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Mammal tooth traces in a ferruginous cave in southeastern Brazil and their relevance to cave legal protection

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Abstract: We describe the first occurrence of biogenic traces made by mammals within an iron formation cave located in the Serra da Ferrugem Ridge, in Southeastern Brazil. These bioerosions are tooth traces produced in boulders, walls and floor within the cave. The traces occur as sets of two or more grooves, which are highly variable in size. The grooves were compared to tooth traces artificially produced by imprinting the incisors of different mammal species collected in the cave region on soft clay. Among those, the following taxa are potential tracemakers: *Akodon* sp., *Oligoryzomys* sp., *Necromys lasiurus*, *Rhipidomys mastacalis*, *Oecomys* gr. *concolor*, *Trinomys moojeni*, and *Hydrochoerus hydrochaeris*. The age of the traces is unknown; therefore, any discussion on its fossil nature is circumstantial. Regardless of its relevance to paleontology, the presence of ichnological features should be considered as an additional cave value, according to the current Brazilian legislation regarding cave protection.

Key words: bioerosion, geophagy, gnawing traces, rodents, ichnology.

INTRODUCTION

Fossil and extant biogenic structures within caves include chemically-induced erosional surfaces and relief construction, such as tubes, burrows, pits, tunnels and scratch traces, variously produced by distinct types of organisms, notably microbial decomposers, plant roots, and assorted invertebrates and vertebrates (Holsinger and Dickson 1977, Macdonald and Terrel-Nield 1991, Lockley and Meyer 2000, Santucci et al. 2001, Lamprinou et al. 2009, Jones 2010, Karkanas and Goldberg 2013). Biogenic structures can also be represented by fossilized feces, i.e. coprolites (Czaplewsky and Cartelle 1998, Santucci et al 2001, Backwell et

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al. 2009, Marcolino et al. 2012, Vasconcelos and Bittencourt 2018).

Due to the shortage and uneven distribution of resources within caves, these environments are generally more restrict to occupation than several non-cave ecosystems (Fernandes et al. 2016). Therefore, a lower diversity of biogenic traces is expected. Yet, explanations for the reduced diversity of biological modifications in soft and hard substrates within caves in comparison to the vast record of non-cave environment bioturbations (Miller 2007) rely not only on its lower alpha-taxonomic diversity or the erosional nature of caves, but also on their rare documentation (Bednarik 1991).

Several studies have demonstrated the role of biological activity as chemical modifiers of caves, including mainly microbial-induced substrate weathering or speleothem construction (Jones 2010 for review), and erosion by the input of metabolic residues, such as carbon dioxide, water and of bat and bird guano (Piccini et al. 2007, Lundberg and McFarlane 2012). Yet, the direct mechanical weathering of caves by organisms is frequently neglected, rendering an equivocal irrelevance to its role as substrate shaper.

Examples of both large- and small-scale burrows completely constructed by organisms have been found in Pliocene to Holocene sites in Argentina and Brazil (Genise 1989, Dondas et al. 2009, Frank et al. 2012, 2015). However, extensive bioturbation within tropical caves is restricted to large tunnels probably produced by mid to moderate-sized extinct ground sloths during the Pleistocene–Holocene in distinct karst areas in Brazil (Carmo et al. 2011, Frank et al. 2011, Bittencourt et al. 2015, Frank et al. 2015). As a contribution to the debate and further scrutiny of the role of vertebrates to the general aspect of cave environments, we report for the first time a distinct type of mammal trace within a cave in southeastern Brazil, which was produced by small mammals using their front teeth for active erosion of the substrate. The traces, which can be related to either geophagy or tooth-sharpening behavior, have been reported in non-cave environments and limestone caves (Bednarik 1991, Martinelli et al. 2013, Panichev et al. 2017), but until now their occurrence within iron formation caves has never been registered.

STUDY AREA AND CAVE FEATURES

Cave CMN-0022 is located in the Monumento Natural da Serra da Ferrugem (Ferrugem Ridge Natural Monument), in the municipality of Conceição do Mato Dentro, in central state of Minas Gerais, southeastern Brazil. The cave developed within Precambrian banded-iron formations (itabirite) of Serra da Serpentina Group, in the western edge of Serpentina Ridge (Fig. 1). Previous studies found a major component of SiO_2 and Fe_2O_3 and a minor composition of manganese, aluminum, potassium, titanium and phosphorus oxides in the itabirites of the Serra da Serpentina Group (Pires e Souza et al. 2014). The cave CMN-0022 comprises a single chamber, which is approximately 22 m long and shows two entrances located at opposite sides along its axis. The sloped northern entrance is 5 meters high (Fig. 2). Other similar caves close to CMN-0022 show no evidence of biogenic traces.

MATERIALS AND METHODS

The traces were documented by photographs and compared to tooth scrape marks produced artificially produced by imprinting the upper and lower incisors of different mammal species on soft clay, following the methodology proposed by Bednarik (1991) and also used by Martinelli et al. (2013). We assessed thirty-three specimens (skulls and mandibles) of rodents, marsupials, lagomorphs, deer, peccary and carnivores (Fig. 3), housed at the collection of Mastozoology (MCN-M) and Paleontology (MCL) of the Museu de Ciências

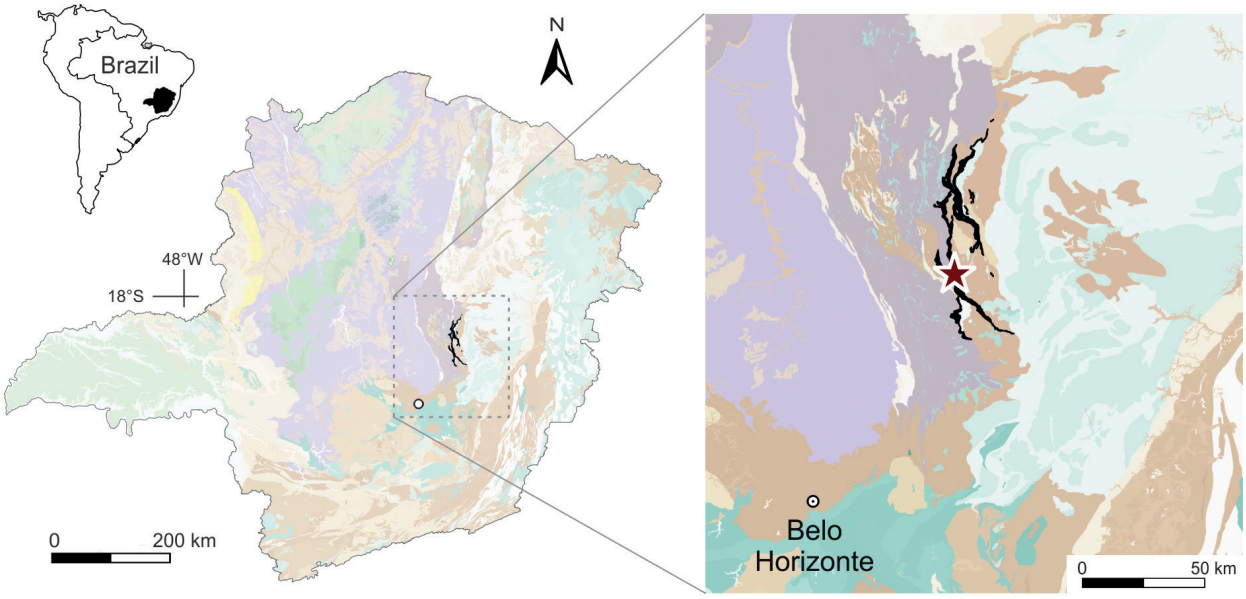

Figure 1 - Geological map of Minas Gerais showing the location of CMN-0022 cave (star). The Serra da Serpentina Group is highlighted in black. Modified from CPRM-CODEMIG (2014).

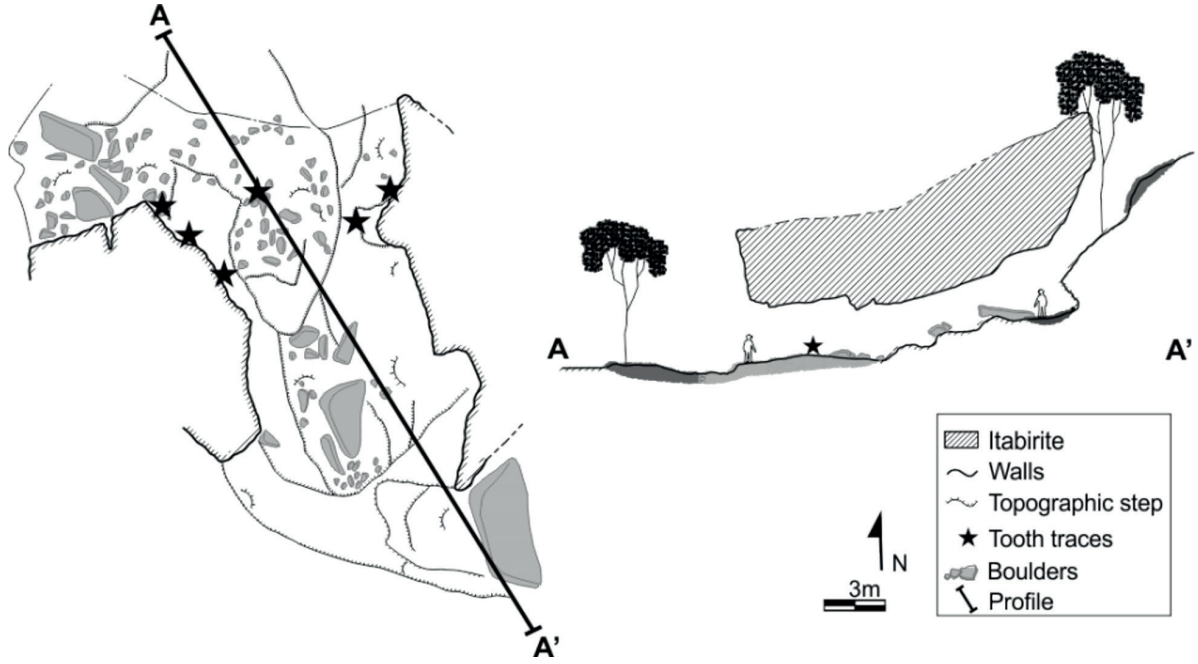

Figure 2 - CMN-0022 cave map and profile showing trace sites. Survey by Carste Ciência e Meio Ambiente.

Naturais of Pontifícia Universidade Católica de Minas Gerais and the Museu de História Natural e Jardim Botânico – Universidade Federal de Minas Gerais (MHNJB-UFMG).

In addition to clay imprinting analysis, we also compared the morphology of the tooth traces directly with dental anatomy of species previously collected in the cave area (Fig. 3). This was necessary because additional evidence of cave dwellers, such as nests, feces or carcasses (see Haglund 1992), along with clay imprinting of all potential producers were not available.

Taxa
Rodentia
Akodon sp.[2]*
Akodon cursor[2]
Akodon cf. *serrensis* (MCN-M 3404)[1]*
Calomys sp.[2]
Calomys callosus (MCN-M 1447)[1]*
Calomys tener[2]
Caluromys philander[2]
Cavia aperea[2]
Cerradomys subflavus (MCN-M 1346)[1]
Clyomys laticeps[2]
Coendou prehensilis (MCN-M 514 e MCN-M 307)[1]
Cuniculus major (MHNJB-P -2274)[1]
Cuniculus paca (MCN-M 2618)[1]
Dasyprocta azarae (MCN-M 3088)[1]
Euryoryzomys sp.[2]
Euryoryzomys russatus[2]
Euryoryzomys cf. *russatus*[2]
Euryzygomatomys spinosus[2]
Hydrochaeris hydrochaeris (MCN-M 57 and MCN-M 2786)[1,2]*
Hylaeamys sp.[2]
Hylaeamys laticep[2]
Hylaeamys megacephalus (MCN-M 1241)[1]*
Kerodon rupestris (MCN-M 3385)[1]
Myocastor coypus (MCL-7141)[1]
Necromys lasiurus (MCN-M 851)[1,2]*
Nectomys squamipes (MCN-M 598)[1]
Oecomys sp.[2]
Oecomys catherinae[2]
Oecomys gr. *concolor* (MCN-M 840)[1,2]*
Oligoryzomys sp. (MCN-M 3119) [1,2]*
Oligoryzomys nigripes[2]
Oryzomys sp. (MCN-M022)[1]
Oxymycterus sp.[2]
Oxymycterus amazonicus (MCN-M 1389)[1]*
Proechimys roberti (MCN-M 1381)[1]*
Rhagomys rufescens[2]
Rhipidomys sp.[2]
Rhipidomys mastacalis (MCN-M 2080)[1,2]*
Trinomys sp.[2]
Trinomys moojeni (MCN-M 2012)[1,2]*
Trinomys setosus[2]
Marsupialia
Caluromys philander (MCN-M 575)[1]
Cryptonanus sp.[2]
Didelphis albiventris (MCN-M 874)[1]
Didelphis aurita[2]
Gracilinanus agilis[2]
Gracilinanus microtarsus[2]
Marmosa sp.[2]
Marmosops incanus[2] (MCN-M 2123)[1,2]
Metachirus nudicaudatus (MCN-M 2918)[1]
Monodelphis sp.[2]
Monodelphis americana[2]
Monodelphis domestica (MCN-M 654)[1]
Monodelphis gr. *americana*[2]
Philander frenatus[2]
Philander opossum (MCN-M 429)[1]
Thylamys velutinus[2]
Lagomorpha
Sylvilagus brasiliensis (MCN-M 1666 and MCN-M 2900)[1,2]*
Primates
Callicebus sp.[2]
Callicebus nigrifrons[2]
Xenarthra
Dasypus novemcinctus[2]
Euphractus sexcinctus[2]
Chiroptera
Micronycteris megalotis[2]
Phyllostomus hastatus[2]
Artiodactyla
Blastocerus dichotomus (MCN-M 212)[1]
Tayassu pecari (MCN-M 124)[1]
Carnivora
Cerdocyon thous[2]
Eira barbara (MCN-M 2981)[1]
Lycalopex sp. (MCN-M)[1]
Procyon cancrivorus[2] (MCN-M 2116)[1]

Figure 3 - List of the mammals used to produce the artificial traces in clay ([1]). Mammals observed and/or collected in the region of the cave by the personnel of the Mastozoology Laboratory of PUC Minas Museum ([2]). Tracemaking species that match the observed traces in the cave are marked with an asterisk.

We also performed additional comparisons with previously published papers about mammal traces on hard substrate (Gobetz and Hattin 2002, Martinelli et al. 2013, Panichev et al. 2017), aiming at the identification of the structures described in this paper.

RESULTS AND DISCUSSION

BIOGENIC STRUCTURES WITHIN THE CAVE CMN-0022

The traces are grooves preserved in low-relief. The traces are numerous (minimally 500 sets of grooves), scattered across the northern entrance of the cave, and mainly concentrated on boulders collapsed from the ceiling and western wall. (Figs. 2, 4). The traces do not restrict to a specific substrate. They occur on both hard and friable surfaces (Fig. 5).

The grooves are randomly distributed in the center and edges of the blocks, orientated perpendicularly, sub-horizontally and horizontally to the ground level. They occur as sets with two or more grooves (Fig. 6), and are highly variable in size. Among the best-preserved traces, quantitative parameters, such as length and width, were taken for 75 traces (Table I). Based on their shape and size, the traces were separated into two morphotypes (the numbers expressed below are based on the mean values of all measurements):

Figure 4 - The black stars indicate the tooth traces in the cave CMN-0022, which are mostly concentrated on the western wall at the northern entrance.

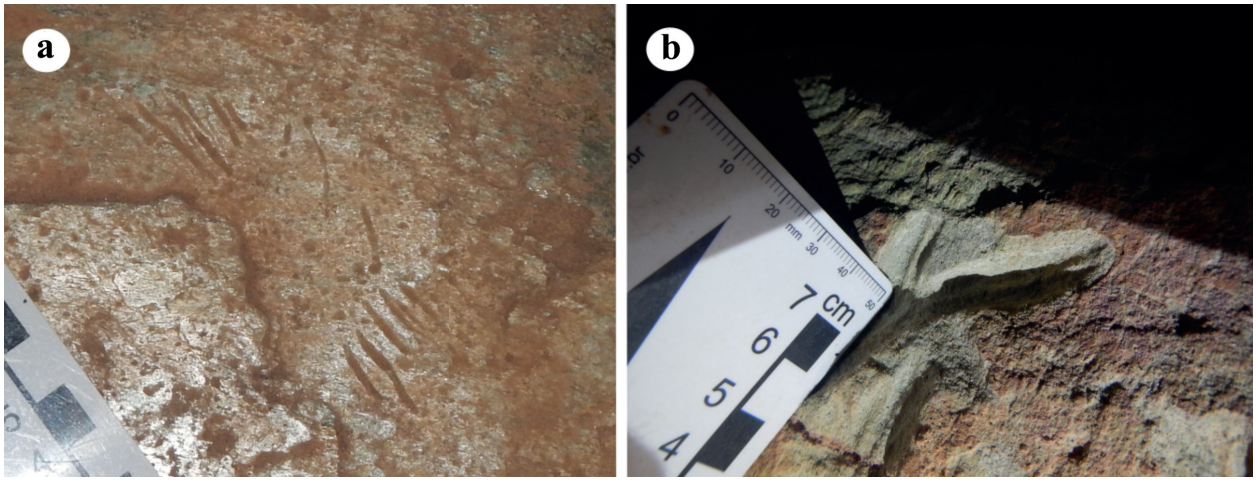

Figure 5 - Traces produced in different substrates within the cave. (**a**) hematite and (**b**) siliceous substrate.

Morphotype I: parallel double-grooved traces, heterogeneous in shape and deepest than the other types. The traces of this morphotype are 18.4 mm long, 5.9 mm wide (both grooves), and 2.85 mm deep (Table I). The trace extremities are of different shapes: rounded (Fig 6, a1), rectangular (Fig 6, a2), forked, serrated and irregular. This morphotype is interpreted as double parallel tooth traces.

Morphotype II: parallel, multiple-grooved traces, which are 19 mm long, 2.58 mm width (individual groove) and 16.6 width (all parallel grooves), and 1.1 mm deep (Table I). These traces have rounded (Fig 6, b1), rectangular (Fig 6, b2) or pointed extremities.

THE NATURE OF THE TRACES AND POTENTIAL TRACEMAKERS

The shape and size of the morphotypes indicate that these traces result from teeth erosion by distinct species of small mammals on the sediments of the sampled cave. The traces are also morphologically consistent with those reported in non-cave outcrops in the United States, Brazil and Russia (respectively Gobetz and Hattin 2002, Martinelli et al. 2013, Panichev et al. 2017) and rodent tooth traces in bones of distinct mammal species (Brain 1981, Shipman and Rose 1983, Fernandez-Jalvo and Andrews 2016). Biogenic structures produced by claw scratching have been reported for other South American caves, and were interpreted as excavations of extinct ground sloths and armadillos (Buchmann et al. 2009, Dondas et al. 2009, Bittencourt et al. 2015, Frank et al. 2011, 2012, 2015). Those traces are distinct from those observed in CMN-0022 by being larger, deeper and not double-grooved.

Tooth traces on rigid substrate are produced by distinct mammal taxa (e.g. rodent, lagomorphs and others). This behavior is generally used for nutrition (geophagy) and sharpening of the teeth with continuous growth (Brain 1981, Johnson 1985, Barlow 2000, Sabatini and Costa 2001, Borrini et al. 2012). Yet, geophagy and gnawing cannot be identified based only on tooth traces. In fact, other than rocky substrates, as reported herein and by other authors (see Gobetz and Hattin 2002, Martinelli et al. 2013, Panichev et al. 2017). Traces of these behaviors are commonly reported in biological substrates, as bones and wood (Johnson 1985, Haglund 1992, Mondini 2002, Stefen et al. 2016). Some mammals (e.g. carnivores), can also produce traces on substrates for territorial demarcation, but these have been reported for non-cave areas (Burst and Pelton 1972, Braga 2014), and cannot be demonstrated for the structures described in this paper.

Due to the diversity of similar mammal species in the cave region and the unexceptional preservation of the traces, we refrained from assigning them to a particular taxon. Instead, we assessed potential producer taxa by comparing their dental anatomy, and their artificial marking on clay, with the shape and size of the described traces. Among the 48 mammal species collected within the cave area, seven are potential producers of the morphotype I, one of which is also the possible agent of the morphotype II.

The smaller ones (morphotype I) are compatible with marks obtained by teeth of the following taxa:

TABLE I
Measurements (in mm) of tooth marks (morphotypes I and II). n = number of measured traces. Average deviation in parentheses.

Morphotype	n	Total length	Groove width	Total width
1	64	175 (60)	27 (8)	59 (14)
2	11	185 (44)	30 (7)	165 (28)

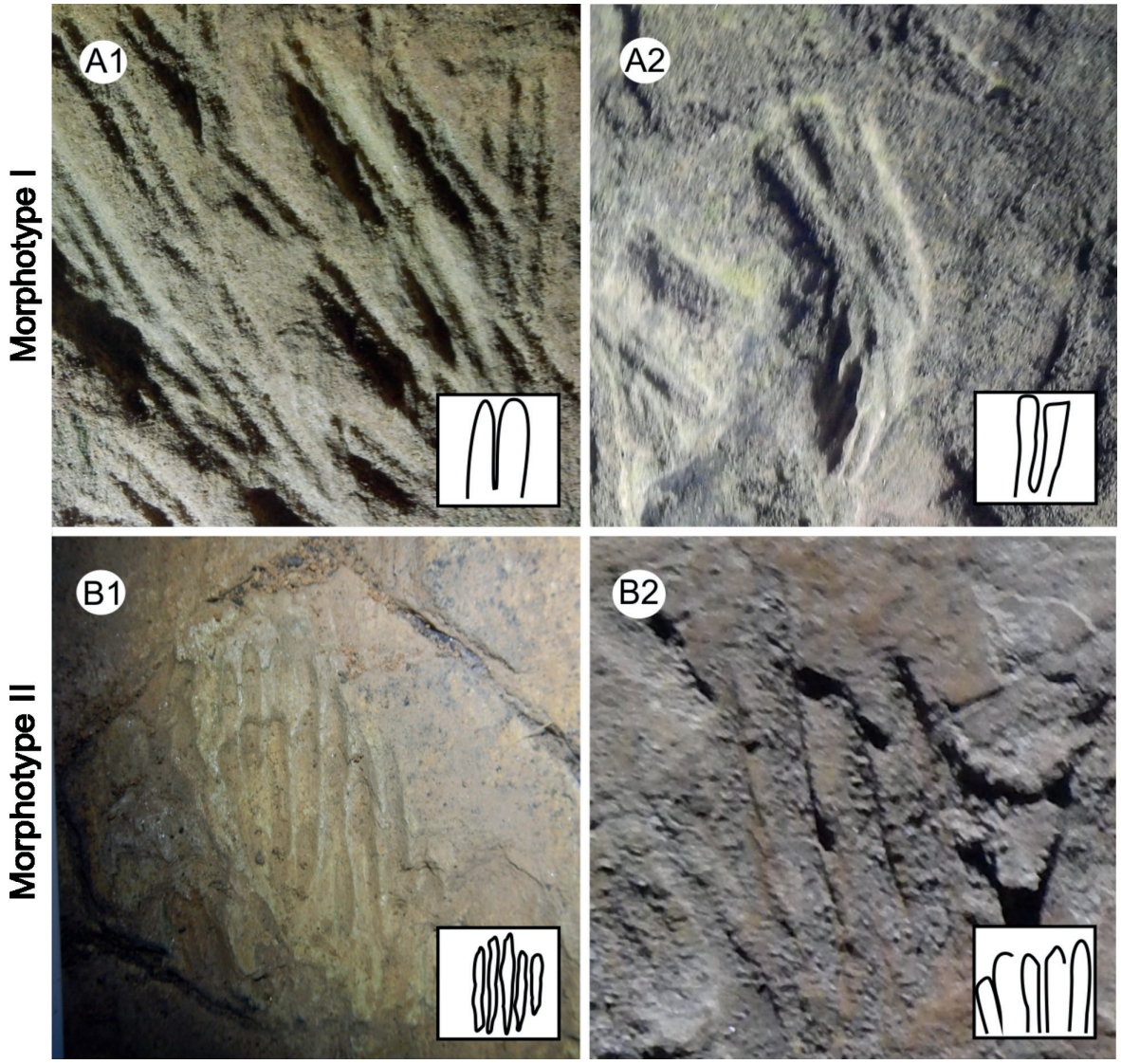

Figure 6 - Tooth traces within the cave: morphotype I (**a**) and morphotype II (**b**). See description in text. Not in scale.

Rhipidomys mastacalis (Fig. 7: 1a; MCN-M 2080), *Oecomys* gr. *concolor* (Fig. 7: 2b; MCN-M 840), *Oligoryzomys* sp. (Fig. 7: 2c; MCN-M 3119), *Necromys lasiurus* (Fig. 7: 2d; MCN-M 851), *Akodon* sp. (MCN-M 3404), *Trinomys moojeni* (MCN-M 2012), *Calomys callosus* (MCN-M 1447) and *Hylaeamys megacephalus* (MCN-M 1241). There is no record of the last two species in the area, but three related taxa, *Calomys* sp., *Hylaeamys laticeps* and an indeterminate species of the genus *Hylaeamys* have been reported in the region of the cave. The larger traces (morphotype II; Fig. 7: 3) was potentially produced by the capybara *Hydrochoerus hydrochaeris* (MCN-M 2786), for which geophagy behavior has been recorded (Mills and Milewski, 2006).

RELEVANCE TO CAVE ASSESSMENT UNDER BRAZILIAN LAW

About 18.000 caves have been officially reported in Brazil until 2018, and most of these are developed within carbonate rocks and iron formations

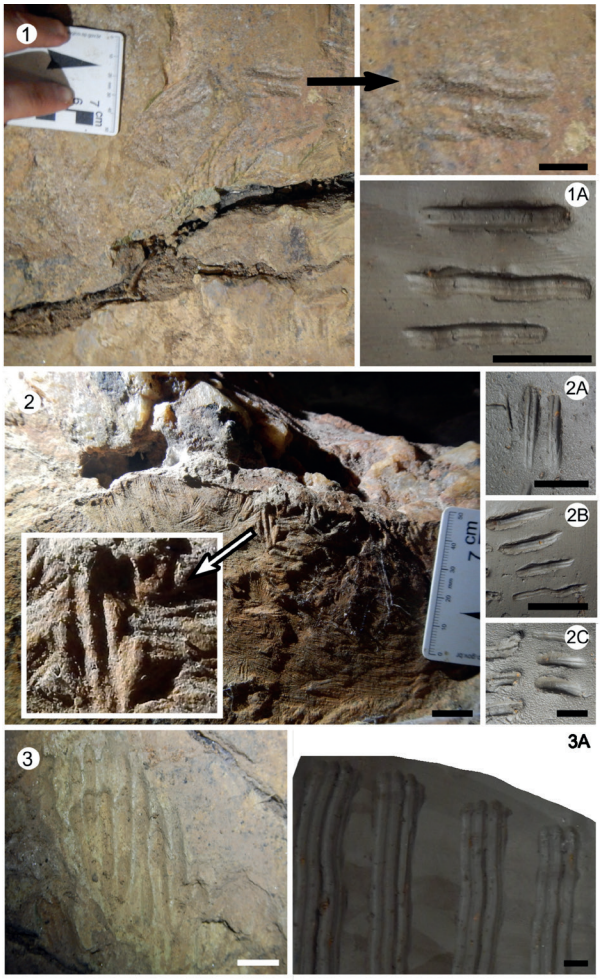

Figure 7 - Teeth traces within the cave (1, 2, 3), and clay imprint of some of their respective potential tracemakers: *Rhipidomys mastocolis* (1a; MCN-M 2080; morphotype I), *Oecomys* gr. *concolor* (2b; MCN-M 3404; morphotype I), *Olygoryzomys* sp. (2b; MCN-M 3119; morphotype I), *Necromys lasiurus* (2c; MCN-M 0851; morphotype I) and *Hydrochoerus hydrochaeris* (3A; MCN-M 2786; morphotype II). Scale bar: 10 mm.

(CECAV 2018). Less common lithologies include marble, quartzites, sandstones and granites (Auler and Farrant 1996, Auler et al. 2001, Oliveira-Galvão 2014). Tooth traces were not formally reported in any of them.

Brazil has specific legislation to deal with cave protection, especially against irreversible damages, such as mining (Brasil 2008, MMA 2017). In general terms, the legislation confers protection to caves, and their suppression is allowed in special cases in which the relevance for conservation is previously evaluated. There are four classes of relevance: Maximal, High, Medium and Low Relevance (see Auler and Piló 2015 for review). The presence of fossils within caves is a criterion for increasing relevance. Yet, the legislation only mentions fossils which were preserved within cave after its formation (e.g. Quaternary mammal bones). There is no mention of biogenic structures formed simultaneously with the cave bedrock (e.g. stromatolites, see Minas Gerais 2005, Brasil 2008, MMA 2017).

The age of the traces described herein is unknown. There is no evidence (e.g., recent carcasses, feces, nests or food remains) of present occupation of the cave by any vertebrate species, including the potential tracemakers. The age of the cave is also unknown due to the lack of datable structures. The traces were probably produced after the partial collapsing from ceiling, but this does not support dating. Some evidences as weathering of grooved surfaces within the cave and the overlapping of older traces by newer ones suggest that the grooves were produced during a long time span (Fig. 8). Yet, the fossil or subfossil nature of the traces, and therefore their relevance from a paleontological point of view, is elusive.

On the other hand, the biogenic traces preserved in the cave CMN-0022 satisfy some criteria demanded by Brazilian federal laws for cave protection (Minas Gerais 2005, Brasil 2008, MMA 2017), including scientific and/or didactic importance, educational use, and bio-geological structures of scientific interest. In this case, the traces can be used as evidence of former occupation by distinct mammal species, implying scientific importance from an ecological point of view. They could also be used for educational purposes, and to public visitation due to aesthetic and scenic appeal.

Figure 8 - Evidences of the overlapping of older traces by newer ones suggest that the grooves were produced during a long time span. Scale bar: 30 mm.

CONCLUSIONS

We describe the first occurrence of biogenic alterations made by mammal teeth within an iron formation cave in the Serpentina Ridge, at Minas Gerais state, southeastern Brazil. The tooth traces are a product of geophagy or sharpening of teeth with continuous growth. The traces were compared with tooth traces artificially imprinted in soft clay. This assessment suggested that at least seven extant taxa are potential tracemakers, all of them still living in the area: *Akodon* sp., O*ligoryzomys* sp., *Necromys lasiurus, Rhipidomys mastacalis, Oecomys* gr. *concolor*, *Trinomys moojeni* and *Hydrochoerus hydrochaeris*.

The age of the traces is unknown, thus its relevance to paleontology is elusive. Yet, regardless of their fossil nature, ichnological features should be considered as an additional value for cave protection, according to the Brazilian legislation.

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AUTHOR CONTRIBUTIONS

A.G.V.: designed the study; A.G.V., J.S.B. and A.S.A. analyzed the results; A.G.V., J.S.B. and A.S.A. wrote the manuscript. All authors reviewed the manuscript.

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