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Bioerosion structures in a Late Cretaceous mosasaur from Antarctica

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Abstract

Bioerosive structures in the cortical region of a vertebra from a mosasaur fall in the López de Bertodano Formation (Upper Maastrichtian) in Seymour Island (Isla Marambio), Antarctica, are reported. The traces studied are similar but not coincident with the described microborings in other fossil bone remains. The morphology and extension of these bioerosive structures are considered as the result of the activity of endolithic organisms on the original vascular channels of the bone. They are approximately straight, anastomosed, and commonly filled with an opaque mineral and framboidal pyrite. As most of the bone structure is well preserved, only the small portion of the cortical region was exposed to the microorganisms' activity. This would mean that the mosasaur individual died well earlier than the burial event. This is their first report of this type of bioerosive structures in a mosasaur fall.

Keywords Bioerosive structures · Marine reptile · Cretaceous · Antarctica

Introduction

Large marine vertebrate falls on the sea floor, e.g., whale carcasses, create significant habitats for the development of diverse and highly specialized communities that take advantage of and are responsible for the bone degradation (Kaim et al. 2008; Danise et al. 2014). In the Mesozoic, prior to the appearance of whales, marine reptile-falls fulfilled similar roles and hosted analogous communities (Kaim et al. 2008). From this point of view, paleoecological studies of fall community allow reconstructing the successional stages that preceded final burial of bone remains (Danise et al. 2014). Among the different successional stages, the last one includes a complex community based on the hydrogen sulfide (H_2S) and other chemical compounds produced by microbial consumption of the lipid-rich bones ("sulfophilic stage"; Smith and Baco 2003). For this reason, the study of microbial activity interpreted by bioerosion traces adds an important contribution to the paleoecology and represents a powerful tool for taphonomic reconstruction (Jans 2008).

The biological degradation or destruction of hard substrates is known as bioerosion and was defined by Neumann (1966) as every form of biologic penetration into lithic (including skeletal) and woody substrates. Different processes may be involved in bioerosion, depending on the kind of activity of the biological agent on the substrate (e.g., feeding on or living in the substrates). Höpner and Bertling (2017) differentiated two types; one includes biting, rasping, drilling, or crushing, with most of the actor's body mass remaining outside the substrate; and the other borings, with most of the actor's body mass sunken into the substrate. In the second type (boring), it is usually distinguished between macroborings and micoborings. While macroborings can be observed with the naked eye, microborings are structures ranging from less than 1 μm up to 100 μm in diameter (e.g., Glaub 1999).

Microbial organisms such as algae, bacteria, and fungi are known to play an important role in the degradation of bones in marine ecosystems and they leave different traces as evidence of their activities (Danise et al. 2012, 2014) considered as microbioerosion. The record of microbial activity was studied in Mesozoic plesiosaur, sea turtle, and ichthyosaur bones, suggesting that similar communities to those of whale falls could have existed associated with carcasses of Mesozoic marine reptiles (Kaim et al. 2008; Danise et al.

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2014; Danise and Higgs 2015). Endolithic microorganisms are and obviously were present in marine ecosystems and are able to metabolize lipids, collagen, and mineral matrix (Davis 1997; Trueman and Martill 2002; Higgs et al. 2011; Liebenau et al. 2015). When they bore into hard substrates, they make cavities that reproduce their body shapes (e.g., Golubic et al. 1981, 2005; McLoughlin et al. 2007; Wisshak and Tapanila 2008). These micro-organisms include phototrophic cyanobacteria and algae, and heterotrophic fungi and bacteria (e.g., Golubic et al. 2005; Wisshak and Tapanila 2008). While fungi and cyanobacteria dissolve the bone matrix, resulting in branching tunnels, bacteria create microscopical focal destructions with a complex morphology, reorganizing the mineral substrate rather than removing it (Jans 2008).

In an ichnotaxonomic approach, Höpner and Bertling (2017) proposed that those bones as a substrate require the same status as rocks/sells and wood as bone is distinct from lithic and xylic substrates in terms of structure, mineralogy, nutritional value, and hardness. Regarding the great importance of substrate types in ichnotaxonomy, trace fossils on bones should be identified by their own names (Höpner and Bertling 2017). One of the earliest authors for microbioerosion in vertebrate remains belongs to Wedl (1864), who described tunnels in fossil reptile teeth, bird egg shells, fish scales, corals, and molluscs from the Mesozoic to the Quaternary. He inferred that the tunnel makers were fungi. Roux (1887) described "*Mycelites ossifragus*" on Mesozoic and Quaternary reptiles, fish bones and teeth, although he did not isolate or identify the producer organism. In marine reptiles, the activity of microbial communities has been recorded in plesiosaurs and turtles from the Upper Cretaceous of the UK and Japan as well as in ichthyosaurs from the Upper Jurassic of the UK (Kaim et al. 2008; Danise et al. 2014; Danise and Higgs 2015). Microbial communities on mosasaur bones, however, have not been documented as yet.

The aim of this work is to report and describe bioerosive structures in a mosasaur fall from Antarctica and discuss their probable origin.

Institutional abbreviations MLP, Museo de La Plata, Buenos Aires Province, Argentina.

Geological setting

The López de Bertodano Formation at Seymour Island (Isla Marambio), Antarctica was originally divided into ten units (Klb 1–10), but recently unit Klb 1 has been considered to be part of the Haslum Crag Sandstone Member of the Snow Hill Island Formation (Macellari 1988; Olivero et al. 2008; Olivero 2012). The lower units are Klb 2–6 (the informal 'rotularia units'), while the upper units are Klb 7–10 ('molluscan units'). The 'Molluscan Units' are highly

fossiliferous, especially Units Klb9 and Klb10, which span the K–Pg boundary (Macellari 1988; Elliot et al. 1994; Zinsmeister 1998). The specimen described in this contribution was collected between Klb 8 and 9. These units consist of massive mudstones and silty, very fine grained sandstones interbedded with glauconitic fine sandstone beds and concretionary horizons. Bivalves, gastropods, and marine reptiles are very common in the molluscan units. These beds represent transgressive shelf deposits followed by a regressive trend in the uppermost part of the López de Bertodano Formation (Olivero 2012). According to Schoepfer et al. (2017), several lines of evidence point to intermittently anoxic to euxinic conditions during deposition, including the presence of pyrite framboids with a size distribution suggesting syngenetic formation in the water column.

Materials and methods

A histological thin-section from an isolated vertebra of a mosasaurid (MPL 88-I-2-1) collected from the Upper Maastrichtian of the López de Bertodano Formation in Seymour Island (Isla Marambio), Antarctica, was analyzed. The thin-section was studied and photographed in natural and polarized transmitted light. The preparation of the histological section was based on the methodology outlined by Chinsamy and Raath (1992). The instruments used are located at the Instituto de Investigación en Paleobiología y Geología, CONICET-Universidad Nacional de Río Negro, Argentina.

Results

The original structure of the bone is well preserved; the histological structures can be identified clearly throughout the thin-section. Pathological signs or chemical dissolution have not been observed. Compacta and spongiosa region macroscopically clearly distinguishable:

Compact cortical region

The outer zone is well defined and vascularized, formed by a matrix-woven fibered bone. In this region, vascular channels are simple and elongated, with an average of 30 μm, and they do not have a preferential orientation (Fig. 1a, b). At higher magnification, a large amount of globose lacunae is observed, with a low development of canaliculi. There are no secondary osteons or reabsorption spaces. In this region, anastomosing micro-channels are recognized. They have an average diameter of 60 μm and their maximum measured length is 500 μm. These channels are superficial, approximately straight, and extend to a maximum depth of 700 μm from the surface.
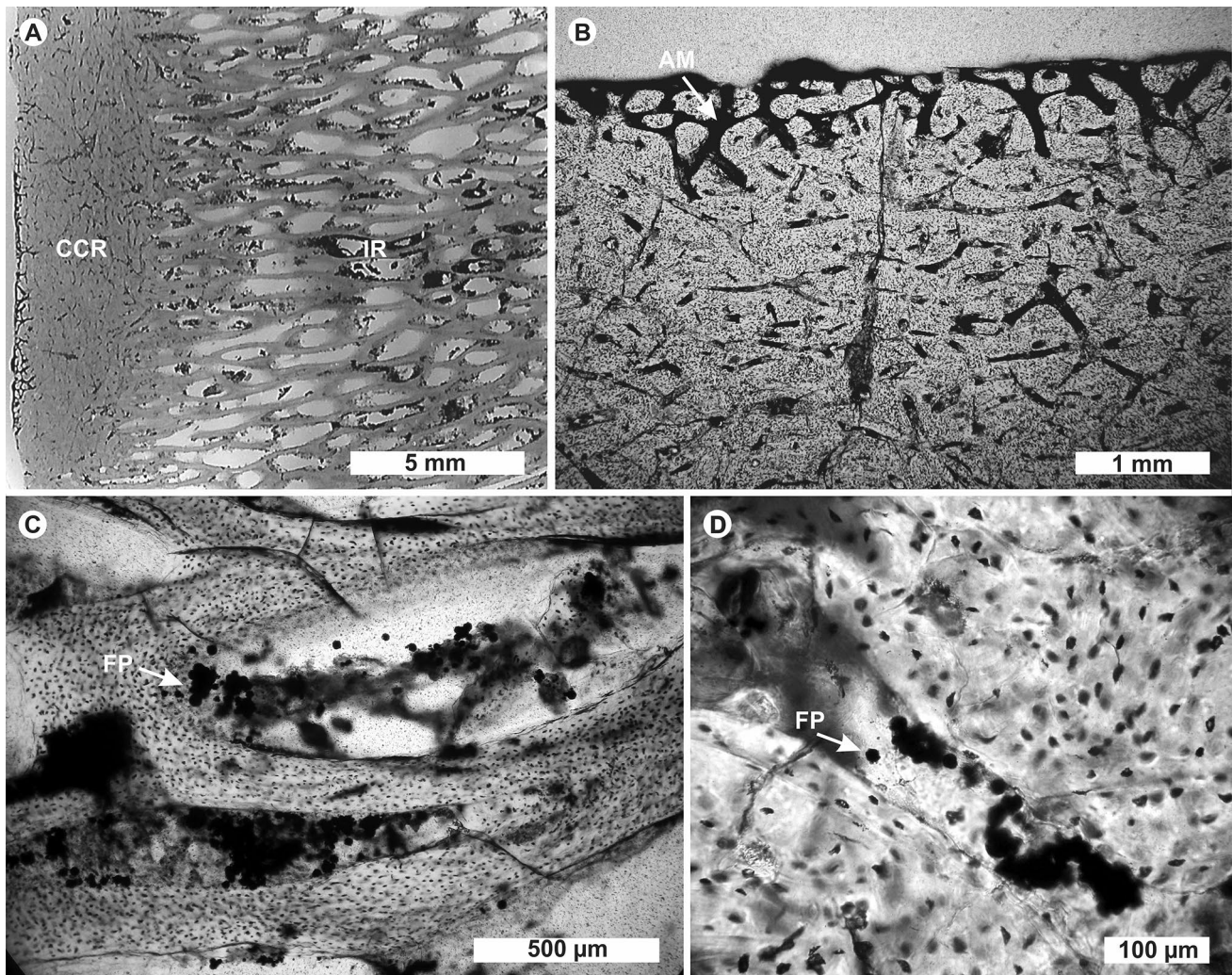
Fig. 1 Thin-section of mosasaur vertebrae MLP 88-I-2-1 from Seymour Island, Antarctica, López de Bertodano Formation, Maastrichtian. **a** General view of this section showing compact cortical region (CCR) and internal region (IR). **b** Detail of compact cortical region exhibiting anastomosing micro-channels (AM). **c** Framboidal pyrite (FP) accumulated in trabecular spaces of internal region. **d** Detail of framboidal pyrite

They have random orientation and perpendicularly penetrate to the substrate (Fig. 1b). They are filled with some opaque minerals, often combined with framboidal pyrite.

Internal region

The inner zone is very porous, being composed of cancellous bone. The trabeculae of this tissue are formed by lamellar bone. In the intertrabecular spaces, it is possible to distinguish rosette-like structures, which are characterized by a dark, opaque nucleus of framboidal pyrite. In this region, neither micro-channels nor other microborings were observed (Fig. 1c, d).

Discussion

The features of bioerosive structures found in this studied sample were compared with traces originating from endolithic microorganisms as described by Wedl (1864), Roux (1887), Martill (1989), Davis (1997), Turner-Walker and Jans (2008), Jans (2008), Danise et al. (2012) among others, in bone remains. For example, cylindrical holes penetrating the outer bone surfaces were reported in plesiosaurid (Kaim et al. 2008); circular surficial openings with a uniform tube section that expands to an irregularly shaped chamber inside the bone was recognized in plesiosaur and sea turtle bones (Danise and Higgs 2015). Also,

non-bifurcating, straight, or slightly curved microtunnels were identified in ichthyosaurs (Danise et al. 2014). However, some differences are recognized in our material.

Bioerosive structures start in the cortical surface and continue no more than 700 μm inwards. They are here interpreted as original vascular channels, which were widened and whose interconnections were increased. These changes are the result of microbial colonization of those pre-existing channels, which were widened twice their original size. According to the strict definition of bioerosion, these microchannels cannot be interpreted as microborings sensu stricto since it is a combination of an original bone structure with a wear caused by biological agents.

Claiming a producer of the biodegradation of the bone (e.g., fungal or algae) is difficult as the tunnels are branched in different ways and at different frequencies, often spreading parallel to the surface (see Golubic et al. 2005). This problem is due to the fact that the reproductive behavior of these unrelated organisms groups may produce identical borings (Golubic et al. 2005). In this sample, the microchannels do not seem to be parallel to the surface, buy they do not represent the host body shapes. In addition, they only occur in the compact cortical region, which makes it difficult to determine whether the producers were phototrophic or not. Moreover, in other studies of fossil whale falls (Amano and Little 2005; Kiel 2008; Shapiro and Spangler 2009), microbioerosion has been attributed to the activity of bacteria, algae. or fungi, but they could not be distinguished.

The presence of iron sulfides (pyrite) in the vascular channels and in the inner region of the mosasaur cancellous bone may be related to the early stages of bacterial bone decay. According to Pfretzschner (2001), sulfide produced by bacterial degradation of bone collagen could have induced iron sulfide precipitation inside small spaces within the bones.

Trueman and Martill (2002) found that the majority of the studied fossil bones from Silurian to Pleistocene showed fungal tunneling as the predominant type of alteration. Bone decomposition mediated by fungi is determined by environmental factors. Its presence can potentially serve as an indicator of burial environments. Bioerosion is a very early post-mortem process, which rapidly proceeds to complete destruction of the bone. Bioerosion can be stopped, and bioeroded bone can survive into the fossil record. One of the mechanisms for halting bioerosion is chemical inhibition of bioeroding microbes. In the case of bioeroded fossil bones, a change in chemical conditions must have occurred during the early burial history of the bone (Trueman and Martill 2002). Intermittent euxinia appears to have been a characteristic feature of this high-latitude environment during the Cretaceous–Paleogene in López de Bertodano Formation (Schoepfer et al. 2017). These chemical fluctuations could have inhibited bioerosion and this contributed to the preservation of the histological structures in the analyzed sample.

In the studied sample, modified walls vascular channels are observed only on the external surface of the bone, while the internal part keeps its structure well preserved. This would indicate that the external part was exposed to the activity of microorganisms, and would mean that the mosasaur individual died well earlier than the burial event, regardless of the type of producer that made the microbioerosion.

Conclusions

The data presented here indicate that the features of microchannels found in this studied sample that iniciate in the cortical surface and continue inwards, are interpreted as originally vascular channels, which were widened and their interconnections were increased. It is proposed that this kind of network is a result of microbial colonization of those preexisting channels. The presence of pyrite in the vascular channels and in the inner region of the cancellous bone may be related to the early stages of bacterial bone decay. The micro-channels are observed only on the external surface of the bone, while the internal part keeps its structure wellpreserved. This would indicate that the external part was exposed to the activity of microorganisms, and would also indicate that the mosasaur individual died well earlier than the burial event. This is the first report of this type of bioerosion structure in a mosasaurs fall.

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