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Giant paleoburrows in the Porto Alegre metropolitan area (state of Rio Grande do Sul, Brazil).

Paleotocas gigantes na Região Metropolitana de Porto Alegre (estado do Rio Grande do Sul, Brasil).

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Abstract: Tunnels dug by semi-fossorial mammals of the South American Cenozoic megafauna are known as paleoburrows and are generally described from isolated records or very restricted regions. A particularly favorable set of conditions allowed the systematic mapping of paleoburrows over more than a decade in the Porto Alegre metropolitan area (Rio Grande do Sul state, Brazil), covering more than 10,000 km^2. Through digital prospecting, media strategies, and fieldwork, more than 400 paleoburrows were found in this region, usually in large-scale anthropogenic excavations. The structures may consist of a single one or several tunnels, reaching up to two or three dozens. Burrows can be open or filled with sediments to a variable extent. More than 80% of the tunnels are filled with sediment, thus classified as crotovines. Their widths range between 0.5 and 3.0 m and their heights are between 0.5 and 2.0 m. Tunnels with a diameter of 1.4 m, with original estimated lengths of more than 50 m, are frequent. Excavation traces on burrow walls and roofs are common, but fossils have not been found. In very flat areas like floodplains or areas with very uneven relief (mountainous), paleoburrows are rare to absent. The largest amount of tunnels was found in regions of hilly and relatively stable relief, dug in different lithotypes except unconsolidated sediments or unaltered magmatic or metamorphic rocks. It is possible that each hill may have several paleoburrows, isolated or in groups, around its base. Thus, the region can be considered the one with the highest known density of paleoburrows of this type in the world so far.
Keywords: Ichnofossils, Crotovines, Megafauna, *Megaichnus*.

Resumo: Túneis escavados por mamíferos semi-fossoriais da megafauna do Cenzoico da América do Sul são conhecidos como paleotocas e geralmente são apresentados isoladamente ou de regiões bastante restritas. Condições especialmente favoráveis permitiram o mapeamento sistemático das paleotocas da Região Metropolitana de Porto Alegre (estado do Rio Grande do Sul, Brasil) ao longo de mais de uma década, cobrindo uma área de mais de 10 mil km^2. Através de prospecção digital, estratégias de mídia e trabalho de campo foram encontrados mais de 400 túneis nesta região, geralmente em escavações antropogênicas de grande porte. Um registro com túneis pode compor-se de um túnel apenas ou por vários túneis, alcançando até duas ou três dezenas. Os túneis podem estar abertos ou então entulhados por sedimentos em maior ou menor grau. Mais de 80% dos túneis estão completamente preenchidos com sedimentos, sendo então classificados como crotovinas. Suas larguras variam entre 0,5 e 3,0 m e suas alturas entre 0,5 e 2,0 m. Frequentes são túneis com 1,4 m de diâmetro, cujo comprimentos originais foram estimados mais de 50 m. Traços de escavação nas paredes laterais e no teto são comuns, mas fósseis corporais não foram encontrados. Em áreas muito planas como planícies de inundação ou em regiões de relevo muito acidentado (montanhoso) as paleotocas são raras a ausentes. A maior quantidade de túneis foi encontrada em regiões de relevo ondulado, relativamente estável, em diversos litotipos exceto sedimentos inconsolidados ou rochas magmáticas ou metamórficas inalteradas. É possível que cada colina ali tenha várias paleotocas, isoladas ou em grupos, ao redor de sua base. Assim, a região pode ser considerada a que possui a maior densidade conhecida de paleotocas desse tipo no mundo até agora.

Palavras-chave: Icnofósseis, Crotovinas, Megafauna, *Megaichnus*.

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1. Introduction

Many organisms, both vertebrates, and invertebrates, dig tunnels as permanent or temporary shelters (Martin, 2017). These bioerosion traces have variable diameters, lengths, and configurations (e.g., Jarvis & Sale, 1971, Reichmann & Smith, 1990). When it comes to fossil organisms, such shelters are considered ichnofossils of the Dominichia ethological class and known as paleoburrows, which are of great importance because they help to document the way of life of these organisms (Bromley, 1990; Buatois & Mángano, 2011). Among terrestrial vertebrates, fossorial and semi-fossorial organisms can be recognized, considering whether they live permanently or only for a certain time in the tunnels they dug (White, 2005). Giant burrowing structures left by ancient organisms of the Cenozoic and preserved in the geological record (paleoburrows) have been found in several areas of South America. These paleoburrows are broadly divided into two ichnospecies, *Megaichnus major* and *Megaichnus minor* (Lopes *et al.*, 2017). Considering the South American megafauna, the only large- and mega-mammals capable of tunneling had been xenarthrans as giant armadillos (Cingulata) and ground sloths (Pilosa), tentatively considered the most probable builders of these ichnofossils.

Considering these paleoburrows, the southern Brazilian region, specifically the states of Santa Catarina and Rio Grande do Sul, has the highest known abundance to date, with several hundred records in each of these states. Another region with a high abundance is located near Mar del Plata (Argentina), where paleoburrows are exposed on the coastal cliffs of the Atlantic Ocean (Imbellone & Teruggi, 1988; Imbellone *et al.*, 1990; Quintana, 1992; Zárate *et al.*, 1998; Vizcaíno *et al.*, 2001).

These regions with a high number of tunnels contrast with others where, at least so far, few or no tunnels have been found. In Brazil, one of the authors (L.G. Lima) surveyed more than 15,000 km of roads in the state of Maranhão without finding any record. Other authors (F.S. Buchmann & M. Fornari) have examined road cuts along hundreds of kilometers of highways in the states of São Paulo, Rio de Janeiro, and Minas Gerais, finding only a few paleoburrows. In other South American countries than Brazil and Argentina, records are rare or absent.

The purpose of this contribution is to describe paleoburrow records found over more than a decade in the metropolitan area of Porto Alegre, the capital city of the state of Rio Grande do Sul, Brazil. Many of these burrows are no longer exposed due to the construction of buildings in the excavated areas or because they were covered by vegetation or destroyed by landslides or later excavations. Its presentation, first, documents a great effort in fieldwork and preserves the obtained results. Furthermore, it shows the high scientific potential of a region with characteristics of the study area, which can provide new scientific data for many years. The work also shows the details that are characteristic of paleoburrow research, allowing the application of the methodology used there in other regions. The study area is an example of the large number of paleoburrows that can be located in a given region and whose record may be possible if favorable conditions are given by human activities and geological and geomorphological factors.

2. Area, material, and methods

2.1 Area

The work area was chosen considering a set of factors. Geomorphology is important, as paleoburrows are not found in very flat regions (coastal plains, river floodplains) nor very rugged regions (mountainous regions with frequent landslides). Regions with a more stable, moderate relief, as a rule, are more conducive to the preservation of paleoburrows. The lithotypes of the region are another determining factor in the preservation of the tunnels, since certain stability of the material, both in its original and altered state, is necessary for the presence and preservation of vertebrate burrows. Finally, a relatively high degree of anthropic activities involving excavation of the terrain is desirable, otherwise, there are no opportunities to discover the tunnels hidden below vegetation and alteration cover. As an example, a given region with predominantly agricultural activities (grazing, agriculture) will provide fewer opportunities to record paleoburrows than another region, with the same geological and geomorphological characteristics, but with a considerable degree of urbanization. Thus, we defined the metropolitan area of the city of Porto Alegre as the study area (Fig. 1). Its geology is favorable to the preservation and detection of paleoburrows and, in addition, the university is located in the city of Porto Alegre, which made it possible to carry out several hundred days of fieldwork over more than a decade. The Porto Alegre metropolitan area covers 10,097 km^2, being the largest metropolitan area in southern Brazil, with 4.3 million inhabitants in its 34 counties (Fig. 2).

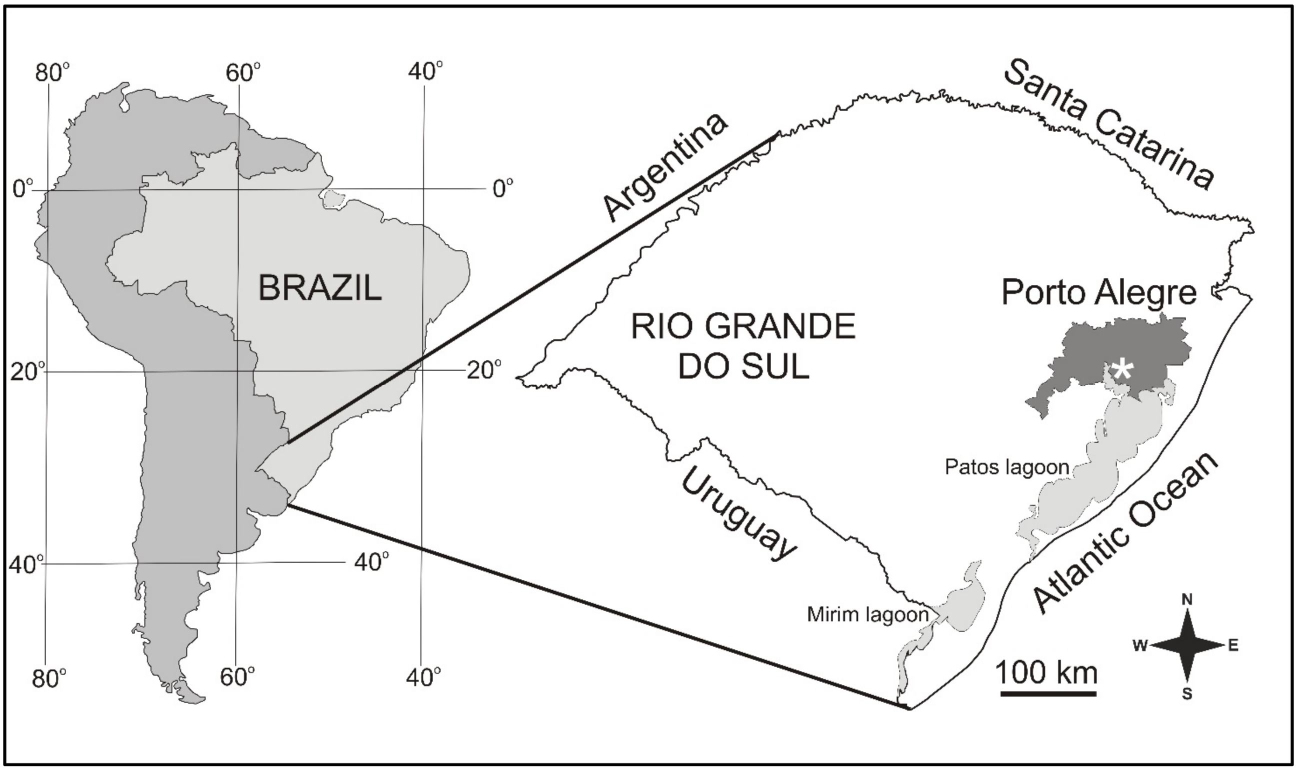

Figure 1. Location of the Porto Alegre metropolitan area.

Figura 1. Localização da Região Metropolitana de Porto Alegre.

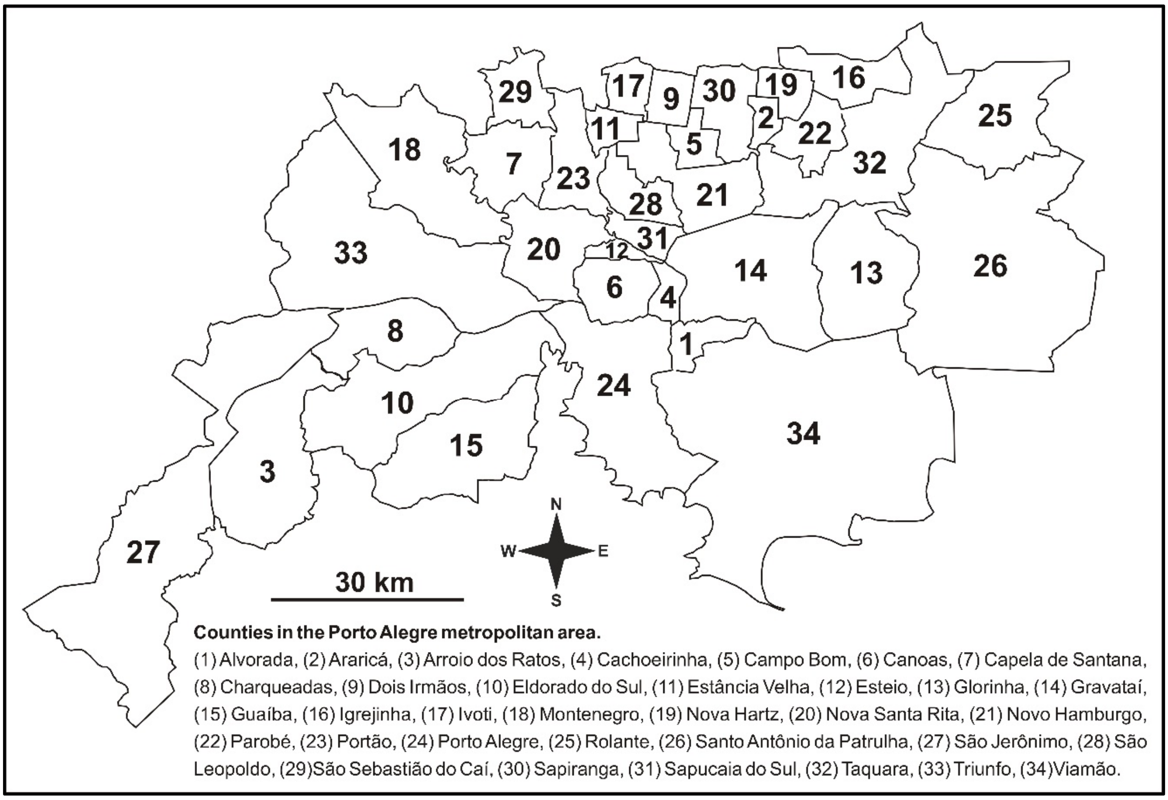

Figure 2. Counties of the Porto Alegre metropolitan area.

Figura 2. Municípios da Região Metropolitana de Porto Alegre.

The area is located on the limits between three geological units: the pre-Cambrian basement (Sul-Riograndense Shield), the Paraná Basin, and the Pelotas Basin (CPRM 2008) (Fig. 3A). The basement, in the south-southwest, hosts mainly Pre-Cambrian granitic lithotypes (syenogranites, monzogranites, granodiorites) and gneisses (Philipp & Machado, 2005). To the north and west, outcrops are related to the lower sequence of the Paraná Basin, in this place formed by three Gondwanic formations (Milani *et al.*, 2007). The Lower Permian Rio Bonito Formation hosts sandstones, siltstones, shales, diamictites, and coal. The Upper Permian Rio do Rasto Formation is composed of sandstones and lutites deposited in lacustrine, deltaic, and aeolian environments. This formation is capped by the Permian Pirambóia Formation, also consisting of aeolian sandstones intercalated with fluvial deposits. These Permian deposits are followed by the aeolian desert sandstones of the Lower Cretaceous Botucatu Formation. The northern limit of the area is marked by rocks of the upper sequence of the Paraná basin, the Early Cretaceous basaltic lava flows of the Serra Geral Group. To the east-southeast, the Pelotas basin forms the coastal plain, constituted of alluvial fans of Pleistocene-Holocene granite-related sediments, fine aeolian sands of former dune fields, and a few peat deposits (Barboza *et al.*, 2021). Large floodplains of the four major rivers (Jacuí, Caí, dos Sinos, Gravataí) are located in the middle of the area.

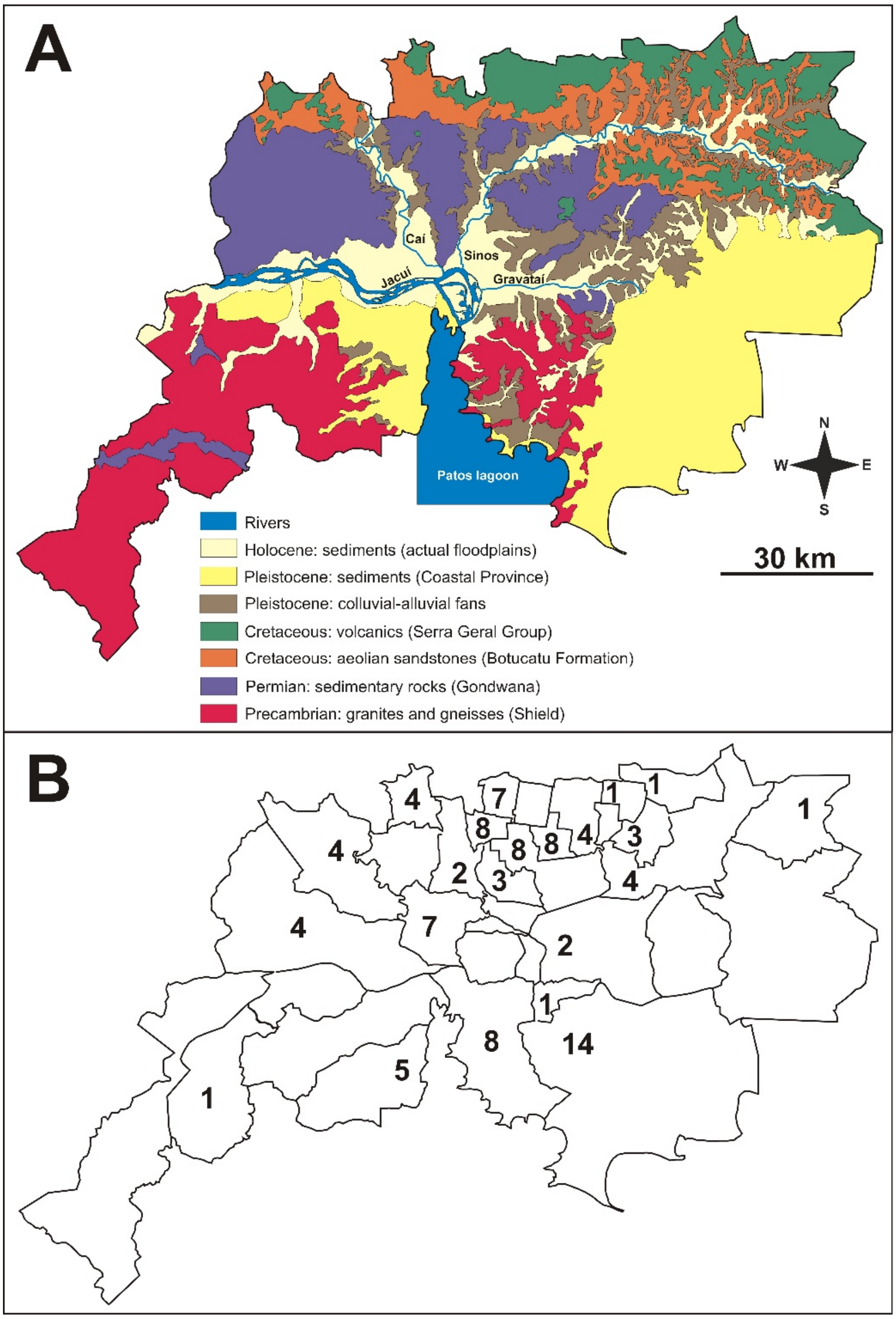

Figure 3. A) Simplified geological map of the study area (based on CPRM, 2008). B) Map of the counties shown in Figure 2 with the number of paleoburrow records (single or clustered tunnels) of each county (see Table 2).

Figura 3. A) Mapa geológico simplificado da área de estudo (baseado em CPRM, 2008). B) Mapa dos municípios com o número de ocorrências de paleotocas (túneis simples ou agrupados) em cada um (ver Tabela 2).

2.2 Materials and Methods

Vertebrate paleoburrows, with some exceptions, are found only when large-scale anthropogenic excavations remove the rubble from landslides or the regolith from the rocks of the area and expose the preserved portions of the tunnels. The purpose of the earthwork may be the construction of housing or industries, road construction or widening, stabilization of slopes, and others. To prevent the slopes created in this way from collapsing, engineering professionals quickly cover the embankments with vegetation (grass) or retaining walls. Therefore, in a matter of a few weeks to months, the possibility of recording exposed tunnels on these sites is lost. This reinforces the need to make the most of any opportunity to find paleoburrows. The opening or widening of a highway, for example, maybe the only or the best opportunity to find paleoburrows in a specific region during a lifetime.

The detection of paleoburrows was carried out through a set of strategies that can be grouped into remote detection, media strategies, and fieldwork (Table 1).

Done much before fieldwork, remote detection consisted of a set of activities searching the internet for texts, photos, and videos related to caves in the study area. In order not to waste time, it is important to identify the `grottos´ that are just small chapels, usually dedicated to Our Lady of Lourdes. Media strategies have been very important in the discovery of more tunnels. Dozens of tunnels were reported by phone or email, including several important and representative records. Some of them are impossible to find with fieldwork, like the 45-meter-long tunnel with more than 3,000 digging traces at the roof, well hidden in a densely forested steep hillside in the mountains of the county of Nova Hartz (Table 2). Several tunnels we heard of, despite many efforts to access them, could not be found.

Table 1: Strategies developed for the detection of paleoburrows.

Tabela 1: Estratégias desenvolvidas para a detecção de paleotocas.

Methods	Details
Remote Detection	
Internet search	Search for pictures and information about caves in the chosen region or county, using all synonyms for caves.
Telephone contacts	The phone book was used to identify and speak with elderly people, a very reliable source for information about caves.
Archaeological literature	Descriptions of archaeological sites in the study area made it possible to identify those that were paleoburrows.
Rabies Control Program	The database of vampire bat shelters includes many tunnels that could be identified as paleoburrows.
Media Strategies	
Newspaper releases	News about paleoburrows, published from time to time, allowed finding many tunnels.
TV programs	Interviews on TV were made sometimes.
Pamphlets	Distribution was made in markets and gas stations.
Homepage	Much information and all the published papers about burrows are available in www.ufrgs.br/paleotocas .
Email	The email paleotocas@gmail.com was created for paleoburrow communication by the public.
Bulletin	For several years, a bimonthly bulletin was edited and distributed.
Fieldwork	
Active search	Inspection of roadcuts, new allotments, large constructions, road building, and widening.
Local residents	It was very helpful to talk to local people, show pictures of burrows, to get information about caves in the region.

Fieldwork consisted of the active search for paleoburrows. In urban areas, the historic center is usually completely buried beneath buildings and without any recent excavations, zeroing the chances of locating tunnels. In peripheral regions, however, the ongoing urban expansion requires large-scale excavations that allow the detection of paleoburrows. When talking to residents, it is necessary to consider and respect the origins to which these people attribute the paleoburrows. Among these are (i) natural origins, (ii) historical characters, and (iii) mythical beings. Often people associate the tunnels with the infiltration and flow of underground waters and talk about tunnels with lengths of many hundreds of meters, crossing hills and mountains. Sometimes even ants are mentioned as tunnel makers. Among historical characters, in regions colonized by descendants of Portuguese settlers, the tunnels are regarded as hiding places for gold caches left by the Jesuit Missions of the 17th and 18th centuries. Other European immigrants, who arrived after the end of the Jesuit Missions, but still when indigenous people were in the area, call the tunnels “indigenous caves”. In addition, slaves and soldiers are sometimes suggested as tunnel builders. In some regions, the memory of specific religious leaders links the tunnels to these characters. A few mythical beings also are mentioned as tunnel builders, like the \`Curupira´ (a male supernatural from the mythology of Tupi-Guarani tribes, whose feet are turned to face backward) and the \`Minhocão´ or \`Boiúna´ (a giant black snake-like burrowing animal that lives near the river), alongside entrenched Bible-based beliefs of floods and pre-historical times.

In completely sediment-filled tunnels (crotovines), excavation is usually not possible due to a lack of team, time, and budget. In these cases, the survey is limited to recording the geographic coordinates of the point, measuring the height and the width of the tunnel, and obtaining scaled photographs. If possible, the probable orientation of the tunnel is measured. Often it is possible to measure the approximate original length of the tunnel from the exposed section to the original position of the limits of the hill. This measure always was made in a straight line, despite knowing that the tunnels usually are sinuous. Open tunnels with less than 0.7 m in diameter cannot be entered. In this case, in addition to the data mentioned above, an attempt is made to record images of the inside of the tunnel, paying special attention to the possible presence of digging traces. Larger tunnels can be traversed, providing the opportunity to measure orientation, width, and height along the tunnel as well as photograph any existing traces. Digging traces, if present, are measured, their numbers are estimated, and silicone casts are made of specific sections.

Over the years, with the learning gained through working on successive paleoburrows, several innovative techniques allowed secure data collection (Fig. 4). Foldable ladders (Fig. 4A) ease the access of tunnels higher in the slopes. Plastic tubes connected to battery-powered exhaust fans (Fig. 4B) supply oxygen to smaller tunnels. Covering the tunnel floor with plastic (Fig. 4C, D) allows work without direct contact with the substrate, preserving the team and equipment and avoiding possible problems with leptospirosis and fungi. As footprints never have been identified in the burrows, this method is acceptable. Masks were used most often, especially in tunnels with fungus on the walls. Helmets were replaced by simple caps, as the smooth walls of the tunnels do not pose a risk of head trauma. LED headlamps proved easy, cheap, and safe to use; the ones with AAA batteries are better than the rechargeable, because during fieldwork there are no options for recharging batteries. Impervious clothing, such as the raincoats worn by motorcyclists, protect against contaminated water and fungus on the tunnel floor. Laser measuring tapes are more useful, accurate, and simpler to use than regular range finders.

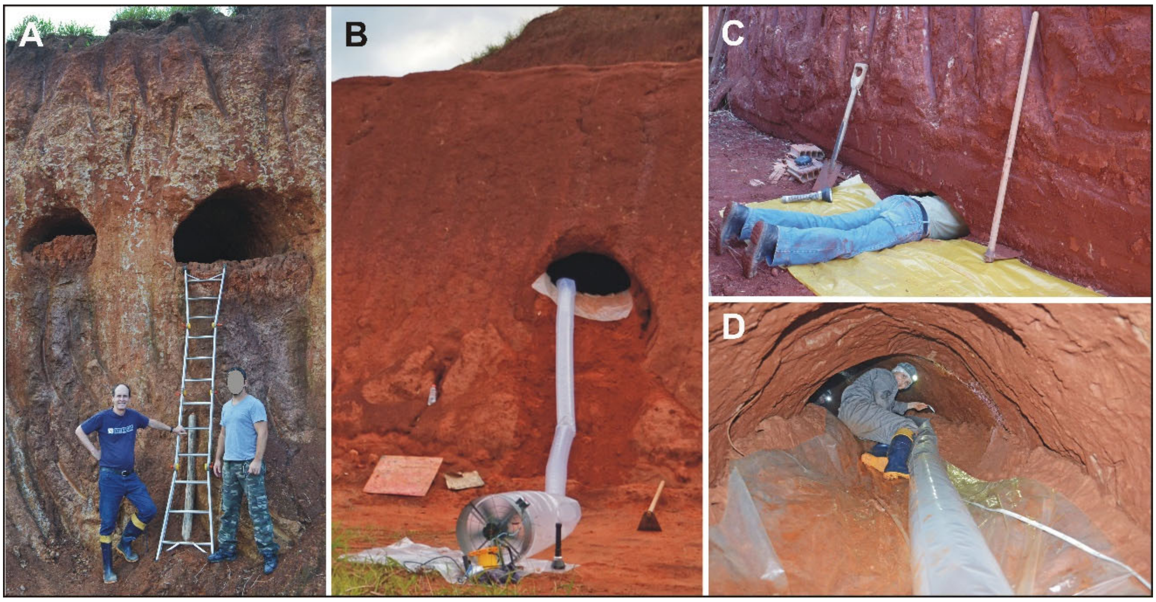

Figure 4: Equipment and aspects of paleoburrow research. Locations are referred to in Table 2. A) Foldable ladder used to access burrows in higher grounds (Estância Velha-6). B) Exhaust fan with plastic tube supplies fresh air inside the burrow (Estância Velha-5). C) Sometimes, access to the tunnels is only possible without claustrophobia (Novo Hamburgo-2). D) Covering the tunnel floor with plastic permits to work cleanly (Novo Hamburgo-2).

Figura 4: Equipamentos e aspectos da pesquisa em paleotocas. Sítios referem às ocorrências da Tabela 1. A) Escada dobrável usada para acessar túneis situados em locais altos (Estância Velha-5). B) Exaustor com tubo de plástico usado para suprir oxigênio em paleotocas (Estância Velha-6). C) Às vezes o acesso aos túneis só é possível sem claustrofobia (Novo Hamburgo-2). D) Cobrindo o piso do túnel com plástico é possível trabalhar de forma limpa (Novo Hamburgo-2).

A painful learning experience was the identification of all the health problems that may be associated with paleoburrow research. Oxygen starvation, for example, is a serious problem in tunnels of smaller sizes. Collapsing of the entrance and of the roof itself in rainy periods may imprison researchers. Drowning sometimes can be a problem. Very dry tunnels in sandstones may contain highly irritating white dust on the floor, which causes acute contact dermatitis. Poisonous animals, like spiders, may hide inside the tunnels. Fungi are very common on tunnel walls and roofs; some may affect individuals with low personal immunity. Bats produce feces whose dust contains Cryptococcosis and Histoplasmosis fungi. Hematophagous bats, besides the leptospirosis virus in their urine, may also carry the rabies virus. Due to the navigation system of the bats, the air inside the tunnels may contain aerosolized virus-contaminated saliva microdroplets, infecting humans through their mucous membranes. Decomposition of feces from large colonies of vampire bats inhabiting unventilated tunnels can generate dangerous levels of ammonia in the atmosphere of these burrows. Hazards from other animals living in or near the tunnels must be considered, like leprosy (armadillos), tetanus (domestic livestock), and lime (ticks).

3. Results

Burrows were found in altered Pre-Cambrian granitic lithotypes, sedimentary Gondwanic rocks, and in their alteration mantle, in altered Cretaceous basaltic rocks, and Pleistocene deposits of colluvial/alluvial fans. Metamorphic rocks are very rare in the area and no tunnels have been found that could be related to them. In short, any material, as long as it is not a loose sediment or an unaltered igneous or metamorphic rock, can host paleoburrows in this region.

One hundred records with paleoburrows were found in the work area, summing 422 tunnels (Table 2). A record may consist of only one paleoburrow or by up to several tens (Fig. 5), the latter situation usually applying to excavations up to 200 m long exposing a side of a hill. In some of such long outcrops, the paleoburrows were found only over the course of several years during which land set-aside was carried out in these places. One paleoburrow (Arroio dos Ratos-1) has no defined coordinates as access to the property was not allowed, but a picture of the tunnel shows a very characteristic paleoburrow, partially filled. The distribution of the records is shown in Figure 3B. In larger counties, the position of the number in the map of Figure 3B indicates the approximate location of the tunnels. All tunnels are of *Megaichnus minor* ichnospecies, except for Nova Hartz-1, which is *Megaichnus major*.

Table 2: Paleoburrow records in the Porto Alegre metropolitan area. The first column provides the name of the county where the record is located and its number inside the county. Geographic coordinates come next. A - Number of open tunnels, B - Number of crotovines (filled tunnels), C - Tunnel width (and length, L) in meters, D – Presence of still preserved (1) or already destroyed (0) tunnels.

Tabela 2: Ocorrências de paleotocas na Região Metropolitana de Porto Alegre. A primeira coluna informa o nome do município onde a ocorrência está localizada e seu número neste município. Seguem as coordenadas geográficas. A – Número de túneis abertos, B- Número de crotovinas (túneis preenchidos), C – Larguras (e comprimentos, L) em metros dos túneis, D – Presença de túneis ainda preservados (1) ou já destruídos (0).

County / Number	Latitude S	Longitude W	A	B	C	D
Alvorada 1	29º 38´ 52.53´´	50º 59´ 38.60´´	-	1	1.5	0
Arroio dos Ratos 1	---	---	1	-	~1.5	1
Campo Bom 1	29º 40´ 38.33´´	51º 04´ 44.90´´	-	2	0.5-0.6	0
Campo Bom 2	29º 40´ 10.65´´	51º 01´ 57.57´´	-	5	~0.6	0
Campo Bom 3	29º 39´ 10.10´´	51º 02´ 40.26´´	2	-	1.5	0
Campo Bom 4	29º 39´ 31.09´´	51º 04´ 23,77´´	-	1	~1.1	1
Campo Bom 5	29º 40´ 51.06´´	51º 02´ 47.65´´	1	10	0.5 – 1.1	0
Campo Bom 6	29º 40´ 35.00´´	51º 01´ 33.00´´	1	-	2,0	0
Campo Bom 7	29º 39´ 14.00´´	51º 03´ 58.00´´	-	1	1.0	0
Campo Bom 8	29º 40´ 03.55´´	51º 03´ 08.35´´	-	>40	~1,0	0
Estância Velha 1	29º 38´ 37.00´´	51º 08´ 45.20´´	-	1	0.8	0
Estância Velha 2	29º 38´ 57.00´´	51º 09´ 13.70´´	-	3	1.4	0
Estância Velha 3	29º 40´ 05.50´´	51º 02´ 27.30´´	4	>4	1.4	1
Estância Velha 4	29º 37´ 45.66´´	51º 08´ 48.65´´	1	-	2.0	0
Estância Velha 5	29º 39´ 41.64´´	51º 11´ 07.14´´	2	>20	1.4	1
Estância Velha 6	29º 39´ 33.18´´	51º 10´ 53.04´´	2	2	1.4	1
Estância Velha 7	29º 49´ 04.16´´	51º 09´ 45.67´´	-	6	~1.0	0
Estância Velha 8	29º 39´ 45.45´´	51º 10´ 36.72´´	-	2	~1.0	0
Gravataí 1	29º 56´ 42.48´´	51º 00´ 24.23´´	-	19	~1.3	0
Gravataí 2	29º 50´ 47.82´´	51º 58´ 36.22´´	1	-	~1.4	1
Guaíba 1	30º 07´ 40.88´´	51º 20´ 08.55´´	1	1	?	0
Guaíba 2	30º 08´ 17.80´´	51º 25´ 26.94´´	1	4	~1.0	0
Guaíba 3	30º 08´ 17.02´´	51º 20´ 55.70´´	1	-	1.5 (8L)	1
Guaíba 4	30º 09´ 13.80´´	51º 22´ 12.20´´	-	15	~1.0	0
Guaíba 5	30º 08´ 16.00´´	51º 21´ 14.00´´	-	~10	~1.4	0
Igrejinha 1	29º 31´ 10.13´´	51º 51´ 44.57´´	1	-	0.8 (5L)	1
Ivoti 1	29º 34´ 51.62´´	51º 09´ 51.22´´	1	3	2.0	1
Ivoti 2	29º 35´ 16.86´´	51º 09´ 14.91´´	-	4	~1.0	0
Ivoti 3	29º 35´ 24.39´´	51º 10´ 16.55´´	-	1	~1.0	0
Ivoti 4	29º 36´ 45.00´´	51º 10´ 34.00´´	1	34	up to 3.0	0
Ivoti 5	29º 36´ 54.93´´	51º 10´ 28.28´´	-	6	~1.0	0
Ivoti 6	29º 33´ 36.39´´	51º 11´ 11.00´´	1	-	1.1	1
Ivoti 7	29º 35´ 18.74´´	51º 09´ 38.91´´	-	2	1.4	0
Montenegro 1	29º 41´ 37.82´´	51º 30´ 17.34´´	-	8	2.0	0
Montenegro 2	29º 43´ 51.16´´	51º 28´ 47.12´´	-	4	1.5	0
Montenegro 3	29º 37´ 53.00´´	51º 38´ 40.00´´	1	-	1-3(25L)	1
Montenegro 4	29º 46´ 51.55´´	51º 33´ 09.27´´	-	1	1.0	0
Nova Hartz 1	29º 34´ 57.62´´	50º 56´ 54.75´´	1	-	3 (37L)	1
Nova Santa Rita 1	29º 50´ 49.40´´	51º 15´ 23.30´´	-	3	1.0	0
Nova Santa Rita 2	29º 50´ 48.53´´	51º 16´ 14.25´´	-	>8	0.5 – 1.0	0
Nova Santa Rita 3	29º 51´ 42.24´´	51º 15´ 46.77´´	-	5	1.0	0
Nova Santa Rita 4	29º 52´ 21.30´´	51º 16´ 19.40´´	-	5	~1.0	0
Nova Santa Rita 5	29º 52´ 14.30´´	51º 16´ 15.60´´	-	2	~1.0	0
Nova Santa Rita 6	29º 47´ 16.70´´	51º 17´ 17.80´´	-	1	1.5	0
Nova Santa Rita 7	29º 51´ 43.00´´	51º 15´ 27.00´´	-	>10	~1.0	0
Novo Hamburgo 1	29º 43´ 31.00´´	51º 01´ 16.00´´	1	-	1.4 (5L)	0
Novo Hamburgo 2	29º 40´ 46.53´´	51º 08´ 33.80´´	5	>10	0.7 – 1.4	0
Novo Hamburgo 3	29º 45´ 38.00´´	51º 02´ 17.50´´	1	-	1.4(16L)	1
Novo Hamburgo 4	29º 45´ 35.22´´	51º 02´ 17.67´´	1	-	1.4(4L)	1
Novo Hamburgo 5	29º 39´ 24.33´´	51º 06´ 17.86´´	-	>8	1.4	0

County / Number	Latitude S	Longitude W	A	B	C	D
Novo Hamburgo 6	29º 40´ 59.50´´	51º 10´ 27.50´´	-	2	0.5	0
Novo Hamburgo 7	29º 39´ 51.63´´	51º 06´ 50.48´´	-	1	1.4	0
Novo Hamburgo 8	29º 39´ 38.97´´	51º 07´ 39.34´´	-	3	~1.0	0
Parobé 1	29º 38´ 06.93´´	50º 52´ 06.34´´	-	10	~1.4	0
Parobé 2	29º 36´ 09.90´´	50º 49´ 13.80´´	-	2	1.0	0
Parobé 3	29º 39´ 00.93´´	50º 52´ 14.57´´	-	4	1.0	1
Portão 1	29º 40´ 52.83´´	51º 14´ 45.06´´	-	3	0.6	0
Portão 2	29º 39´ 53.95´´	51º 16´ 18.99´´	1	-	1.5 (04L)	1
Porto Alegre 1	29º 05´ 08.80´´	51º 08´ 50.10´´	2	-	1.0 (44L)	1
Porto Alegre 2	30º 04´ 12.25´´	51º 08´ 32.18´´	1	-	1.5	0
Porto Alegre 3	30º 09´ 22.40´´	51º 12´ 46.50´´	3	4	~1.4	0
Porto Alegre 4	30º 06´ 36.00´´	51º 08´ 09.00´´	2	-	1.0	0
Porto Alegre 5	30º 07´ 07.90´´	51º 14´ 32.10´´	1	-	1.4 (07L)	1
Porto Alegre 6	30º 08´ 55.35´´	51º 11´ 47.08´´	1	-	1.4 (25L)	1
Porto Alegre 7	30º 04´ 34.00´´	51º 08´ 27.00´´	1	-	1.2 (11L)	1
Porto Alegre 8	30º 04´ 23.77´´	51º 08´ 15.43´´	1	-	~0,5	1
Rolante 1	29º 36´ 08.20´´	50º 29´ 15.41´´	-	1	~2.0	1
São Leopoldo 1	29º 48´ 43.50´´	51º 05´ 27.41´´	2	-	1.5 (43L)	1
São Leopoldo 2	29º 47´ 14.50´´	51º 08´ 49.39´´	1	-	~1.0	0
São Leopoldo 3	29º 48´ 12.31´´	51º 05´ 04.24´´	1	-	~1.0?	0
São S. do Caí 1	29º 34´ 55.50´´	51º 21´ 07.90´´	-	5	~1.0	0
São S. do Caí 2	29º 33´ 48.55´´	51º 21´ 37.50´´	-	3	1.4	0
São S. do Caí 3	29º 35´ 43.14´´	51º 21´ 12.84´´	-	3	~1.2	0
São S. do Caí 4	29º 38´ 08.85´´	51º 18´ 39.51´´	1	-	1.5 (L20)	1
Sapiranga 1	29º 40´ 12.00´´	51º 00´ 33.00´´	4	~15	1.4	0
Sapiranga 2	29º 37´ 57.88´´	50º 58´ 22.39´´	1	-	1.0	1
Sapiranga 3	29º 37´ 43.10´´	50º 58´ 08.10´´	1	-	1.4 (26L)	1
Sapiranga 4	29º 38´ 35.24´´	50º 58´ 44.03´´	-	1	>2.0	0
Taquara 1	29º 37´ 21.34´´	50º 48´ 13.35´´	1	-	1.8 (10L)	1
Taquara 2	29º 39´ 55.16´´	50º 43´ 41.47´´	1	~12	2.2 (12L)	0
Taquara 3	29º 39´ 53.80´´	50º 45´ 53.63´´	-	1	0.5	0
Taquara 4	29º 37´ 14.50´´	50º 48´ 11.89´´	-	>10	1.4	1
Triunfo 1	29º 39´ 25.19´´	51º 38´ 33.61´´	1	-	0.5	1
Triunfo 2	29º 40´ 51.75´´	51º 40´ 34.00´´	-	1	~1.0	1
Triunfo 3	29º 41´ 49.24´´	51º 39´ 12.00´´	1	-	0.5 (60L)	1
Triunfo 4	29º 41´ 12.82´´	51º 39´ 09.92´´	3	-	1,2(>8L)	1
Viamão 1	30º 04´ 34.52´´	51º 00´ 40.39´´	1	-	0.5 (55L)	1
Viamão 2	30º 06´ 13.43´´	51º 02´ 33.5´´	1	-	0.5 (30L)	1
Viamão 3	30º 07´ 31.24´´	51º 03´ 35.94´´	1	-	1.0 (130L)	1
Viamão 4	30º 02´ 20.50´´	51º 01´ 13.10´´	1	-	0.5 (20L)	1
Viamão 5	30º 06´ 16.53´´	51º 03´ 20.66´´	1	-	no info.	0
Viamão 6	30º 02´ 52.00´´	51º 00´ 14.00´´	-	3	~1.0	0
Viamão 7	30º 05´ 39.10´´	51º 06´ 11.00´´	1	-	1.0 (80L)	1
Viamão 8	30º 05´ 47.70´´	51º 06´ 23.50´´	1	-	1.0 (60L)	1
Viamão 9	30º 05´ 20.70´´	51º 06´ 06.80´´	1	-	?	1
Viamão 10	30º 05´ 15.40´´	51º 06´ 04.60´´	1	-	?	1
Viamão 11	30º 05´ 36.70´´	51º 05´ 34.50´´	1	-	~1.0 (45L)	1
Viamão 12	30º 05´ 45.20´´	51º 05´ 45.60´´	1	-	? (37L)	1
Viamão 13	30º 08´ 39.03´´	51º 02´ 37.82´´	1	-	0.7 (>40L)	1
Viamão 14	30º 09´ 51.73´´	50º 59´ 43.89´´	1	-	~1.0 (>6L)	1

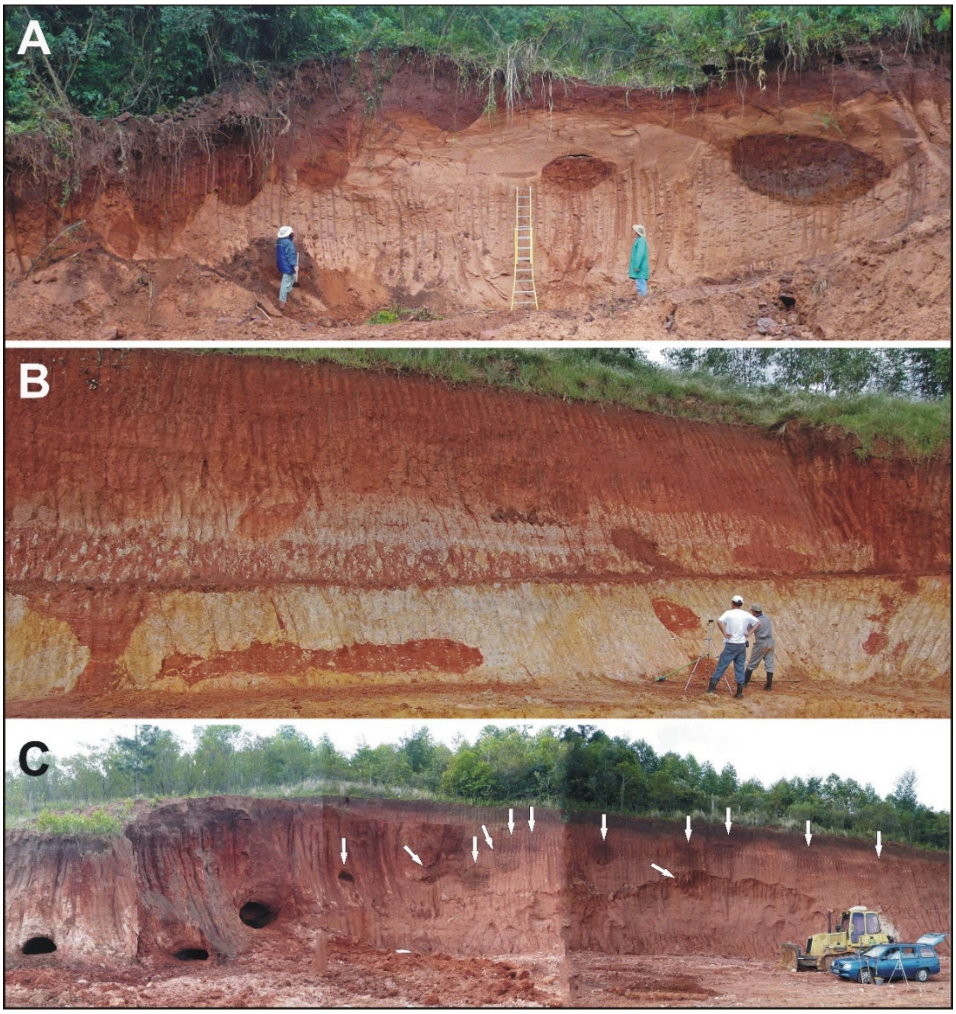

Figure 5: Partial view of three records of clustered paleoburrows. A) Ivoti-4, which showed 34 crotovines over a distance of 750 m. B) Campo Bom-8, with more than 40 crotovines over a distance of 200 m. C) Sapiranga-1, with 12 crotovines and 3 open and connected tunnels over some 100 m.

Figura 5: Vista parcial de três ocorrências com agrupamentos de paleotocas. A) Ivoti-4, que mostrou 34 crotovinas numa distância de 750 m. B) Campo Bom-8, com mais de 40 crotovinas numa distância de 200 m. C) Sapiranga-1, com 12 crotovinas e 3 túneis abertos e conectados em algo como 100 m.

The paleoburrows were classified as `open´ or `filled´ according to the degree of infilling. Of the tunnels, 76 (18%) were classified as open and 346 (82%) were filled. `Open´ refers to any tunnel that is not filled with sediments deposited by rainwater after it has been abandoned by the burrowing organism (Fig. 6). Among open tunnels, several show their original features, while many of them were filled with more than 50% with sediments. Some open tunnels exhibit sinkholes and canyons along their length, with the sediments of these collapse structures filling the remaining tunnel segments almost completely (Fig. 7). It is impossible to enter and go through them and there are no original features left on the walls, and the roofs of these paleoburrows. Such tunnels are common in the counties of Triunfo and Viamão.

Few systems of still open tunnels were found, and, in these, the diameters of the individual tunnels usually varied. In the Novo Hamburgo-2 record, for example, detailed measurements of the tunnels showed five different widths of 0.63-0.79 m, 0.75-1.20 m, 0.88-0.96 m, 1.00-1.18 m, and 1.10-1.46 m (Nogueira *et al.*, 2012).

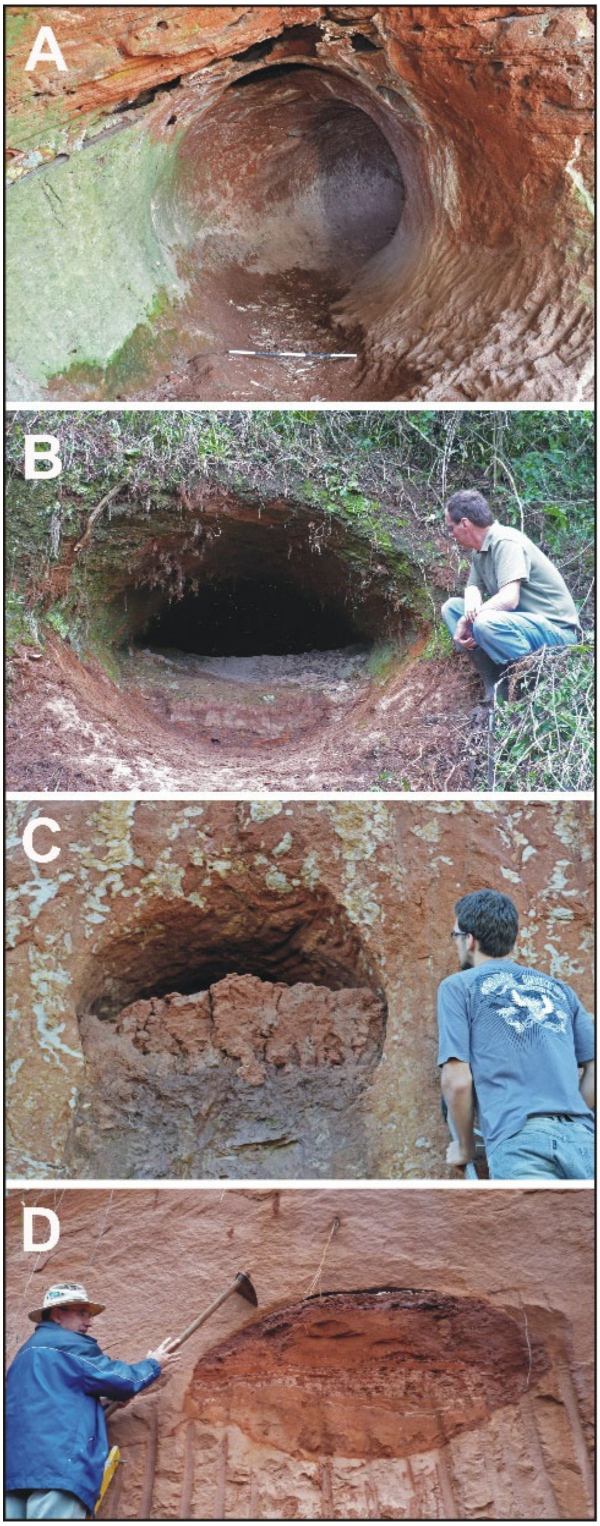

Figure 6: Paleoburrows with varying degrees of infilling. A) Completely open (Gravataí-2, scale of 0.5 m). B) Partially filled (Ivoti-1, width of 2.0 m). C) Partially filled (Estância Velha-6, width of 1.4 m). D) Almost filled (Ivoti-4, width of ~1.5m).

Figura 6: Paleotocas com graus variáveis de preenchimento. A) Completamente aberta (Gravataí-2, escala com 0.5 m). B) Parcialmente preenchida (Ivoti-1, largura de 2.0 m). C) Parcialmente preenchida (Estância Velha-6, largura de 1.4 m). D) Quase completamente preenchida (Ivoti-4, largura de ~1.5 m)

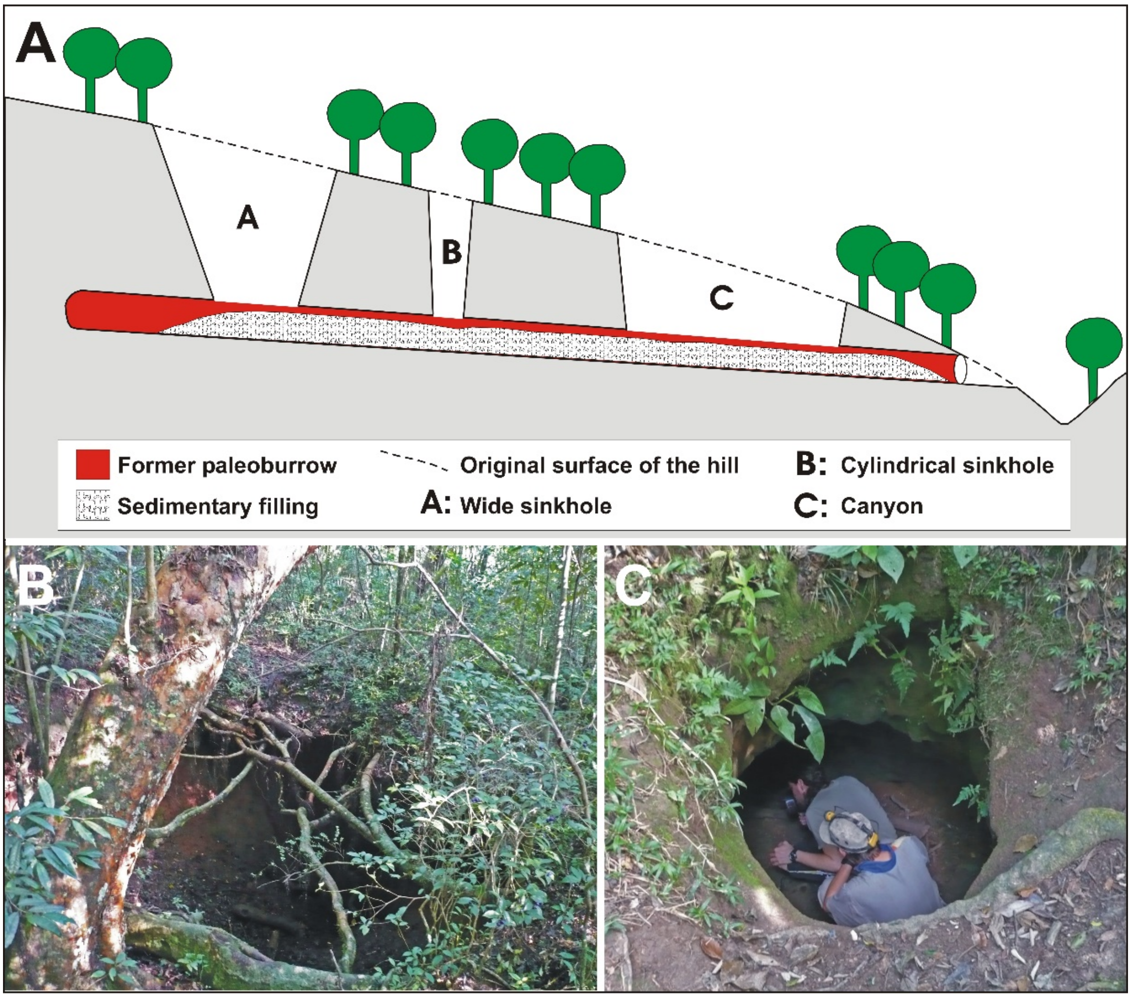

Figure 7: Paleoburrows destroyed through a succession of sinkholes. A) Schematic cross-section, not to scale, of a destroyed paleoburrow with sinkholes and a canyon. B) 8-meter wide and 3-meter-deep sinkhole in the forest. Viamão-1. C) One-meter-wide cylindrical sinkhole, one of several sinkholes of one of the tunnels in Porto Alegre-1.

Figura 7: Paleotocas profundamente destruídas através de uma sucessão de dolinas. A) Seção esquemática, sem escala, de uma paleotoca destruída com dolinas e um canyon. B) Dolina com 8 m de diâmetro e 3 m de profundidade na floresta. Viamão-1. C) Dolina cilíndrica com um metro de diâmetro, uma das várias dolinas de um dos túneis de Porto Alegre-1.

On the walls and the roof of the tunnels, digging traces are common. Features generated by water running down the walls and traces left by animals that reoccupied the tunnel may occur. Rock art left by pre-colonial peoples was not found in the study area but occurs in some big-sized paleoburrows (*Megaichnus major*) in other regions (Frank *et al.*, 2012a). Vandalism produced by visitors is common in paleoburrows whose size allows visitation, as Sapiranga-3. Digging traces are so well preserved in lithotypes of indurated clay, as in Novo Hamburgo-2, that they seem to have been made recently. In the Lower Cretaceous aeolian sandstones of the Botucatu Formation, like Gravataí-2, the degree of preservation is also high, but the traces are not as clear as in clayey sediments. Altered volcanic (basaltic) and plutonic (granitic) rocks do not favor preservation and tunnels excavated on these rocks are almost devoid of such traces. In tunnels with diameters of ~1.4 m, the digging traces are triple (Fig. 8A, B), but in the Nova Hartz-1 paleoburrow, the traces are double (Fig. 8C, D). Frank *et al.* (2012b) presents a detailed description of the different kinds of traces that may occur in paleoburrows.

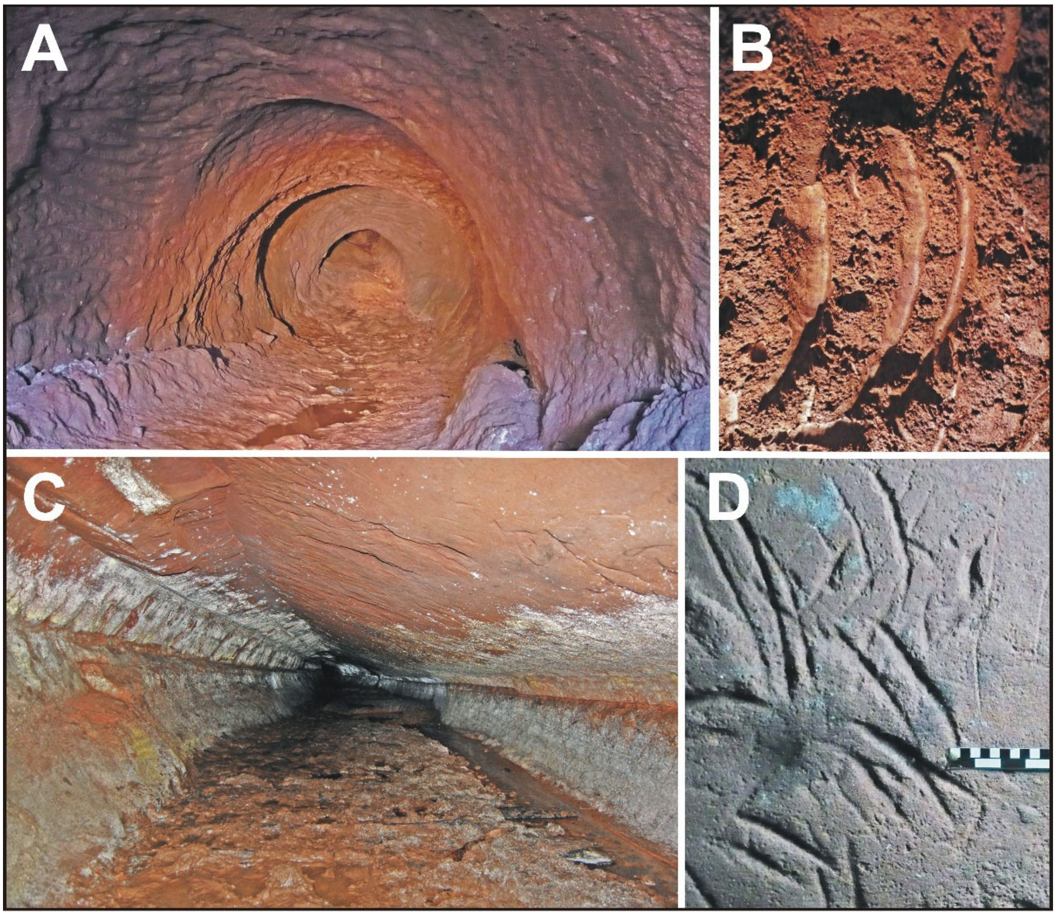

Figure 8: Digging traces found in some tunnels. A) 1.4 m wide paleoburrow from the record Novo Hamburgo-2, with its walls covered with traces. B) Triple digging trace at the roof of one of the tunnels of Novo Hamburgo-2. Length: 0.25 m. C) Nova Hartz-1 is a 3 m wide and 1.8 m high tunnel. D) Double digging traces on the roof of Nova Hartz-1. Scale in cm and inches.

Figura 8: Traços de escavação encontradas em alguns túneis. A) Paleotoca com 1,4 m de largura da ocorrência Novo Hamburgo-2, com suas paredes cobertas por traços. B) Traços de escavação de três dedos no teto de um dos túneis da Novo Hamburgo-2. Comprimento: 0.25 m. C) Nova Hartz-1 é um túnel com 3 m de largura e com 1,8 m de altura. D) Traços de escavação de dois dedos no teto de Nova Hartz-1. Escala em cm e em polegadas.

Digging traces always occur in open tunnels, but their degree of preservation varies with the host rock of the tunnel. They are so well preserved in lithotypes of indurated clay, as in Novo Hamburgo-2, that they seem to have been made recently. The degree of preservation is also high in the aeolian sandstones of the Botucatu Formation (Upper Triassic – Lower Jurassic), like Gravataí-2, but the traces are not as clear as in clayey sediments. Altered volcanic (basaltic) and plutonic (granitic) rocks do not favor trace fossil preservation and tunnels excavated on these rocks are almost devoid of traces. The most common traces are digging traces, which are of two types in the study area. In tunnels with diameters of ~1.4 m, the digging traces are triple (Fig. 8A, B), but in the Nova Hartz-1 paleoburrow, the traces are double (Fig. 8C, D). Smoothed roofs due to the continuous brushing of the animals´ backs also are common. Frank *et al.* (2012b) presents a detailed description of the different kinds of traces that may occur in paleoburrows.

Completely filled tunnels (crotovines) are, in most cases, easy to identify, as the infilling has distinct colors and textures than the host rock (Fig. 9). However, when the infilling is composed of the same sediment that hosts the tunnel, combined with a certain degree of alteration or degradation of the outcrop, the recognition can be very difficult (Fig. 9A, Fig. 5C). Depending on the lithotype, after an intense alteration it may be difficult or impossible to define whether a given circular or elliptical feature is a filled paleoburrow or some sedimentary or alteration structure. The outline of the crotovine may be circular, elliptical, or elongated and corresponds to the angle at which the tunnel was intersected by the excavation. If the cut was perpendicular to the tunnel, the shape is circular, being increasingly elliptical in cuts made oblique to the tunnel axis (Fig. 9B). In several situations, the tunnels were sectioned parallel to their length, either horizontally (Fig. 9C) or in almost vertical section (Fig. 9D), showing up as elongated crotovines.

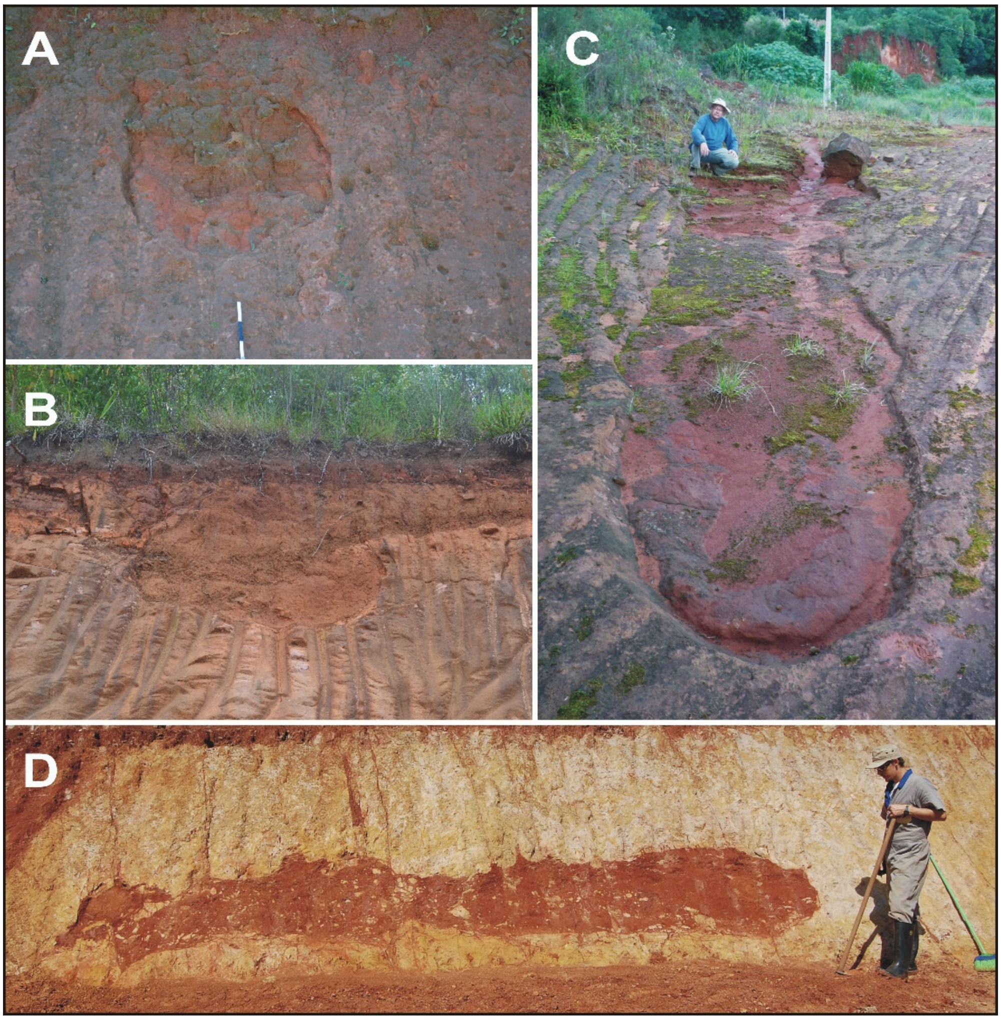

Figure 9: Completely sediment-filled paleoburrows (crotovines). A) Crotovine with circular cross-section, found in Nova Santa Rita-3 (scale bar = 0.3 m). B) Crotovine with elliptical section, from São Sebastião do Caí-3. Width ~1.2 m in diameter. C) Horizontally exposed crotovine from Ivoti-4. D) Longitudinally exposed crotovine, from Campo Bom-8.

Figura 9: Paleotocas completamente preenchidas com sedimentos (crotovinas), A) Crotovina de seção circular, da ocorrência Nova Santa Rita-3 (escala = 0,3 m). B) Crotovina de seção elíptica, de São Sebastião do Caí-3. Largura aproximada de 1,2 m. C) Crotovina exposta horizontalmente, de Ivoti-4. D) Crotovina exposta longitudinalmente, de Campo Bom-8.

The description of the sedimentary fill was not carried out in detail, since it contributes little to the understanding of paleoburrows. Most of the time, it is a uniform filling with discrete horizontal bedding. When the infilling of a tunnel was not uniform, some attention was devoted to describing its details, which usually consist of several horizontal layers of sediments of different colors and compositions. Sometimes stones are found in the infilling, isolated, or even forming stone lines. In several crotovines, levels of dark chocolate brown clay were observed, composed of smectite clay minerals, most likely decanted after episodes of flooding of the tunnel during rainy periods. Several times operators of excavation equipment (backhoe loaders) reported that, during earth or rock removal, they suddenly had their work areas flooded when they removed the clayey sediment plug from a tunnel and the water accumulated inside the unobstructed part of the tunnel segment spilled out. In open tunnels, the brown clay forms layers with mud cracks on the floor. Once exposed to the sun, the clay crumbles resembling a weathered shale.

The measurement of crotovines of circular or elliptical shapes refers always to the width of the feature, with the height usually being smaller. The crotovines are mostly elliptical; there are only a few exactly circular-shaped. In the case of clustered paleoburrows, we indicate the maximum and minimum diameters of the tunnels (Table 2). Quite frequent (~40%) are paleoburrows with original diameters between 1.0 and 1.4 m. Considering the remaining portion of the tunnels and the distance to the original surface of the hill, these structures could have reached lengths of more than 50 m.

Most (77.5%) of the tunnels recorded over these years (56% of the records) are no longer available, usually because constructions were built on top or in front of them or because the slopes collapsed or became vegetated. Some paleoburrows, however, have been exposed for decades and will probably remain so, as there is no interest on the part of the owners to destroy them. Novo Hamburgo-4, for example, is composed of an open tunnel from which drains a considerable and constant water volume. This water was used for decades to supply a tannery and today is used to supply the swimming pools of a leisure park. Nearby, the site Novo Hamburgo-3 also drains rainwater. At its entrance was built, decades ago, a water tank with a submerged pump that supplied with water to the school next to the property. The paleoburrow Nova Hartz-1 has been visited for decades by neighbors, despite being partially flooded; the current owner denies access. Guaíba-3, located on the pulp mill property, received protection from the company. Some tunnels, like Triunfo-3, are deeply eroded, forming a succession of tunnel segments, dolines, and ravines that will remain this way, slowly being destroyed by water and vegetation. Other paleoburrows, such as Porto Alegre-1, have been known for decades, being regularly visited by people. The site Porto Alegre-6 is in a protected area and most likely will not be destroyed.

4. Discussion

Research of Domichnia-type ichnofossils produced by burrowing species of the Cenozoic megafauna is, as a rule, presented as descriptions of a single or few structures in a restricted area. In Argentina, such papers are of Quintana (1992), Zárate *et al.* (1998), Vizcaíno *et al.* (2001), Dondas *et al.* (2009), Cenizo *et al.* (2016) and Cardonatto & Melchior (2018). In Brazil, research of such approach is from Padberg-Drenkpol (1933), Berqvist & Maciel (1994), Buchmann *et al.* (2009, 2016), Carmo *et al.* (2011), Frank *et al.* (2012a, 2013, 2015, 2022), Ruchkys *et al.* (2014), Lopes *et al.* (2017), Faria *et al.* (2019), Vidal *et al.* (2019), Budke *et al.* (2020) and Schipanski *et al.* (2022). From other South American countries, the paper of Hostnig (2019) describes a cave in Peru where digging traces attributed to ground sloths of the megafauna are covered by pre-Hispanic paintings. These records characterize the sites but do not convey an idea of the amount of this type of structure in a given region.

Some papers discuss tunnels found in defined areas, such as Zárate *et al.* (1998), which presented 42 burrows in an area of roughly 500 km^2 centered in the city of Mar del Plata (Argentina), with four of the five studied sites located along the Atlantic Ocean coastal cliffs. Vizcaíno *et al.* (2001) indicate another region in Argentina, near the city of La Plata, 340 km north of Mar del Plata, as another site with large burrows, but without presenting numbers and area. In Paraguay, Souberlich *et al.* (2017) describe three paleoburrows in an area of 5.5 km^2 located southwest of the city of San José de los Arroyos. In Brazil, Santos *et al.* (2021) present 19 open and filled tunnels in an area of 1,571 km^2 in the border region between the states of Santa Catarina and Paraná. Also in Brazil, Bechtel *et al.* (2022) list 19 big-sized paleoburrows (*Megaichnus major*) found in the southeast of the state of Santa Catarina, in an area of 2,830 km^2. The survey presented in this paper, covering an area of more than 10,000 km^2 with more than 400 tunnels, is therefore unprecedented and was only possible due to a particularly favorable set of factors, with a team, time, budget, availability for fieldwork, and a region full of paleoburrows near our working place, the Federal University of Rio Grande do Sul.

The number of paleoburrows found was, as expected, very low to zero in the counties located mainly in river floodplains, such as Alvorada, Canoas, Cachoeirinha, Charqueadas, Eldorado do Sul, Esteio and Sapucaia do Sul. However, the closest elevations at the edges of the floodplains, generally composed of Holocene alluvial-colluvial deposits, already host tunnels (e.g., Nova Santa Rita-3). It was also difficult to locate burrows in regions with very smooth relief, as in the counties of Capela de Santana and Nova Santa Rita. Counties with very rugged relief, on the other hand, such as Nova Hartz and Igrejinha, also showed few paleoburrows. These counties, hosting the border of the highlands of the volcanic rocks (basalts and rhyolites) of the Serra Geral Group, sometimes suffer from massive landslides after intense rain. This phenomenon affects all the counties located on the northern limit of the study area; the last such event occurred in the 1980s. A single period of intense rainfall every century could mean tens of massive landslide events since the extinction of the megafauna, a condition that implies the destruction of almost all the existing burrows in these regions. The most favorable relief for the occurrence and preservation of paleoburrows is an undulating, relatively stable relief.

The large number of paleoburrows found in counties with such a favorable relief is surprising. During the systematic search on the outskirts of the cities, currently, under urban expansion, it was common to end a day of fieldwork with several new burrows found. Talking to old residents, we received reports of \`holes´ that no longer exist and that may have been paleoburrows, according to the descriptions. As a rule, almost any excavation of a bigger size will expose paleoburrows in such areas. On two occasions, we were called by the Federal Prosecution Service, concerned with the preservation of these features, which could be considered paleontological sites according to existing laws. We explained that the preservation of all the tunnels would prevent any large-scale excavations, including the installation of huge industrial buildings, the opening of allotments, the building, and the widening of highways, as there is always a high probability of the presence of tunnels. Once this reality was exposed, the prosecutors filed their requests for information.

Very extensive cuts on hillsides expose, as a rule, a greater number of paleoburrows, up to several tens. Among examples of this type are the records Campo Bom-8, Ivoti-4, Novo Hamburgo-2, and Sapiranga-1. This suggests that especially favorable sites have been used for millennia for the excavation of burrows by successive generations of various types of burrowing organisms, perhaps one type predominating over the other at each site. Conditions that make a site favorable are likely a stable substrate that forms the hill and the slope angle. Similar records with several burrows also were found outside the study area. The excavations related to the widening of road BR-116 between the cities of Guaíba and Tapes, south of the study area, were monitored along a 75 km profile between 2013 and 2022. In the 48 roadcuts thus created, almost 200 tunnels were exposed, most of them forming clusters on specific slopes (Marin *et al.*, 2016).

The geometry of the tunnels makes it possible to assess the probable original characteristics of these ichnofossils. Tunnels found open, even only in short segments of 5 or 10 m, always turn out to be sinuous to variable degrees; they curve horizontally or go up or down inside the hills. In Novo Hamburgo-2, for example, one of the tunnels rises 4 m in a distance of only 10 m. In the Porto Alegre-6 site, a similar situation presents. The (excavated) entrance, 2 m long, forms a \`T´ intersection with a 25-meter-long tunnel that turns 90 degrees north and then descends for almost 5 m, being filled at its end. The evaluation of the layout of a system of branched tunnels is ideally carried out from long and open tunnels, which are rarely found in the state of Rio Grande do Sul. In the neighboring state of Santa Catarina such tunnel systems are common (e.g., Frank *et al.*, 2022). In the county of Morro Grande (28º41´20.17´´S, 49º47´19.15´´W), a system of wide, open, and connected tunnels presents more than eight entrances over four floors but was not described yet due to the difficulty to map it. Therefore, the presence of several tunnels remaining – open or filled - next to each other may be related to an original tunnel system with tunnels that branched both horizontally and vertically. Situations of this type in the study area are Estância Velha-3, Ivoti-4, and Novo Hamburgo-2.

The type of substrate in which the tunnels were excavated is unimportant, as long as it is not unconsolidated sediment or unaltered igneous or metamorphic rock. In the study area, similar amounts of tunnels were found in the aeolian sandstones of the Lower Cretaceous Botucatu Formation (e.g., Ivoti-4), in the Permian sandy sedimentary rocks of the Rio do Rasto Formation (e.g., Campo Bom-8) and in altered Pre-Cambrian granitic rocks, the latter predominating in the counties of Porto Alegre and Viamão. The type of substrate has a direct relationship with the degree of preservation of excavation traces on the walls and ceiling of the tunnels: the Permian sedimentary rocks preserve best, the Cretaceous sandstones preserve much less and altered granitic and basaltic rocks preserve almost nothing.

No fossil remains such as bones, hair, excrement, or others were found so far inside the paleoburrows. The rainwater that infiltrates the hills ends up flowing out of the burrows, reducing the possibility of preserving organic remains. Dry tunnels are very rare. The occurrence of such remains, on the other hand, would not necessarily characterize the burrowing organism, since reoccupation of burrows by other animals is common, both for extinct species (e.g., Cenizo *et al.*, 2016) and for living species (e.g., Gopher Tortoise Management Plan, 2012). Smaller tunnels are in general attributed to giant armadillos, whereas much larger tunnels are attributed to giant ground sloths. Thus, tunnels with diameters between 0.5 and 0.8 m are certainly from armadillos, as modern examples show that these animals do not dig tunnels much wider and taller than the width of their bodies (e.g., Hickman, 1990). The largest current armadillo in South America, *Priodontes maximus*, which weighs up to 55 kg, digs tunnels that are only 0.43 m wide and 0.36 m high, on average (Eduardo Fernandez-Duque, pers. comm., 2010). For comparison, the largest extinct armadillo, *Pampatherium typum*, had a body width of around 0.8 m (Fariña, 1996, Vizcaino *et al.*, 2001). Large tunnels, measuring 2 m in diameter or more, may have been excavated by sloths. For tunnels with intermediate widths, there is still no consensus, being attributed to either giant armadillos or smaller sloth species. In the 1.3-meter-wide tunnels, the existence of digging traces along the tunnel ceiling suggests the excavation by sloths, more mobile than armadillos. Diameter variations of tunnels in the same system may be related, for example, to differences in sizes between burrowing animals, to adults and juveniles both excavating tunnels, to burrowers excavating tunnels larger than their body width, and other factors.

The ages of the tunnels were not possible to determine yet, as there was nothing inside them that can be dated. The lower age limit is the approximate time of the megafauna extinction, between 8,000 and 12,000 years ago. The tunnels are probably of different ages, from a few tens of thousands of years to hundreds of thousands of years. Novo Hamburgo-2 shows a situation that suggests the presence of several generations of tunnels. There, an open tunnel was excavated in contact with a filled tunnel dug earlier and then abandoned and filled with sediments (Fig. 10A). This hypothesis of many generations of tunnels applies to regions with stable reliefs and with very low erosion rates. Such erosion is often shown by crotovines whose upper portion was already destroyed by the slow downward advance of the alteration mantle (Fig. 10B).

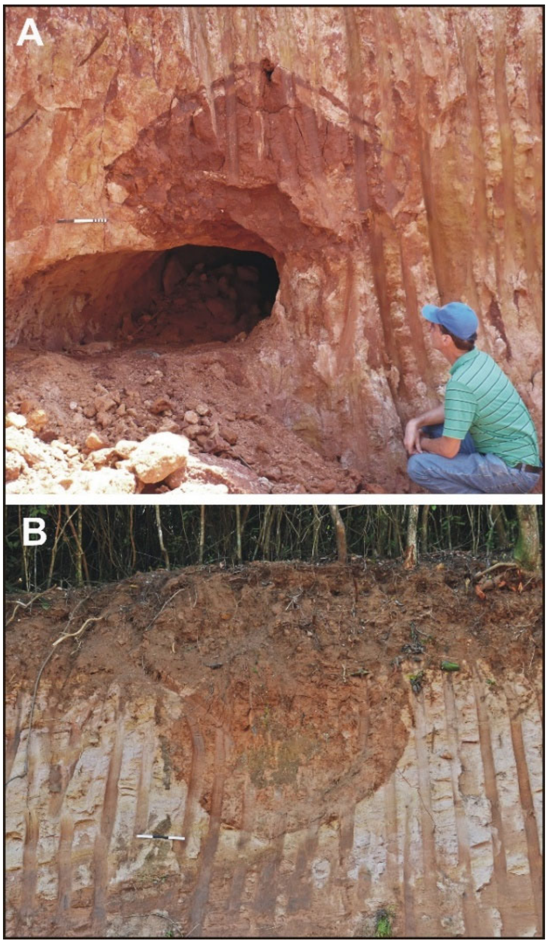

Figure 10: A) An open tunnel excavated in contact with a filled tunnel. The scale of 0.3 m. (Novo Hamburgo-2). B) Filled tunnel with its top destroyed due to the slow downward advance of the alteration mantle. The scale of 0.3 m. (São Sebastião do Caí-2).

Figura 10: A) Um túnel aberto escavado em contato com um túnel preenchido. Escala de 0.3 m. (Novo Hamburgo-2). B) Túnel preenchido que teve seu topo destruído em função do lento avanço para baixo do manto de alteração. Escala de 0.3 m. (São Sebastião do Caí-2).

The distribution of paleoburrows in the study area strongly suggests that any hill may have one or more of these structures, isolated or clustered, near the drainages that surround it, mainly around its base. Already in the 1980s, the archaeologist Pedro Ignácio Schmitz S.J., whose research of archaeological sites included the \`indigenous underground galleries´ (as they were known at the time), stated to the newspaper \`Zero Hora´ that \`there are many of them here. They are common in the counties of Porto Alegre and Viamão, on the edge of the hills´ (Zero Hora, 1980). The higher and further to the center of the hill, the lower the chance of finding paleoburrows, an empirical observation that was confirmed in several large excavations not only in the study area but also in other regions.

Future research on paleoburrows in the study area is unlikely to provide results that differ from those obtained so far. In the surveyed region, we have probably located all the historic paleoburrows, which are open and have been visited by the laypeople or have been used for some purposes (e.g., water supply) for many decades such as those of Igrejinha-1, Sapiranga-3, Sapiranga-4, Novo Hamburgo-3, Novo Hamburgo-4, and Porto Alegre-1. New paleoburrows will certainly be found in this region as other large-scale excavations are carried out. The record of additional burrows that may be found in these excavations requires constant attention before the excavated outcrops are obstructed or destroyed. Regular fieldwork would be necessary, at intervals of two or three months, in order not to lose any records. However, these new findings will only increase the number of tunnels recorded for the region, confirming the high density of tunnels in the area, almost all being *Megaichnus minor*.

5. Conclusions

A systematic survey over more than a decade in a >10,000 km^2 area in the Porto Alegre metropolitan area, revealed one hundred sites with paleoburrows, totaling 422 tunnels. The most likely producers of the burrows are Xenarthra of the South American megafauna, either giant armadillos or ground sloths. The tunnels occur almost exclusively in undulating and relatively stable relief, neither too flat nor too rugged. More than 80% of the tunnels are found in the form of crotovines. More or less 40% of the tunnels show diameters of around one meter, with a special frequency of tunnels with 1.3 m. The largest tunnel was almost 3 m wide, 2 m high, and 40 m long. Estimated original lengths, obtained when the situation allows it, are always of several tens of meters, with the possibility of reaching 50 m or more. Tunnels are always sinuous, both horizontally and vertically. Fossils have not been found, but excavation traces are frequent, with 3-toed and 2-toed claw traces. The distribution of the tunnels suggests that sites especially favorable in relation to the substrate and slope of the terrain were used by many generations of excavating animals. Comparing this region with records of paleoburrows in other locations, both in Brazil and abroad, we found no parallel in the number of tunnels. Thus, it is possible that the Porto Alegre metropolitan area is, at least for the time being, the region with the largest number of this kind of paleoburrows in the world.

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