxon *Renichnus*. For which reason the authors propose that they should be considered as a compound trace fossil constituting a record of an ichnogenetic sequence related to ontogeny.

Finally, Villas et al. revised an Upper Ordovician Peruvian brachiopod Research Topic from the Proto-Andean margin of Gondwana and compared it with material from Wales (Avalonia). They check the type of biotic relationship between these brachiopods and their borers (polychaete spionids), which are the producer of *Palaeosabella* on their shells. Based on their results, authors suggest for an early stage a parasitic relation and, later on, a commensalism between borers and hosts. Despite the critical taxonomic differences between both provinces and of the large geographic distance between them, authors were able to identify that both hosts and borers covered the same route the Sandbian in a successful long-distance biotic relationship to come across the Rheic Ocean.

The future of bioerosion looks promising since the field is active, and a new generation of ichnologists graduating in this field in recent years is emerging. Papers included in this Research Topic suggest key future directions are likely to include 1) new technologies like microcomputer tomography or AI, 2) better quantification of alteration processes on acidic oceans, 3) bioerosion trace fossils that go deeper in time.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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