ABSTRACT

This work updates the present knowledge about the tunnels excavated by Cenozoic vertebrates in the four southernmost states of Brazil and discusses whether the producers of the different kinds of tunnels can be identified and how. At a regional scale, tunnels are common in the states of Rio Grande do Sul and Santa Catarina, but rare in the states of Paraná and São Paulo. A few isolated occurrences are known from some other states, but data is still too scarce to allow any conclusion. Only ~30% of these tunnels are not entirely clogged with sediments and can be entered for investigation. The diameters of the tunnels range in three intervals of ~0.8, ~1.3 and > 2.0 m and lengths of individual tunnels may reach up to 100 m. Often, several clogged and/or open tunnels show up on the same location, suggesting that the tunnels form systems. The interconnected tunnels and chambers of such systems sum tunnel lengths of several hundred meters. On the walls of ~20% of the tunnels, three different groups of structures can be found: (i) inorganic marks such as grooves produced by running water and anthropogenic traces such as Indian rock art, post-colonial tool marks and vandalism (scratches); (ii) scratches from the paleovertebrates that dug the tunnel; and (iii) traces from re-occupying animals, extinct or not. Some tunnels host several thousand traces, especially digging scratches. Biogenic action produced by plant roots and inorganic processes, represented by running water inside the tunnels, produces a characteristic set of clogging and destruction features. The roof of the tunnel often collapses and the broken material is washed inside the tunnels. On the surface, this process results in a series of aligned craters and holes while the tunnel is clogged with sediments. The producers, considering the South American Megafauna during the Cenozoic, possibly were giant armadillos and ground sloths. The present wetness of the tunnels suggests that they were excavated during a drier climate than today, mainly for shelter. Ongoing investigations aim to clarify the questions that remain such as ventilation of the tunnel systems and the origin and interpretation of the surface structures on the walls.

Key words: ichnofossils, paleovertebrates, burrows, tunnels, South America, megafauna.

INTRODUCTION

Large-diameter ichnofossils in the form of tunnels excavated by Cenozoic fossorial vertebrates are, so far and to our knowledge, restricted to South America. Only a few places in other continents host structures of the same kind, but those are much older and much smaller, with maximum lengths and diameters of 6.0 and 0.5 m, respectively (e.g., Groenewald, 1991; Miller et al., 2001; Popa & Kedzior, 2006; Varrichio et al., 2007; Martin, 2009; Sidor et al., 2009; Modesto & Botha-Brink, 2010; Riesc et al., 2011; Talanda et al., 2011). The South American tunnels (“paleocuevas” in Spanish and “paleotocas” in Portuguese) are...
sometimes called “paleoburrows”, but this term is best known as applied to *Domichnia*-type ichnofossils of invertebrates (worms, mollusks and crustaceans) (e.g., Bromley, 1990, Buatois & Mángano, 2011). The preferred term for the much larger South American paleovertebrate structures is “tunnels”.

Despite the probable occurrence of paleovertebrate tunnels (from now on referred as “tunnels” in this text) in the entire South American continent, descriptions of such structures are available only from Argentina and Brazil. In Argentina, many dozens of big-sized (Ø of up to 2.0 m) tunnels, 97% of them completely filled with sediments (“crotovines” or “krotovinas”), can be found in the region between the cities of Mar del Plata and Miramar. Most of them have appeared at the cliffs along the Atlantic coast and some have been found during underground construction works (Imbellone & Teruggi, 1988; Imbellone et al., 1990). The origin of these tunnels has been attributed to giant armadillos (Quintana, 1992) and ground sloths (e.g., Zárate et al., 1998; Vizcaíno et al., 2001).

In Brazil, the first written record of tunnels was presented by Padberg-Drenkpol (1933), who speculated about the origin of tunnels. Later, teams of archaeologists found and described several dozens of tunnels during archaeological prospectings (e.g., Chmyz & Sauner, 1971; Rohr, 1971, 1984). Recent paleontological research of these structures started with Berqvist & Maciel (1994) and later with the team of the Paleotocas Project (Buchmann et al., 2003, 2005, 2008a,b; Buchmann, 2008; Frank et al., 2008a, b, 2009; Lopes et al., 2009; Frank et al., 2010a-h; Frank & Buchmann, 2009; Ogando et al., 2010; Stevaux et al., 2010; Landell et al., 2010; Lima et al., 2010). These papers have added a huge volume of new information on the subject, raising several questions and many research possibilities. This contribution presents an overview of the tunnel research done until now in Brazil, detailing the characteristics of the tunnels and outlining the challenges of this research in the future, especially concerning more precision about the producers of these structures.

**MATERIAL AND METHODS**

The discovery of tunnels relies on systematic regional fieldwork, inspecting every huge anthropogenic cut in the terrain, which allows recognizing the open and sediment-filled tunnels that sometimes show up when the cuts surpass the thick weathering profile and expose the less altered rocks (and tunnel remnants) in the inner portions of the hills. Nevertheless, many tunnels are hidden in such a way that they can only be found after putting considerable effort in getting a hint from somebody familiar with the area, then finding and contacting a person who knows the place and, finally, using a huge logistical support structure to inspect the tunnels. People are contacted through a media program that raises public awareness related to these tunnels (Frank et al., 2010a). Methods of the media program include regular releases to newspapers, reports in TV programs and pamphlets that are distributed in public places. Additionally, a homepage (www.ufrgs.br/paleotocas), several videos (on www.youtube.com) and an e-mail (paleotocas@gmail.com) were made available to the public. The latest news is reported in a bimonthly bulletin, which is accessible as a PDF file on the homepage and printed for people without internet access. More than half of the tunnels in our database, including some of the most interesting, were found through the media program.

After finding the tunnels, their location is registered (geographic coordinates) and the tunnels are measured (width, height, orientation, and inclination). The local geological and geomorphological aspects are annotated and pictures are taken to register the structure as a whole as well as special details. Digging scratches are measured, their numbers are estimated, and silicone casts are made of specific sections. Sediment-filled tunnels are only measured (width and height) and photographed.

The preservation of the traces of the tunnel walls and roofs is one of the biggest challenges of tunnel research. For a detailed study, casts have to be made. These casts must be made not on horizontal surfaces, like in the case of footprint casts, but on vertical and usually negative surfaces. Several materials have been tried out until now such as plaster and several kinds of silicone. The casting material must have an adequate fluidity, be chemically harmless and has to work on humid surfaces. The ongoing, geologic or anthropogenic, destruction of the tunnels turns this into a pressing issue.

Dating the tunnels is almost impossible because common geochronological methods are useless in such a situation. In crotovines and in some tunnels without erosional features, it may be possible to recover, using special techniques (e.g., Freeman, 2010), microfossils from sediments inside the tunnels to apply palynological methods for some time constraints. As a whole, however, attempts with such methods have never been made and they still must be tested as a valid geochronological method for tunnels.

**GEOLOGY OF THE STUDY AREA**

The research on the vertebrate tunnels found in the south of Brazil started in Rio Grande do Sul State (RS) and was extended to Santa Catarina (SC), Paraná (PR), São Paulo (SP) and Minas Gerais (MG)
states (Figure 1). Tunnels have been found excavated in unconsolidated substrates, sedimentary rocks and weathered igneous and metamorphic rocks of any geological age. Loose sediments of floodplains, coastal plains and alluvial fans host tunnels less often.

Most of the tunnels were found in two geological domains: the Paraná Basin and the Basement. The Paraná Basin is an intracratonic basin with an area of more than $1.10^6 \text{ km}^2$ that extends from Uruguay to the center of Brazil (Zalán et al., 1990). In this basin, many tunnels were excavated in the Upper Jurassic – Lower Cretaceous coarse, reddish, continental aeolian sandstones of the Botucatu Formation and in the weathering mantle of the volcanic basaltic and rhyolitic rocks of the Lower Cretaceous Serra Geral Formation (Paraná-Etendeka Continental Flood Basalt Province) (Peate, 1997). The Basement covers the center of RS and a narrow strip along coast of the Atlantic Ocean, to the north. There, in-situ weathered, coarse-grained, Precambrian plutonic rocks such as granites, and similar metamorphic rocks like gneiss, provided to the paleovertebrates substrates suitable for digging.

CHARACTERISTICS OF THE TUNNELS

A large dataset of tunnels discovered until June 2011 with around 200 open tunnels and 300 sediment-filled tunnels, in almost 150 different spots in the five southern Brazilian states, supports the characteristics described herein. Tunnels with a high degree of preservation always repeat a well-defined morphology that is characteristic and diagnostic for all of them, even if sometimes a set of destruction features (described next) masks this shape. This work updates the present knowledge about the tunnels, and discusses whether the producers of the different kinds of tunnels can be identified and how it can be done. The tunnels cited and illustrated are listed in Table 1.

**General shape**

The final shape of the tunnels is composed of a sequence of queued ellipsoidal sections whose longer axes are horizontally aligned (like a row of lying eggs). The length of these sections start at around 0.5 m, they are, most often, a little bit longer than 1 m, but they can reach 2.5 m. Each section has a slightly concave roof and equally slight concave lateral walls. Vertical “arches” separate neighboring sections. This shape is very evident and most commonly found in the roof of smaller-sized tunnels and may be called the “successive-excavation-steps shape” (Figure 2). In larger tunnels (width > 2.0 m), this shape is less developed but easily recognized.

**Tunnel size**

**Diameter**

The diameter measurements consider only original diameters, evidenced by roofs and lateral walls with claw scratches (digging traces). Extremely well preserved empty tunnels are the exception. Tunnels are very often much higher than they were originally, because running underground waters erode its floors and rock slabs fall from the roof, subsequently disintegrating and washing away. These processes may double the width of the tunnels and the height may reach up to 4.0 m. On the other hand, tunnels filled with sediments constitute more than 60% of the occurrences. Only partly filled tunnels show a flat bottom and a lower height than width. Measurements of the diameters of completely filled tunnels are used with caution because it is not usually possible to see if the man-made cut that exposes the filled tunnel is exactly perpendicular to the tunnel axis. On the cuts, the filled tunnels often show nearly perfect circular sections (Figure 3D).

Original diameters of the tunnels are grouped in three size categories (Figure 3). The smallest tunnels have widths that range from 60 to 90 cm (Figure 3A). Usually, their height is somewhat smaller around 50 or 70 cm. Diameters of the most common tunnels range from 1.2 to 1.5 m (Figure 3B). The largest tunnels present widths of more than 2.0 m, and up to 4.1 m (Figure 3C). Their sections are not circular, but elliptical. The height of these tunnels may reach 2.0 m. Height and width usually decreases toward the end of the tunnel by at least 30%.
Length

It seems that the proximal sections of most of the tunnels are usually filled with sediments and remain hidden. These tunnels are only found after large man-made excavations remove the front part of the tunnel-bearing hills. For this reason, many lengths refer to tunnel remnants. Tunnel remnants with lengths between 3 and 20 m are very common. Longer tunnels may reach lengths of 30 to 40 m, especially if they were excavated in lithified rocks like sandstones. These tunnels are usually very well preserved, with a low degree of infilling and/or collapsing.

In Porto Alegre and Viamão cities (RS), 18 tunnels have been found measuring more than 50 m and up to 100 m (Stevaux et al., 2010). The tunnels are excavated in situ weathered plutonic rocks such as granites and gneiss and have been heavily impacted by the forest that grew up above them, with a lot of clogging and collapsing features. Their size always falls within the range of smaller tunnels. Similar features occur in the weathered material (eluvium and colluvium) that covers volcanic rocks (Serra Geral Formation) in the North of the same state. The measuring of these tunnels is more difficult due to their small sizes, associated destruction features and the water that usually flows inside them.

Tunnel orientation

The orientation of the tunnels is related to their size: tunnels with diameters of more than 2.0 m are

Table 1. Location of the paleovertebrate tunnels cited and portrayed in this text. Abbreviations: RS, Rio Grande do Sul State; SC, Santa Catarina State; MG, Minas Gerais State.

<table>
<thead>
<tr>
<th>Code</th>
<th>Municipality and State</th>
<th>Property</th>
<th>Latitude S</th>
<th>Longitude W</th>
</tr>
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<tr>
<td>Site-01</td>
<td>Novo Hamburgo (RS)</td>
<td>João</td>
<td>29º 40’ 45.79”</td>
<td>51º 08’ 34.16”</td>
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<tr>
<td>Site-02</td>
<td>Urubici (SC)</td>
<td>João Lima</td>
<td>28º 03’ 23.68”</td>
<td>49º 28’ 40.60”</td>
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<tr>
<td>Site-03</td>
<td>Boqueirão do Leão (RS)</td>
<td>Laudir Ogliari</td>
<td>29º 19’ 23.81”</td>
<td>52º 26’ 17.53”</td>
</tr>
<tr>
<td>Site-04</td>
<td>Sapiranga (RS)</td>
<td>CETRISA</td>
<td>29º 40’ 11.59”</td>
<td>51º 00’ 32.58”</td>
</tr>
<tr>
<td>Site-05</td>
<td>Campo Bom (RS)</td>
<td>Loteamento Fauth</td>
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<td>51º 03’ 08.13”</td>
</tr>
<tr>
<td>Site-06</td>
<td>Estância Velha (RS)</td>
<td>Manoel</td>
<td>29º 40’ 05.50”</td>
<td>51º 09’ 26.90”</td>
</tr>
<tr>
<td>Site-07</td>
<td>Urubici (SC)</td>
<td>Raimundo Wiggers</td>
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<td>49º 32’08.40”</td>
</tr>
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<td>Donizetti Willermann</td>
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<td>49º 28’ 30.60”</td>
</tr>
<tr>
<td>Site-09</td>
<td>Rio Acima (MG)</td>
<td>Caverna P-38</td>
<td>20º 01’ 52.00”</td>
<td>43º 40’ 48.00”</td>
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<tr>
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<td>Loidemar</td>
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<td>50º 56’ 54.75”</td>
</tr>
<tr>
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<td>São José do Hortêncio (RS)</td>
<td>Paulo Führ</td>
<td>29º 29’ 30.55”</td>
<td>51º 12’ 28.91”</td>
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<td>Site-12</td>
<td>Lindolfo Collor (RS)</td>
<td>Josué Amorim</td>
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<td>Fazenda</td>
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<td>Fazenda Refúgio</td>
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</table>
mostly horizontal, whereas tunnels with smaller diameters may rise or descend several meters along a tunnel section of a few dozens of meters. Such vertical changes may reach values of 3 m along a tunnel section of 30 m, for example. Measuring of these changes in elevation is usually impossible in filled tunnels, in short tunnels remnants and in tunnels of smaller sizes with erosional and clogging features, most often with running water inside.

However, some filled tunnels have been monitored during the anthropogenic excavations that exposed them and it was possible to verify, but not to measure, that the filled tunnels are usually oriented upwards inside the hills. The same conclusion was reached for the tunnels excavated in regoliths of plutonic and metamorphic rocks, despite the normal clogging and erosional features of these tunnels. Usually, they start at a lower point on the hillside, always
near a water source like a creek or river. Following the erosional features that align on the surface alongside the tunnels (craters, dolines, vertical cylindrical shafts, etc), a line up the hill can be traced, up to a final crater near the top of the hill that allows the entrance to the end of the tunnel.

In some cases, sets of interconnected tunnels form systems (see clustering and tunnel networks next) that are mostly open and well preserved.

**Clustering and tunnel networks**

In contrast with many isolated tunnels that are spotted in undisturbed terrains, anthropogenic cuts that remove huge volumes of sediments or altered rocks may expose hillsides with clusters of tunnels, either open or filled with sediments. At Site-05, for example, a 110 m long and 10 m high cut exposed 30 filled tunnels. At Site-06, a 30-m long cut exposed two open tunnels and two crotovines. At Site-04, a 40 m-long cut exposed three open tunnels and 10 filled tunnels (Figure 4, on the top) (all site details in Table 1). At this last site, three 1-m wide tunnels converged to a circular chamber with an arched roof and a flat floor. At floor level, its diameter was of 1.7 m and its height reached 0.6 m in the middle of the chamber (Frank & Buchmann, 2009). Such occurrences show that the tunnels studied herein form complex three-dimensional networks, also including chambers, with several openings to the surface and with total lengths that may reach more than 100 m.

Remains of such tunnel systems are better preserved in sites of SC than in those of RS. Site-07 (Table 1) was studied by Rohr (1971) as SC-Urubici-10. The tunnel is located at the top of a small hill besides a creek. The open section of the tunnel is 18 m long, 1.4 to 2.1 m wide and ~0.8 m high. The extremes of this section of the tunnel are clogged with sediments; both clogged tunnels descend the hillsides. From the accessible section of the tunnel, two other clogged tunnels branch out to the east and two other clogged tunnels branch out to the west, suggesting that the entire hill, whose diameter is of ~50 m, is crossed by tunnels in all directions. Site-08 (SC-Urubici-12 of Rohr, 1971) shows a highly complex outline (Figure 4, at the bottom) and again several clogged tunnels branch out from the accessible section of the tunnel system in several directions. In MG, a tunnel system (Site-09, whose investigation is not finished yet) has shown a total tunnel length of 340 m.

**Regional density**

At first, tunnels were known only from a few scattered points in the southern states of Brazil. Systematic fieldwork in the metropolitan region
of Porto Alegre (RS) has shown that these tunnels may have a high regional density. In this region, locations with one or more tunnels sometimes are at distances of only 500 m from each other (Frank et al., 2009). Despite the many factors that destroy and hide the tunnels in these mostly urban areas, a regional tunnel system density of at least one system each 15.5 km² was calculated. The actual density is much higher, at least one system each 5 km². In some cases, it seems that each hill hosts one or more locations with tunnels.

Considering the south and southeast of Brazil, it seems that the density is high in RS and SC (Figure 1). In contrast, PR and SP, in spite of thousands of kilometers of road survey, intensive digital prospecting in the internet and the media program, have turned up less than a dozen spots with tunnels. Research in MG is only at the beginning and not conclusive so far.

As a rule, relief and the outcropping rocks are the main factors that dictate the regional density of tunnels. Plain regions and the ones with outcropping unweathered crystalline rocks are devoid of tunnels. Hills and mountains with very steep hillsides, on the other hand, have suffered several landslide events through geological time and the tunnels, if present, have probably been destroyed.

If the local geomorphology is composed of smooth hills, the usually very thick (>10 m) weathering mantle hides the tunnels, which are usually clogged with sediments. These hidden tunnels only appear if large anthropogenic excavations remove a
portion of the hill. In different towns and cities, such excavations are common around the old urban core, in the ring-like area where present urban expansion encroaches on former rural areas.

The highest tunnel densities, considering the database constructed until now, occur at two altitude intervals: 0-100 m and 700-1,000 m. These regions show relatively high hills formed of sediments and rocks that allow excavations (alluvial fans, sedimentary rocks, weathered plutonic and volcanic rocks, etc). An outstanding example is Urubici (SC), with more than, so far, 35 locations with tunnels of different sizes identified and, with some of them, placed close together (e.g., 4 locations in 1,300 m). This situation is due to a rare local combination of factors, such as a favorable geological constitution for digging (sedimentary rocks) and an appropriated relief (high hills).

Internal surface morphology

From the whole set of paleovertebrate tunnels found so far, four groups can be distinguished based on their internal surface morphologies on the walls – i.e., features that may be classified according to their origin and that may provide hints about the identity of the tunnel producer. From the whole set of tunnels, 60-70% are completely filled with sediments (Frank et al., 2008) (Figures 3D-E). Only a few show some distinct features on small exposed parts of their walls. From 10 to 15% show variable degrees of filling but show no distinct features such as the tunnels with collapsed roofs and/or walls. The same applies to those excavated in situ weathered plutonic (e.g., granites) and volcanic (e.g., basalts, rhyolites) rocks and in the regolith (eluvium, colluvium and alluvium) derived of such lithotypes. 10 to 15% of the tunnels exhibit only grosser features such as large digging traces along its walls. Faint traces, like dragging imprints, are usually not found. This group includes tunnels hosted in laterites (in MG) and in sandstones – usually the coarse sands of the Botucatu Formation. Only a small percentage of tunnels, around 5-10% of the whole set, show a high diversity of imprints. Such tunnels are usually the ones excavated in fine-grained sediments like weathered clayey material or clayey sand – and siltstones. Even faint marks like drag marks are preserved; sometimes of exceptional quality.

Inside the tunnels of these last two groups, the lateral walls and the roofs are usually covered with hundreds to several thousands of marks and traces. In contrast, the floors of the tunnels only very rarely show some kind of trace since the bottom of the tunnels is easily eroded or covered with sediments. Some of the tunnels in sandstones show completely smooth lateral walls and roofs, with digging traces only near the base of the walls and at the end of the tunnel. A short overview will be given about the traces and the marks, tentatively classifying them accordingly to their origin in four groups.

Inorganic and anthropogenic features

Underground waters entering the tunnels are the rule in the present, wet climate of Southern Brazil. Very distinctive features in several tunnels excavated in sandstones are vertical grooves on the tilted out tunnel sides (Figures 5A-B). These grooves are 2-3 mm wide and up to 1 m long, developing one next to the other, sometimes even covering the entire side of the tunnel. Like small channels, they were carved by water that slowly oozes out from the walls through the porous and permeable sandstone and flows down the tunnel sides, carrying sand grains down to the floor of the tunnel.

If the tunnel entrance is clogged, the entire tunnel may flood with water. The standing water, often very muddy, covers the walls of the tunnels with a layer of clay until it seeps out. The layer covers and masks all kinds of features on the walls. If the tunnel dries out, mud cracks develop on this layer (Figure 5C). Sometimes, horizontal clayey overhangs develop on the tunnel walls, with a width up to 10 cm perpendicular to the wall and a length that may reach 50 cm (Figure 5D). The genesis of this feature has not been understood, but it must be related to the flooding of the tunnel.

Some tunnels host, on lateral walls, 2-3 cm deep sinuous grooves, sometimes with a thicker end or beginning (Figure 5E). These grooves are mostly vertical or subvertical on the tunnel walls and do not occur on the roof. Holes in the walls are associated with these grooves. The width of the holes ranges from 2 to 5 cm and their depth is of a few centimeters. In some cases, only a few scattered holes are present, but the tunnel side may show regions with densely spaced holes (Figure 5F).

Anthropogenic features are common in open tunnels with sizes that allow human presence inside. Brazilian history divides such features in pre-colonial and colonial. Pre-colonial traces are the petroglyphs (rock art) produced by several different Indian Traditions that lived in Southern Brazil (e.g., Rohr, 1971, 1984; Prous, 1991) and who sometimes used the tunnels. Post-1500 traces are represented by tool (pickax) marks, which have been produced by people who dug inside the tunnels to look for treasures (Rohr, 1971, 1984), and vandalism, such as name-scratching on the walls of the tunnels, that has often been inflicted by visitors.
Features produced by burrowing paleovertebrates

In some cases, complex surface features are found on the walls. Common morphologies are composed of large grooves whose width and length may reach 4.0 and 60 cm, respectively (Figures 6A-B). Their orientation is mostly horizontal to subvertical. It is often possible to confirm two or three parallel marks (Figure 6C). Density is highly variable: in some tunnels, even the larger ones, only a few dozen of these structures can be found, whereas other tunnels may show 2,000 to 4,000 (e.g., Frank et al., 2010c). In MG, a tunnel excavated in laterites has shown well-defined grooves at a height of 3.1 m. While many grooves develop a similar pattern, a single tunnel shows a very different one (Site-11). In this tunnel, the grooves are short (4 to 15 cm long), narrow (0.8 cm), mostly vertical and with a density up to 700 grooves per square meter. This density is around 2-3 times higher than the one of the common grooves (Lima et al., 2010) (Figure 6D).

Several other types of features are much rarer than the grooves. In some tunnels excavated in finer-grained (clayey) material, we found flat surfaces, up to 50 cm long and 20 cm wide (Figure 6E). At Site-01, two of the six tunnel remains show very distinctive small and discrete features with an alignment up to four crests (Figure 6F). Cone-shaped marks around 10 cm wide and up to 5 cm deep are very rare (Figure. 6G). In several tunnels, the roofs and the upper part of the lateral walls are formed by completely smooth surfaces (Figure 6H).

Features produced by animals that re-occupied the tunnels

Smaller holes near the roof of open tunnels may be occupied by small groups of bats. At the entrances of these holes, there are often radiating grooves, a few mm wide and with lengths between 10 to 20 cm. The number of these grooves varies from a handful to around 20.

PRESERVATION OF THE TUNNELS

After the burrower and later occupants abandon the tunnel, biogenic and abiotic processes destroy the tunnels. Anthropogenic destruction may be direct and complete when removing a hill partially or completely. In a few tunnels, which were thought to bear hidden treasures, minor anthropogenic destruction occurred through pickaxes, shovels, and other tools. Indirect anthropogenic destruction occurs when exotic trees (Eucalyptus sp.) are planted on the surface above the tunnels. Their roots are much deeper than those of native plants and hit the...
tunnels, speeding up the destruction processes (see next). As a rule, however, the lithotypes that host the tunnels are very tough and digging is very tiring. The speed of weathering processes is higher in fine-grained alluvium and sedimentary rocks and in weathered materials (regolith, weathered igneous rocks) and slower in sandstones. Clogging and erosion are the most important processes.

Clogging processes

Materials that fill the tunnels may be divided in three main categories: (i) clay brought in by underground waters, (ii) materials (sediments, rock fragments, etc) from the tunnels themselves (endogetic), and (iii) materials from outside the tunnel (exogenic). Underground waters that fill the tunnels in some cases are muddy and, after the flooding of the tunnel, stand still for a long time until they seep out. This allows the clay to settle down, forming horizontal layers of very pure clay at the bottom of the tunnels. This process repeats seasonally at every rainy period, particularly in tunnels hosted in the sandstones of the Botucatu Formation, depositing dark brown clay that looks like chocolate and with a good luster. In a few cases, almost the entire tunnel is filled with this dark brown clay. Most often, however, clay layers alternate with layers formed by other materials (sand, pebbles, rock slabs, etc), resulting of a slow and stepwise infilling history of the tunnel (Figure 3D).

Endogenic materials are rock slabs that fell from the lateral walls or the roof (Figure 7F) and loose sand and mud derived from the weathering of farther and
higher lying parts of the tunnels. Tunnels excavated in rocks other than the stable sandstones easily fill with such material (Figure 7A). The same happens with tunnels in weathered plutonic and volcanic rocks. The action of shrub and tree roots is the main biogenic factor of this destructive process. When the root of a plant goes through the roof of a tunnel (Figure 7C), a way down is opened and water drips or even drains permanently into the tunnel, along the roots. As time passes, this link to the surface widens and, after the death of the plant and the rotting of the root, this waterway opens completely, starting a geologically fast destruction phase of the tunnel at this spot. If a big tree grows exactly over the tunnel, its network of long and strong roots destroys the structure of the rock or weathered material on this spot,

Figure 7. Clogging and erosional processes. A, Tunnel filled by a third. Original lower limit is beneath the right boot of the observer (Site-13); B, completely filled tunnel in Botucatu Formation sandstones. Its width, of 3.2 m, is such because the tunnel was cut at a curve (Site-14); C, roots hanging from the roof of a 0.9 m wide tunnel (Site-01); D, cylindrical hole, 2 m deep, that connects to a tunnel in depth (Site-15); E, schematic section (not to scale) of a tunnel in weathered plutonic rocks with destruction features like aligned craters and holes; F, keyhole section of a tunnel with eroded floor. The diameter of the upper original circular section is about 1.3 m. Arrow points to a rock slab that has recently fallen from the roof. Background light is from observer (Site-16); G, 10 m wide and 4 m deep crater in the woods that connects to an eroded tunnel in depth. Person (at upper right) is 1.7 m tall (Site-17).
facilitating the destruction processes. At the end, the broken rock slowly slides down due to creep action or is washed down with time, and the tree remains somehow “hanging” above or at the side of a big (Ø > 5m) crater that appears in the woods, even with a very gentle topography on this spot. This destruction process of the tunnels opens wide (Ø up to 10 m) and deep (up to 4 m) craters (Figure 7G) and cylindrical holes (Ø 0.5-2.0 m) (Figure 7D), and the entire material of the space now occupied by the craters and holes is transported inside and through the tunnels, sometimes filling them completely. It is important to state that gullies, typical erosional features unrelated to paleovertebrate tunnels, are not formed at such sites, but only closed craters that are linked underneath by a more or less clogged tunnel (Figure 7E).

Exogenic materials are the sediments and vegetal remains washed in from outside the tunnel, usually through the entrance or through the open holes and craters. A common process on the surface is the creep movement of the material of the weathering mantle (regolith), slowly sliding down the hillsides through geological times. During rainy periods, the soaking of the weathered material eases and accelerates this process. This way, clay and sand unrelated to the host rock of the tunnels are washed in, filling the tunnels partly or completely. In the light red sandstones of the Botucatu Formation, tunnels filled with exogenic materials are easily spotted at the cuts due to the dark brown or almost black color of the infilling (Figure 7B). Organic material derived from the vegetation on this spot, such as leaves and branches, are also deposited inside the tunnel.

Erosional processes

Paleovertebrate tunnels constitute natural giant macropores of the hosting lithotypes. Rainwater that infiltrates through the porous and permeable rocks leaves the hills and mountains through the tunnels down to main drainage courses. After rain, it is almost impossible to spot a dry tunnel. In some tunnels, we have seen cracks at the walls discharging waters for two weeks after a daylong of heavy rain. Additionally, water constantly drips from the roof of the tunnels. The action of these underground waters is the main factor for eroding the tunnels. The flowing waters erode the floors, creating deep trenches well beneath the former circular section of the tunnels. The final shape of the tunnel is that of a keyhole (Figure 7F) with an upper circular section and a lower rectangular section.

A combined action of clogging and erosional processes is usually seen at the tunnels. Higher portions of the tunnels are eroded and lower portions are clogged. Collapsing of the roof may open, on specific parts of the tunnels, wide spaces that look like former chambers. When mapping and interpreting the tunnels, original surfaces must be carefully separated from walls and features produced by the destruction processes. While the former provide important information about the tunnel, the latter are casual and only give hints about the nature and the intensity of the destruction processes.

DISCUSSION

Despite the few tunnel descriptions found in literature until now, our effort could demonstrate that vertebrate tunnels are a common ichnofossil, at least in Southern Brazil, found in a great number of locations. Ignored by paleontologists, dozens of tunnels have been spotted in the last four decades by archaeologists, who considered them to be “underground Indian galleries” (e.g., Chmyz & Sauner, 1971; Rohr, 1971, 1984; Prous, 1991; Monticelli & Landa, 1999; Farias & Kneip, 2010). Indeed, the few tunnels with rock art on their walls, and that contain ceramic and lithic material inside that attest to occasional human presence, are true archaeological sites. However, the tunnels are usually devoid of any pre-colonial human traces and are only ichnofossils.

The original shape of the tunnels (“successive-erosion-steps shape”) probably relates to the stepwise construction of the tunnel, whose excavation is a very energy-consuming process, even if several burrowers work together. Not only is the excavation difficult, but the removal of the unearthed material - the cleaning of the tunnel – also requires a huge amount of work. It must be remembered that the unearthed material weighs more than $2.10^4$ kg.m$^{-3}$ of excavated rock. This material has to be removed, sometimes for several dozens of meters, to the entrance of the tunnel and then disposed outside. We hypothesize that the burrowers used to deepen the tunnels episodically, excavating them in sections. Therefore, each arch that separates two sections can be seen as indicative of a pausing by the producers. The same tunnel morphology was recorded in different types of substrates, such as sediments, sedimentary rocks and weathered igneous and metamorphic rocks.

The interpretation of the morphologies of the walls reveals several clues about the tunnel producers. The grooves, the most abundant and conspicuous features related to the diggers, were produced during the excavation of the tunnel and are digging marks, also called claw marks (Buchmann et al., 2009b). If 2 or 3 of them are parallel, they relate to a single paw stroke. Flat surfaces, usually parallel to the tunnel axis, were interpreted as being made by the dragging of the
carapace of a Dasypodidae digger alongside the tunnel walls. The conical feature found at Site 04 (Figure 6G) was seen as produced when the elbow of the digger rammed the wall accidentally. The completely smooth roofs and walls of some of the larger tunnels in sandstones may be related to the intensive usage of the tunnels for a long time by several generations of huge paleovertebrates, with the back of the animals touching and rubbing the tunnel roof and walls until the surface was evened out and all traces destroyed.

Since all kinds of sediment and rock, other than unweathered crystalline rocks, were found to host tunnels, the age of the host rocks must be seen as rather independent of the age of the tunnels, with a younger age limit placed at the late Pleistocene-Early Holocene, corresponding to the extinction of the mega-fauna (Fariña & Vizcaíno, 1995). The positions of the tunnels usually fit nicely within the present landscape considering nearby water sources, which seemed to be a control for the paleovertebrates. Therefore, there is a close association of the tunnel entrances with the present base level. Since landscapes underwent a defined cycle with geological time (Pazzaglia, 2003), this also indicates that the age of the tunnels most probably does not extend farther than the Cenozoic.

Therefore, the diggers have to be looked for within the South American Megafauna, a concept applied to mammals whose body masses exceed a few hundreds of kilos (Fariña & Vizcaíno, 1995). The megafauna includes taxa such as litopterns (Machaeromastodon), toxodons (Troxodon), llamas (Lama, Hemionus), horses (Equus, Hipidion), glyptodons (Glyptodon, Panochthus, Doedicurus, Neoryurus, Sclero- calypthus), bears (cf. Arctotherium), saber-toothed cats (Smilodon), mastodons (Stephanomastodon), giant armadillos (Pampatherium, Holmesina, Proproopus) and ground sloths (Megatherium, Erethistherium, Glossotherium, Lestodon, Mylodon, Scelidotherium, Castorops) (Fariña & Vizcaíno, 1995). Morphological adaptations for digging are found only among the armadillos and the ground sloths (Bargo et al., 2000), restricting the digger identity, at first, to these two groups.

A fundamental assumption is that a digging animal, vertebrate or invertebrate, does not excavate a tunnel much wider than its body (e.g., Hickman, 1990). If the tunnel is larger than strictly necessary, it will only allow the entry of larger predators. An example of this general rule is found in Priodontes mascinus, the largest living South American armadillo, whose body mass is around 55 kg. In spite of this size, its tunnels measure only 43 cm in average width and 36 cm in height (Eduardo Fernandez-Duque, pers. comm., 2010). The diameters of the open paleovertebrate tunnels found until now classify them in at least three size ranges (~0.8 m, ~1.3 m, > 2.0 m), with the possibility of a better refinement in future. From the three size classes, the narrowest one can be attributed to giant armadillos of the genera Proproopus Ameghino 1881, Pampatherium Ameghino 1875 and Holmesina Simpson 1930. A similar conclusion was reached by Dondas et al. (2009), who attributed 1.0 m wide burrows (Type III) to Pampatherium typum (Figure 8).

The medium sized tunnels (width of ~1.3 m) were attributed by Zárate et al. (1998), Vizcaíno et al., (2001) and Dondas et al. (2009) to digging ground sloths, and the largest tunnels definitively have to be attributed to larger species of ground sloths. Therefore, different species of sloths excavated tunnels with diameters

![Figure 8. Paleovertebrate tunnel sizes and their probable producers. Each section of the bar at the top equals 1 m. Top left: size of the tunnel described by Quintana (1992), attributed to a dasypodid. Top right: the 2 size classes found by Zárate et al. (1998). The interpretation of these tunnels as sloth tunnels was emphasized by Vizcaíno et al. (2009). Middle: size classes as proposed by Dondas et al. (2009). These authors attributed Type I to a mylodontid, Type II to Scelidotherium leptocephalum and Type III to Pampatherium typum. Bottom: the 3 size classes of tunnels referred to in this contribution with the suggested producers.](image-url)
ranging between little more than 1 m to more than 3 m. In the end, the analysis of the digging traces may further advance the definition of the sloth species in the future. However, only double or triple claw marks among the scratches can help by measuring the distance between the grooves and comparing them with the claws of the sloths. Nevertheless, it is not correct to simply compare the bones of the paws of the several different armadillo and sloth species with the grooves inside the tunnels, searching for a fit. One has to consider that the claws of the paws do not fossilize, only the bones, and that the bones are usually much smaller than the claws, as can be seen in present-day armadillos and anteaters. Moreover, in a single species, there may have been larger male and smaller female diggers due to sexual dimorphism, besides smaller digging offspring. The analysis of digging traces has to work with these uncertainty factors.

The length of the tunnels is an intriguing factor in this discussion. As previously described, lengths of several dozens of meters are common and tunnel networks with summed tunnel lengths of several hundred meters have been spotted. Large living burrowers, like the above-cited Priodontes maximus and the African aardvark (Orycteropus afer), usually excavate tunnels with lengths of less than 10 m, despite the many different predators for both animals. Only the permanent chambered dens, produced and used by the aardvark females, may sum tunnel lengths of some dozens of meters (Knöthig, 2005). Extremely long tunnel systems have to be related to an important factor for the paleovertebrates. Larger predators have to be excluded from this list of factors, since the only big-sized carnivores in the megafauna were the saber-tooth cats (Smilodon) and the bears (Architherium), both smaller than the sloths (Fariña & Vizcaíno, 1995). The sloths, due to their much bigger size and the defense provided by their powerful claws, would probably have been immune to predators, much like rhinos and elephants are in Africa today.

The main reason for the long tunnels may be of paleoclimatic nature. In the rainy, present-day climate of Southern Brazil, the tunnels are uninhabitable because of their wetness. Water dripping from the roofs, running on the floors and spouting from cracks in the walls after rainy days is commonplace in the tunnels, even during the drier summer seasons. Some tunnels even fill completely with water and have been used as horizontal water wells by landowners (e.g., Site-12). These facts let us conclude that the tunnels relate to much drier paleoclimates. Whether these paleoclimates were hot or cold remains an open question; both require long tunnels for thermal isolation from the surface climate. Colder paleoclimates could have been a decisive factor for the building of isothermal tunnel systems with year-round warmer temperatures that allow some kind of hibernating of the burrowers during the winter, like present-day bears in the Northern Hemisphere. This factor may explain the high tunnel system density in the high and still cold region of Urubici (SC), mentioned earlier.

Future research of paleovertebrate tunnels will have to answer another set of questions, in addition to the discussion on the burrower identity previously outlined. The oxygen supply of long tunnels is one of those questions. In our team, we have often had trouble in long and/or narrow tunnels with the ongoing consumption of the oxygen of the tunnel atmosphere during inspections that sometimes were as short as 30 min. The big-sized paleovertebrates must have worked out a well-engineered ventilation system for the tunnel systems. It is possible that a main system of habitation tunnels and chambers were connected to several secondary tunnels whose apertures allowed the entry of fresh air. This tentative idea needs field evidence for support and refinement.

The number of tunnels found until now in Southern Brazil strongly suggests that the tunnels are common at least throughout South America, in regions where local favorable factors of geology and geomorphology are available. The dispersion of armadillos and ground sloths during the Tertiary covers the region from Patagonia to Alaska (e.g., White & MacPhee, 2001). If the digging behavior of armadillos and sloths produced the tunnels found in Southern Brazil, the same ichnofossils may be present in large tracks of South America and maybe Central and North America. Digital prospecting of “cave” pictures has already provided a few images of probable paleovertebrate tunnels in Northern Brazil, in the states of Pará, Piauí, Pernambuco and Roraima, but these tunnels have yet to be inspected. Besides Brazil and Argentina, however, no tunnels have been detected in any other country of the Americas. An information exchange was undertaken with some speleological groups (e.g., Ogando et al., 2010) to verify if these cave enthusiasts know of any caves with the characteristics of the paleovertebrate tunnels, but this attempt was not successful.

CONCLUDING REMARKS

The large set of huge paleomammal tunnels found in southern Brazil show that burrowing behavior was common in that region among specific animal groups of the Cenozoic. The highly variable regional distribution of the tunnels relates partially to local geological and geomorphologic conditions, including a sharp contrast between some Brazilian states with a lot of tunnels (RS and SC) and other states with only a few (PR and SP).
Most tunnels were excavated in sedimentary rocks, weathered igneous and metamorphic rocks and sediments of any age older than the Holocene. Tunnels located in sandstones are especially well preserved, showing its original shape and a plethora of traces on their walls: from diggers and re-occupying animals. Using these tunnels as reference, the remnants of smaller tunnels in weathered igneous and metamorphic rocks can be identified with great confidence, even without any traces on their walls.

After searching for several years through shorter tunnel remnants, several better preserved tunnel systems have been found, showing that the paleovertebrates often, or always, excavated highly complex 3-D tunnel systems. Tunnels of these systems are sinuous and raise and descend inside the hills and mountains, bifurcate and meet at larger chambers; a geometry whose general characteristics still have to be understood.

The confident identification of the diggers of the different sized tunnels is a most challenging issue. Since the possible ages of the tunnels cover the entire Cenozoic and relate to dozens of species of armadillos and sloths, it is not clear how precise this identification will be possible in the future. A system to classify the tens of thousands of digging scratches found inside the tunnels will have to be worked out, focusing only on those that may be compared to paleomammal paws. Even then, the possibility of sexual dimorphism within armadillo and sloth species may raise more difficulties in establishing a relation between scratch sizes and individual digger species. First of all, more tunnels have to be found to base future work on a larger data set.

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