KARSTIC FEATURES GENERATED FROM LARGE PALAEOVERTEBRATE TUNNELS IN SOUTHERN BRAZIL

CARACTERÍSTICAS KÁRSTICAS GENERADAS A PARTIR DE GRAN TÚNELES DE PALEOVERTEBRADOS EN EL SUR DE BRASIL

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Abstract

In Southern Brazil, large palaeovertebrates like giant armadillos (Dasypodidae, etc) and ground sloths (Mylodontidae, Megatheriidae) from the Pleistocene Megafauna excavated tunnels for shelter. Most tunnels have diameters between 0.8 and 1.3 meters and 30 until 100 meters in length. The longest tunnels, however, reach lengths of more than 40 meters, widths of up to 4 meters and heights of 2 meters. Destruction of these tunnels by geologic processes generates a set of features that are characteristic of karst geomorphology (e.g., dolines). If the tunnels do not become clogged by sediments that are washed in from outside, they constitute short underground waterways. The action of flowing waters inside the tunnels may collapse its roofs, widen its walls, and erode its floors, forming caves. If the tunnel is located in a depth of only a few meters, the collapse features surface and form sinkholes, vertical shafts, and dolines. Such features have been observed related to tunnels excavated in sedimentary terrains (sandstones) and in regions with weathered igneous rocks (granites and basalts). Despite the absence of any soluble minerals in these rocks, these karst-like processes and features will occur in localized spots is such terrains, often forming aligned features that reflect the tunnel underneath.

Key-Words: palaeovertebrates; tunnels; palaeoburrows; crotovines; karst.

Resumen

En el sur de Brasil, gran paleovertebrados como armadillos gigantes (Dasypodidae, etc) y perezosos terrestres (Mylodontidae, Megatheriidae) de la megafauna del Pleistoceno excavaran túneles en busca de refugio. La mayoría de los túneles tienen un diámetro entre 0,8 y 1,3 metros y longitudes de 30 metros, hasta 100 metros. Los mayores túneles, sin embargo, alcanzan una longitud de más de 40 metros, una anchura de hasta 4 metros y una altura de 2 metros. La destrucción de estos túneles por los procesos geológicos genera un conjunto de rasgos que son característicos de la geomorfología kárstica (por ejemplo, dolinas). Si los túneles no se obstruyen por los sedimentos que son arrastrados desde el exterior, constituyen cortos ríos subterráneos. La acción de las aguas que fluyen dentro de los túneles puede derrumbarse sus techos, ampliar sus paredes, y erosionar sus suelos, formando cuevas. Si el túnel está situado en una profundidad de sólo de unos pocos metros, las formas de colapso aparecen en la superficie, con la formación de sumideros, ejes verticales y dolinas. Estas características se han observado en materia de túneles excavados en terrenos sedimentarios (areniscas) y en regiones con rocas ígneas (granitos y basaltos). A pesar de la ausencia de minerales solubles en estas rocas, estos procesos característicos de karst se producirán en puntos localizados en estos terrenos, a menudo formando formas alineadas que reflejan el túnel por debajo.

***Palabras-Clave**: paleovertebrados; túneles, paleocuevas; crotovinas; karst.*

1. INTRODUCTION

When rocks composed entirely or partially by soluble minerals are subjected to dissolution, a very distinctive set of superficial and/or underground features develop, like foibes, flutes, runnels, clints, grikes, caves, dolines, cenotes, vertical shafts and others. Most common are such features on carbonate rocks attacked by mildly acidic meteoric waters. The study of these features started with Cvijic (1893), who presented the landforms of the Dinaric Kras region. The name “Kras” was Germanicised to “karst” and today is applied to modern and ancient dissolutional phenomena worldwide (Sweeting, 1972; Jennings, 1985; Ford; Williams, 2007). Karst landforms are known from all continents except Antarctica. In Brazil, for example, carbonate and non-carbonate karst terrains cover 5 to 7% of the surface of the country (Auler; Farrant, 1996).

Being a geomorphologic concept, karst is not bound solely to carbonate rocks like limestones, dolomites and marbles, the most common lithotypes with karst landforms. Extensive karst in gypsum is known from the Ukraine and from the USA (e.g. Klimchouk et al., 1996; Johnson, 2008) and karst in halite develops in outcropping evaporitic rocks (e.g. Cooper, 2002). Erosion of thick layers of sandstone also produces karst (e.g. Shade, 2002). Less understood processes develop karst forms in granites (e.g. Willems et al., 2002, Psotka; Stanik, 2006) and on the surfaces of quartzites and basalts, which may present the typical dissolution karst features known as “karren”.

Special situations concerning the development of characteristic karst forms like caves and collapse features (dolines) may occur in glaciers when melting produces underground hollow spaces. The same occur in basaltic lava flows that preserved empty lava tubes, the former lava feeders to the lava flow front. The lava tubes form tubular caves, often with some roof collapsing (skylights). Mechanical washout (piping) in sedimentary clastic strata also results in underground waterways and associated collapse features, developing a set of karstic features. Many authors call these features “pseudokarst”, but this term is increasingly abandoned and replaced by “karst”.

This contribution presents a very special situation concerning the development of karstic features. We present and discuss karst formed in sandstones and weathered plutonic rocks starting from tunnels dug by palaeovertebrates. In the same way as in soluble rocks and lava tubes, these tunnels constitute the first stage for the development of caves and associated collapse features.

2. PALAEOVERTEBRATE TUNNELS

Features found exclusively in South America, to our knowledge, are tunnels dug by extinct mammals of the Pleistocene Megafauna. From Argentina, some descriptions are available from the region between the cities of Miramar and Mar del Plata (Quintana, 1992; Zárate et al., 1998; Vizcaíno et al., 2001; Dondas et al., 2009). In Brazil, Padberg-Drenkpol (1933), Chmyz; Sauner (1971) and Rohr (1971) presented pioneering data. The latter two classified the tunnels as “underground Indian galleries”, an interpretation still found in the Brazilian archaeological literature. Recently, however, a great amount of new occurrences has been found (e.g., Buchmann et al., 2003, 2008, 2009; Lopes et al., 2009; Frank et al., 2010a, 2010b, 2010c, 2010d). Up to now, this new dataset comprises more than 120 sites with tunnels. Each site hosts between one and 30 tunnels, summing 310 tunnels, 200 of them clogged with sediments.

These palaeovertebrate tunnels, also called palaeoburrows, are classified as ichnofossils of the Domichnia type (Fig. 1). Most often, only remnants of the original underground shelters, composed of a network of criss-crossing tunnels and chambers, are found. Many of the tunnels are completely filled with sediments that have been washed in after the abandoning of the tunnel by the digging mammal. Such filled tunnels are called crotovines (Fig. 1-C).

Diameters of the tunnels range between 0.8 and 4.2 meters. Three distinct sizes have been recognized until now: the narrowest tunnels show a width of 0.8 meters (Fig. 1-A). The most common tunnels have widths that range between 1.1 - 1.4 meters (Fig. 1-B). Very rare are the so-called megatunnels, whose widths surpass 2.0 meters, up to 4.2 meters (Fig. 1-D). Many of the open tunnels show digging and contact marks on the walls and the roof (Fig. 2).

As the tunnels usually are only remnants, the lengths may be anything between a few meters and more than 100 meters. Smaller tunnels branching out from larger ones are common. The narrower tunnels may display vertical displacements of more than 4 meters, the wider tunnels are mostly horizontal. The tunnels were dug in any material than hard rock: unconsolidated sediments, weathered and unweathered sedimentary rocks, and weathered igneous plutonic and volcanic rocks. They occur in any altitude from almost sea level to more than 1,400.00 meters. Regionally, palaeovertebrate tunnels seem to be scarce in the Brazilian territory, but are abundant in the southernmost states of Rio Grande do Sul and Santa Catarina. In these two states, however, density is far from uniform: whereas in some regions only one tunnel is found every 100 or 200 km^2, in other regions almost every hill hosts a set of tunnels.

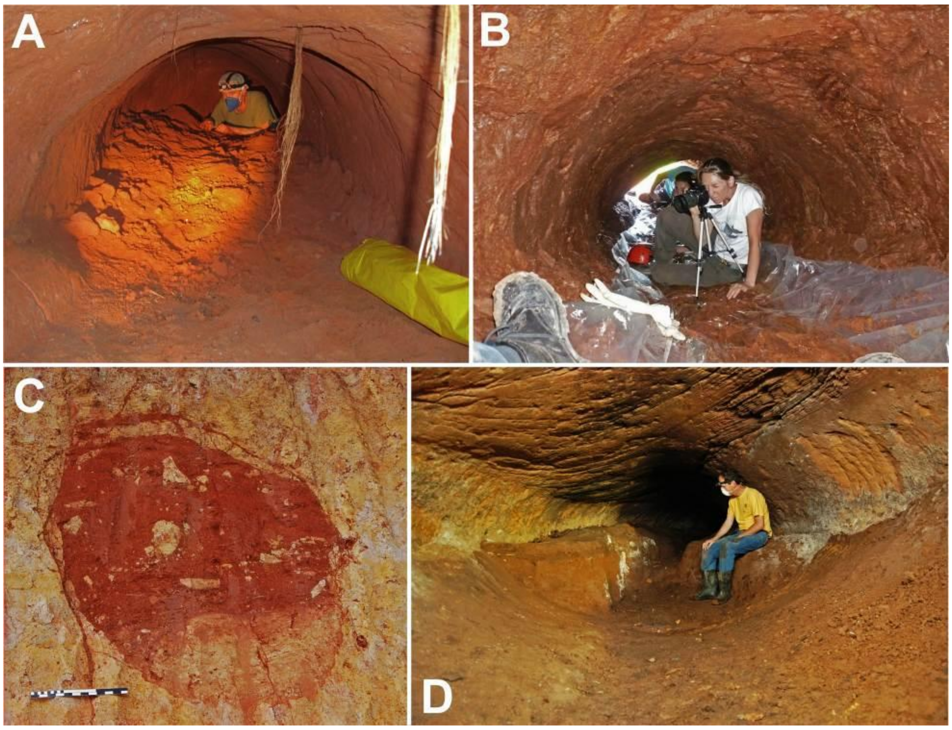

Fig. 1: Typical open palaeovertebrate tunnels of the narrowest type (A), medium-sized (B) and a megatunnel (D). A completely filled tunnel (crotovine) is shown in C. Scale 30 cm.

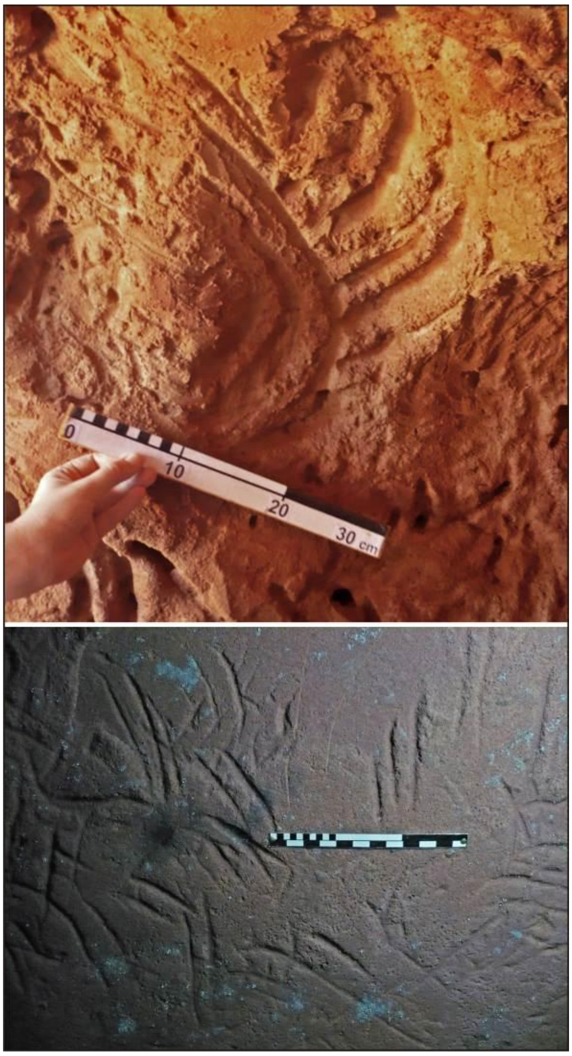

Fig. 2: Digging marks on the walls of palaeovertebrate tunnels. Scales 30 cm.

The builders of the tunnels probably are giant armadillos (e.g. *Pampatherium*, *Holmesina*, *Propraopus*) and ground sloths (e.g. *Megatherium*, *Eremotherium*, *Glossotherium*, *Lestodon*, *Mylodon*, *Catonyx*) (Fig. 3). It seems that the narrowest tunnels (Ø ~0.8 m) are from the armadillos, the wider tunnels from different genera of ground sloths, whose body masses range between 0.8 and 5.0 tons (Fariña & Vizcaíno, 1995).

3. STUDY AREA

Limited by logistical reasons, the search for paleovertebrate tunnels embraced only the four southernmost Brazilian states (Fig. 4-A). As already stated, only two states (Rio Grande do Sul and Santa Catarina) host a large number of tunnels. The karstic features that will be presented and discussed here have been found related to tunnels in the metropolitan region of the city of Porto Alegre, in the state of Rio Grande do Sul (Fig. 4-B).

Geologically, the region comprises, in the South, low (< 300 m) hills of the very complex Precambrian basement, constituted by the 550 M.y. Dom Feliciano Granitic Suite and the 609 M.y. Pinheiro Machado Granitic-Gneissic Complex, coarse-grained granites and gneiss that outcrop on the top of the hills but develop a deep (> 10m) quartzose-clayey weathering mantle in interhill regions.

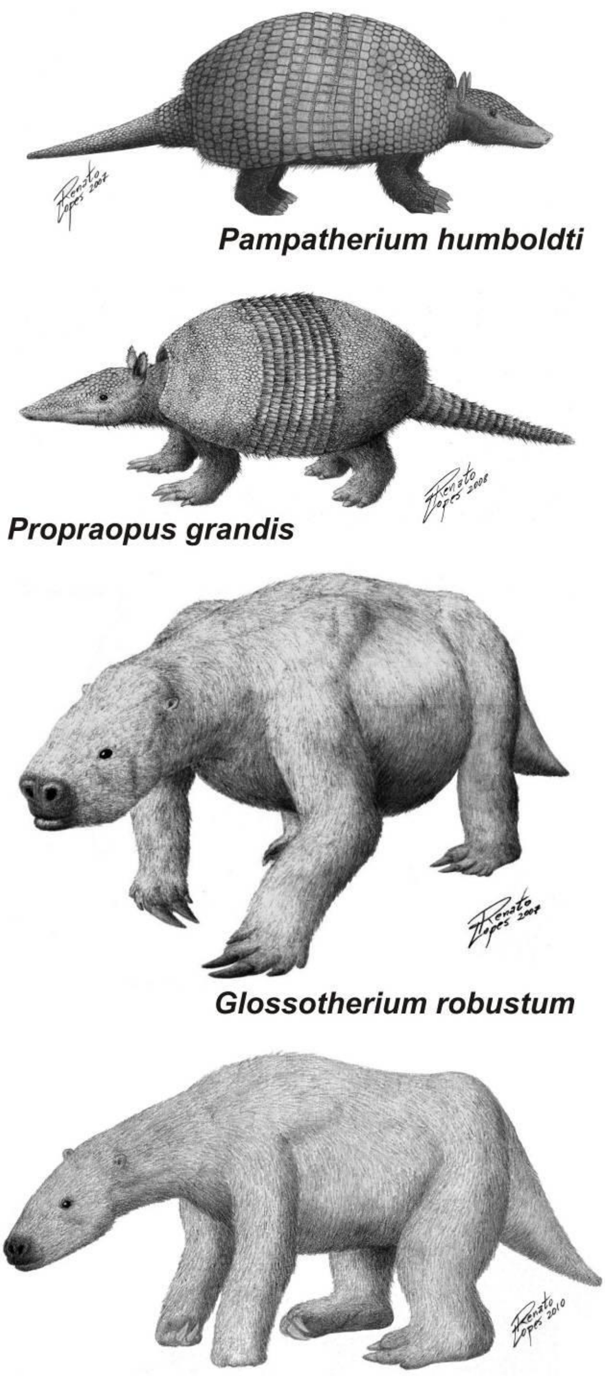

Fig. 3: The builders of the palaeovertebrate tunnels probably are giant armadillos and ground sloths, like the ones pictured here. Drawings of R.P. Lopes, not to scale.

To the North, the sedimentary sequence of the large intracratonic Paraná basin (Upper Ordovician – Cretaceous) (Milani et al., 1998) form W-E trending strips of successively younger strata. The sedimentary rocks (mudstones, fine-grained sandstones, etc) of the Permian Formations have been grouped in a single unit in the geological map of Fig. 4. Of interest in this contribution, however, is the Late Jurassic – Early Cretaceous aeolian continental sandstone of the Botucatu Formation (Scherer, 2000). This medium- to coarse-grained reddish rock is the relict of a 1.5 million km^2 arid continental area who covered not only the entire Paraná basin, but extended beyond its limits. Some layers of this sandstone underwent diagenetic silicification, forming silcretes that sustain the relief as "inselbergs". Very conspicuous at the outcrops of this sandstone is the characteristic large scale aeolian cross bedding (Fig. 5A) who dictates the forms of the outcrops, its economic usage (e.g. sidewalk flags) and, to some extent, the internal shape of the palaeovertebrate tunnels there excavated. The limits of the sedimentary units presented in the geological map of Fig. 4, however, are far from conclusive due the smooth relief and the thick weathering mantle of this area. In addition, the rocks do not contain any macrofossils, some units are composed of very similar lithotypes and most of the area is heavily urbanized.

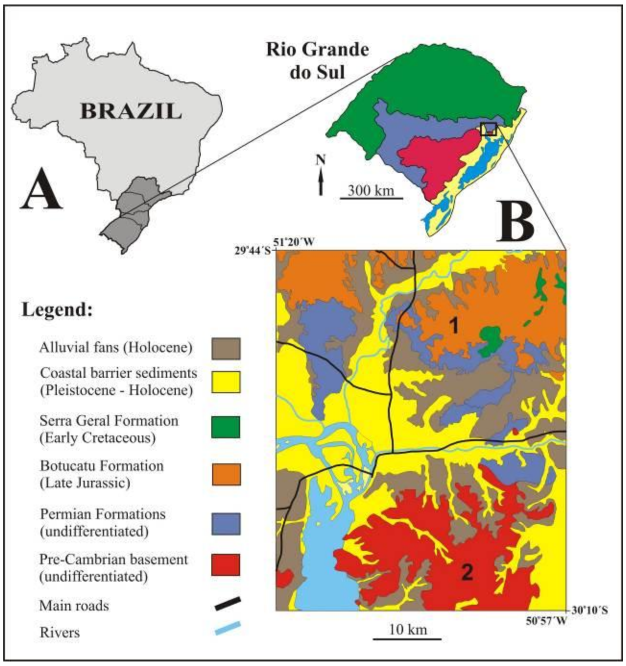

Fig. 4: Location of the study area and simplified geological map of the region. As urban areas cover most of the area, the cities have been omitted from the map. Numbers refer to the described locations (see text).

The plutonic and the sedimentary rocks of the study area are crossed by several rivers, whose floodplains where formatted by the Pleistocene–Holocene sea level changes and related coastal barriers formed along the Atlantic Ocean coast (Villwock et al., 1986). These sandy-clayey sediments are covered by recent alluvium.

Holocene alluvial fans are abundant in the study area, bordering the outcrop areas with higher relief of all rocks. The sediments of these fans (sandstones, mudstones and conglomerates) are always related to the nearby host rock: in the South, the fans contain sediments related to the granitic-gnaissic rocks of the basement. To the North, clayey sediments, sands, and gravel related to the Early Cretaceous volcanic Serra Geral Formation (Paraná-Etendeka Continental Flood Basalt Province) compose the fans. Whereas the sand- and mudstones most often are difficult to distinguish from other units, the conglomerates with its huge (Ø up to 0.9 m) basaltic clasts are very conspicuous.

4. METHODS

Successful palaeovertebrate tunnel prospecting starts with own fieldwork, but relies heavily on a set of initiatives whose main goal is to achieve public understanding of science. Even dealing with a public unaware of the existence of tunnels dug by extinct large mammals, more than a half of the tunnel occurrences, including some very important ones, have been communicated by interested people. This people take notice of this subject through newspaper reports, our internet site (www.ufrgs.br/paleotocas), and pamphlets that were distributed by the team. Besides, several tunnels have been identified through digital prospecting of “cave” pictures in the internet. In the same way, some of the “caves” known by the State Rabies Control Program and by park rangers of protected lands are tunnels. When collapse features indicated a tunnel underneath, the tunnels were found with an auger, lowering a probe with a headlight and a webcam connected to a notebook to shoot pictures of the tunnel (Fig. 6)

The collecting of data concerning the tunnels obeys a methodic scheme. Coordinates and altitude are taken with a precision Global Position System (GPS) device. The geomorphologic insertion and the host rock are analyzed, than the state of preservation is described, especially concerning the infilling of later sediments (kind, amount, layered or not). On completely filled tunnels, only width and height are measured. If open, the length, width and height (every 50 or 100 cm) and vertical displacement are measured. Digging and contact marks on the walls and roof are pictured and silicone molds are made. During this step, care is taken to minimize the unavoidable health and life risks. Even without any fossil found inside until now, this possibility always is considered. When necessary and possible, the landowner is contacted and requested to help preserving the tunnel.

5. KARSTIC FEATURES RELATED TO PALAEOVERTEBRATE TUNNELS

Despite the occurrence of palaeovertebrate tunnels in all kind of materials except unweathered rocks, karstic features are not associated to most of the tunnels. If the rock is very stable or covered by a layer of resistant rock, the tunnel stay preserved open without any karstic feature. In fine-grained sedimentary rocks, on the other hand, the tunnels usually are found completely filled with sediments, which are probably derived from the weathering mantle. However, palaeovertebrate tunnels excavated in sandstones and in weathered plutonic rocks present karstic features, which are described and discussed below.

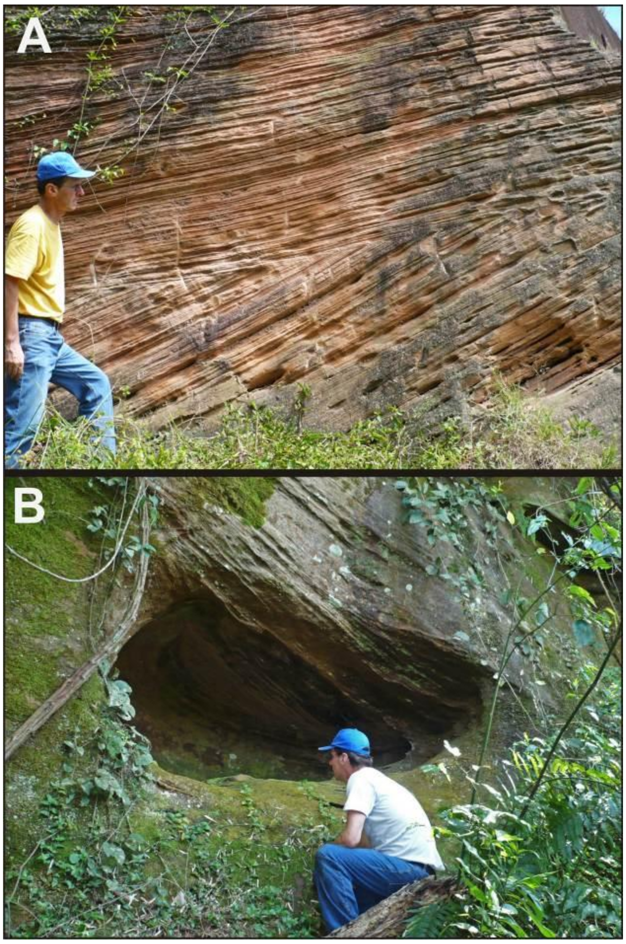

Fig. 5: (A) Large -scale aeolian cross strata in sandstones of the Botucatu Formation. (B) One of the innumerable hollows that can be found on the vertical cliffs of Botucatu sandstone.

5.1 Karstic features in sandstones

Sandstones may present hollow spaces that may be oriented horizontally or vertically. Horizontally oriented hollows can be found easily on the abundant vertical walls of sandstones of the Botucatu Formation in the study area (Fig. 5B). These walls show off on the sides of the hills and may reach several tens of meters in height. They only form when the sandstones are slightly silicified by faulting and/or diagenetic processes. The hollows exhibit a wide range of forms and sizes that are somewhat similar to some of the karst features described from granitic rocks. The origin of these hollows, in many cases, is difficult to explain and may be related to the action of wind and water thorough time on exposed sandstones with lithification inhomogeneities. This contribution, however, will deal only with the vertically oriented hollows that may be classified as karstic features.

Karstic features in sandstones were found, until now, in a region in the municipality of São Leopoldo, close to the Sapucaia hill (Fig. 4, number 1). The area, of one square kilometer, encompasses the properties of Jürgen Strauch and Alberto Cassel, centered at 29^{o} 48´26´´S, 51^{o}05´18``W. The region is composed of sandstones of the Botucatu Formation, mined in large scale for more than a century in the neighboring "da Paula" hill.

In the property of Jürgen Strauch, two eyewitnesses have told us about the existence of a paleovertebrate tunnel some 50 years ago. Both eyewitnesses played, as teenagers, inside the tunnel that was up to 1.5 meters high and about 15 meters long, with openings at both ends. One of them, Alberto Cassel, formerly the owner of the land, closed the openings with tree trunks and earth 45 years ago, while plowing the field with a tractor. Then the land, a gentle NW facing hillside, was used as a wheat and soybean field, do not showing any holes or craters. Jürgen Strauch bought the property 40 years ago and stopped planting, so that the land was undisturbed during this period, developing an open forest composed of eucalyptus trees and native shrubs.

Exactly at the place indicated by Alberto Cassel as of being of the former paleovertebrate tunnel, we found five more or less aligned funnel-shaped craters and an outlet (Figs. 7, 8). The craters and the outlet do not existed at first, as confirmed by Alberto Cassel. Each crater shows a small (Ø < 40 cm) hole at the bottom. The distance between the first crater and the outlet is of about 53 meters. Family Strauch told us that a water jet emerges from the outlet after heavy rains. Our attempts to reopen the tunnel entrance downhill were unsuccessful, even using a backhoe. Several tens of boreholes, up to 5 meters deep, were made between the craters with an auger, trying to find tunnels underneath. A few ones hit tunnels at a depth of 2.5 - 3.2 meters, compatible with the depth of the original palaeovertebrate tunnel. Pictures obtained with the probe (Fig. 9) show highly irregular tunnels, some 50 cm wide and 70 cm high, whose shape has nothing in common with palaeovertebrate tunnels. The tunnels do not connect the craters in a straight line, quite the contrary, they are sinuous, and branching, sometimes running parallel to the level curves.

Fig. 6: Investigation of deep tunnels was carried out with boreholes made with an auger. When a tunnel is found, a probe with a headlight and a webcam connected to a laptop is lowered in the borehole to shot pictures.

The tunnels are located well beneath the upper 1.5 meter thick layer of former agricultural land, composed of more or less loose sands. Downward the clay content of the sand increases. At the level of the tunnels, the decomposed sandstone, with a high clay content, is very compact and difficult to cross with the auger. Only one more isolated crater was found on another site in this property, but was not investigated yet. At a whole, craters are not a regional feature at this hillside nor on the neighboring hills.

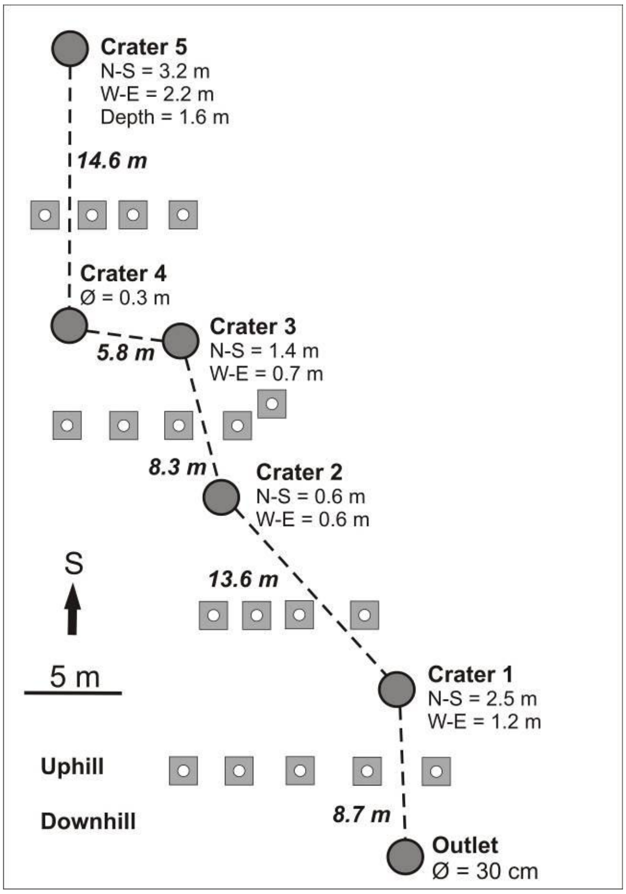

Fig. 7: Plan view of the crater sequence found on the Jürgen Strauch property. Squares indicate location of the boreholes. The altitude difference between the outlet and crater 5 is of about 7 meters.

In the property of Alberto Cassel, the investigation of the craters is much easier because the land is not more used for crop or tree planting, but only as pasture. Craters of different sizes appear at several spots. For presentation reasons, they can be grouped in two size classes: small and big (Figs. 10, 11).

Small craters refer to collapse features with diameters of up to 2.0 meters and depths of, at most, 1.0 meter. Such craters align in a very conspicuous manner on two spots. The first spot shows seven craters aligned over 27 meters (Fig. 10), the second spot has five craters along a distance of 10 meters. Deviations of the craters from a straight line connecting the first and the last craters are small, of less than 1.5 meter. Most intriguing is their occurrence on sometimes almost horizontal surfaces. A set of boreholes was made between the small craters of the second spot, showing that the craters are not straightly connected to a single tunnel running underneath, but are related to a branching system of short narrow tunnels that sometimes are parallel to the level curves. These craters, accordingly to the testimony of the landowners, are long-lived. Even filled with earth several times, they open again after some time.

Fig. 8: Craters of the Strauch property. Top: crater 4 has a diameter of only 30 cm. Bottom: the biggest crater is crater 5 (outlined). The tunnel at its base connects to the outlet, more than 50 meters away.

Big craters are much wider and deeper than the small ones (Table 1 and Fig. 11). Testimony of Alberto Cassel demonstrates that the craters only developed after the land rests from intensive farming. Two crater alignments were identified (Table 1), both converging to a small stream. Partially clogged tunnels with evident collapse features of the roof link the craters underneath (Fig. 11). Borings at this site showed that loose, former agricultural, soil occurred to a depth of more than one meter, followed by decomposed sandstone still with its typical reddish color and with increasing clay content downwards. At a depth of 4.0 meters, a layer of highly water-saturated sands with a thickness of about 30 cm overlays the sound sandstone rock. The tunnels are located in the sound sandstone, at a depth of more than 5 meters. The sandstone itself exhibits a medium lithification degree, turning it possible to traverse it very slowly with the 7cm wide auger.

Fig. 9: Pictures of the tunnels linking the craters of the Strauch property. Picture at the bottom shows the auger inside one of the tunnels and illustrates the difficulty to hit the narrow tunnels at 3 meters depth.

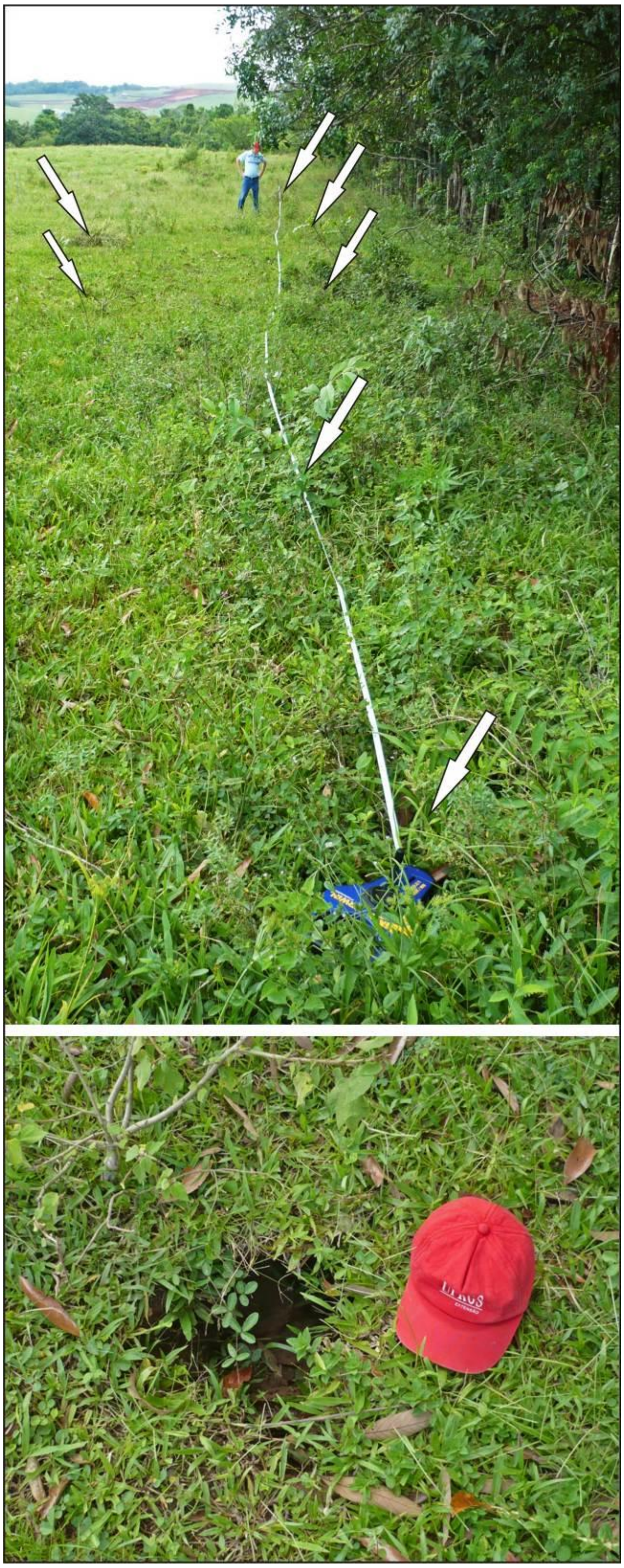

Fig. 10: Small craters of the Cassel property. Top: Seven craters (arrows) aligned over 27 meters on an almost horizontal surface. Bottom: The smallest craters are the size of a cap.

5.2 Karstic features in weathered plutonic rocks

Research of karstic features in weathered plutonic rocks was concentrated in the municipalities of Porto Alegre and Viamão. New occurrences in the neighboring municipality of

Guaíba will be investigated soon. On the tops of the hills, unweathered plutonic rocks crop out, without the occurrence of any palaeovertebrate tunnel and related karstic features. However, in interhill terrains of smooth relief, where the granitic and gnaissic rocks are deeply (>10m) weathered, palaeovertebrate tunnels are much more common than thought. In the Saint Hilaire Park (Viamão), for example, the density is of at least a tunnel every 200 hectares. Most of the tunnels are deeply hidden in the forest and only have been found with the guidance of park rangers and agents of the State Rabies Control Program. Tunnels in these terrains always are of the narrowest type, with original diameters of about 80 cm (Fig. 12A). Most of them nowadays do not show the typical profile of a palaeovertebrate tunnel due to erosion of the floor, collapse of parts of the walls and the roof and clogging by washed-in sediments. They never show digging marks on the roof and the walls. The length is always of more than 50 meters; 100 meters are common. The entrance of the tunnels usually face the small streams between the hills, the end is somewhere uphill. The slow destruction of these palaeovertebrate tunnels by geological processes follows a very typical scheme (Fig. 13 – top). The set of 16 tunnels found until now (Table 2) allows the presentation of the main characteristics of this scheme.

Karstic features related to these tunnels may be very big and can be classified in two types: holes and craters. Holes are cylindrical vertical openings with diameters of up to one meter and depths of up to two meters, always connected to the tunnel in depth (Fig. 13 – A, B). These features show almost vertical walls. Craters are openings that may reach diameters of more than 10 meters and depths of more than 4 meters (Fig. 13 – C, D). Usually, on the downhill-facing side of the craters, a tunnel remnant is found, that may be more or less clogged by sediments or eroded. When clogged, only a small (Ø < 30 cm) hole is found, where the rainwater leaves the crater. If eroded and collapsed, the tunnel remnant may reach heights of up to 2.2 meters. An example of this type is the tunnel at Refúgio Farm (Viamão), which allows walking upright inside for more than 50 meters (Fig. 12B). Testimony of several people demonstrated that this tunnel is open and visited by curious people for more than 50 years, a situation also found for other tunnels of this type. Typically, several craters of different sizes may align along a single tunnel, until reaching a small outlet near of a stream (Fig. 13 - top).

Fig. 11: Big craters of the Cassel property. Top and middle: craters may be 2.0 meters deep. Bottom: more than 4.5 meters deep, in the sound sandstone, half-clogged tunnels with collapse features show off.

Very often, the sediments of the craters and holes fill the hollows completely, and the only hint of the former (now clogged) single tunnel or tunnel system underneath is a series of craters and/or holes of different sizes that appear randomly distributed in an area of less than a hectare.

5.3 Karstic features in weathered volcanic rocks

Examples of karstic features can be found also in altered volcanic (basaltic) rocks of the lava flows of the Cretaceous Serra Geral Formation (Paraná-Etendeka Continental Flood Basalt Province). Chmyz; Sauner (1971), for example, describe a horizontal tunnel in the state of Paraná (near of the city of Campina da Lagoa), linked to the surface by 3 vertical holes, each one 1.2 meters wide and 2.0 meters deep. Recent (Feb/2011) investigation of this site (24º39´28.52´´S, 52º50´11.78´´W), however, concluded that these holes are no longer open. Nowadays, the only hint of the tunnel is a spring on the hillside whose water suddenly disappears, reappearing more than 100 meters downhill.

Table 1: Widths and depths of the big craters on the two alignments at the Cassel Property

	Alignment One - NW-SE - 43.0 m long	
	First crater	Second crater
Width (m)	2.3 x 3.0	5.3 x 3.1
Depth (m)	0.5	2.0
Distance from the outlet (m)	35	43
	Alignment Two - N-S – 17.0 m long	
	Single crater	
Width (m)	3.3 x 3.6	
Depth (m)	1.6	
Distance from the outlet (m)	17	

6. DISCUSSION

At first, it have to be considered if the craters shown in this contribution are really related to palaeovertebrate tunnels or related to the action of underground water and/or burrows made by present-day organisms.

The action of flowing underground water may result in tunnel erosion (piping) and seepage erosion. Tunnel erosion is the removal of subsurface soils in pipe-like erosional channels (Boucher, 1990, 2004). It develops under a wide range of physico-chemical conditions in highly erodible and therefore dispersive geologic materials (Masannat, 1980). Piping may develop, for example, in terrains whose high content of salts induce to sodicity problems, in terrains composed of loose particles (e.g., volcanic tuffs, loess) or when a more resistant rock layer overlays a less resistant rock layer. The resultant tunnels may be wide (Ø up to 4m) but always are located at shallow depths, usually of less than 1.0 meter, rarely up to 2.4 meters (Boucher, 2002). Along the tunnels, vertical collapse features (sinkholes) develop, which may coalesce to form open gullies.

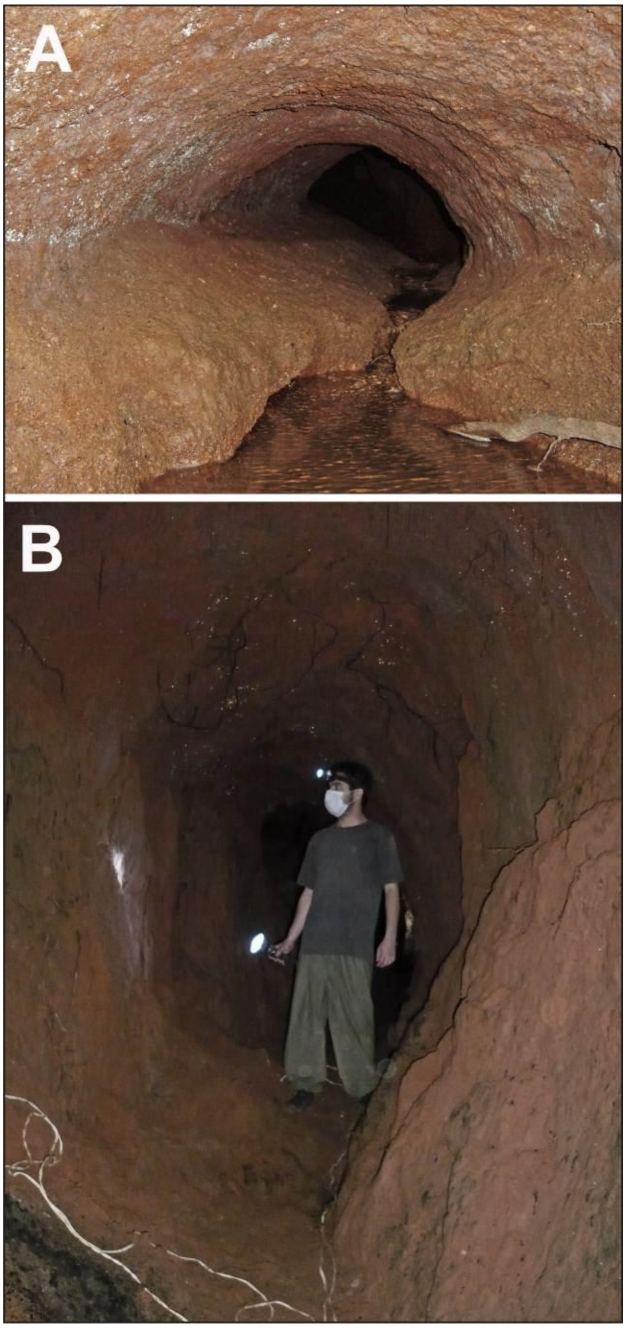

Fig. 12: Images of palaeovertebrate tunnels in terrains of weathered plutonic rocks. A: Tunnel with the typical original profile, slightly eroded on the floor. Width ~80 cm. B: A heavily modified tunnel through erosion on the floor and collapsing of the walls and the roof.

Seepage erosion (or sapping) is the process of lateral subsurface transport of non-cohesive sediments by liquefaction of the particles, usually out of steep walls with exposed sediments like streambanks and riverbanks. The prerequisite for seepage erosion is the existence of more or less horizontal water-restricting horizons (e.g., less-permeable clay layers) located above the water table (Fox et al., 2006). Such horizons induce large hydraulic gradients towards stream channels. Due to seepage erosion, the banks usually undergo rapid slope failures.

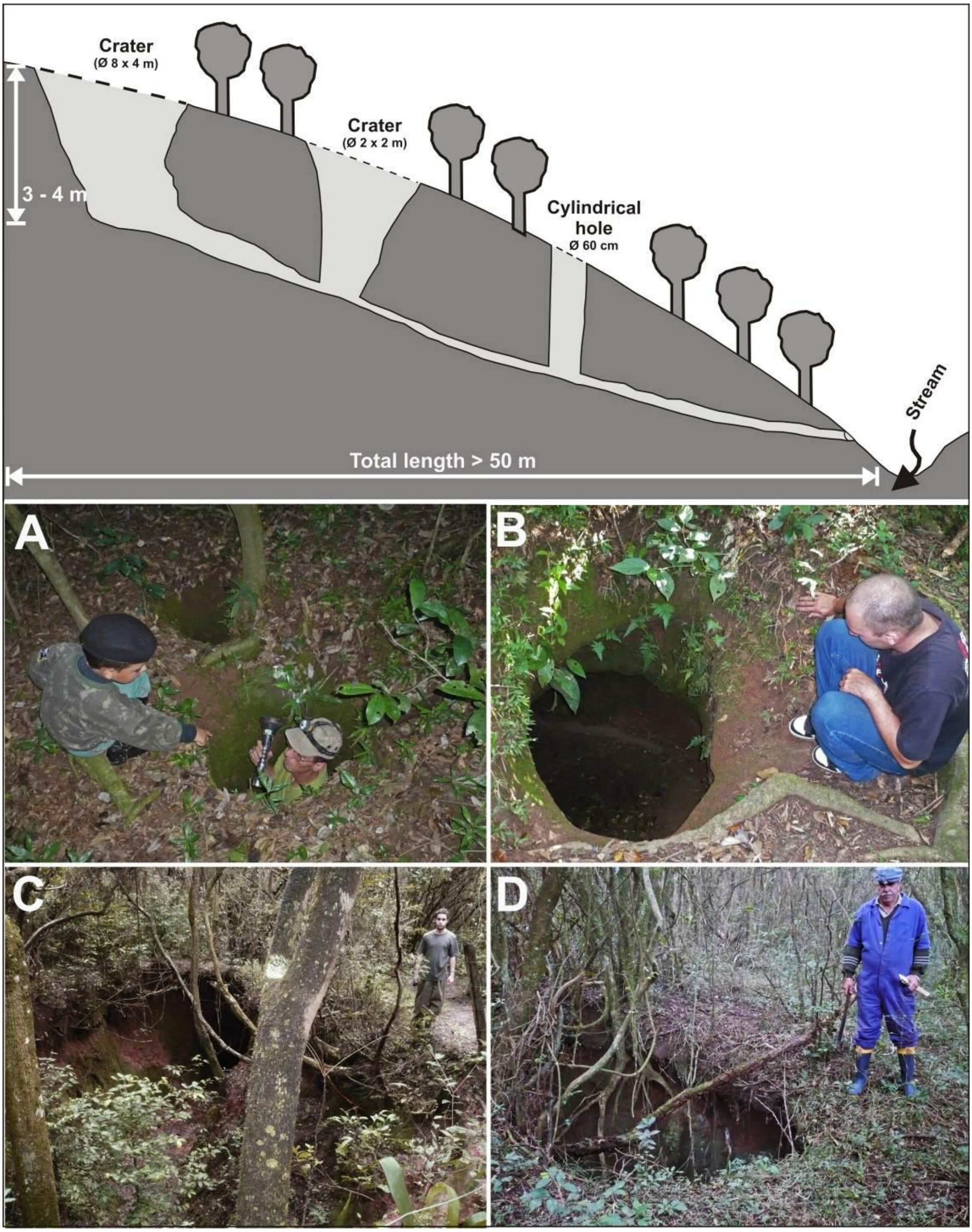

Fig. 13: Aspects of the karstic features related to palaeovertebrate tunnels in weathered plutonic rocks. Top: Idealized cross section of a palaevertebrate tunnel in weathered plutonic rocks showing the crater alignment and the outlet near the stream. Not to scale. A-B: Holes that link the surface to the tunnel underneath. At "A", person standing in the hole is 1.84m tall. C-D: Big-sized and long-lived craters that are usually found related to these occurrences.

Table 2: Location of the palaeovertebrate tunnels and associated collapse features found until now in the municipalities of Porto Alegre and Viamão, in the state of Rio Grande do Sul.

Nr	Name	Latitude S	Longitude W	Length (m)	Number of collapse features
01	Beco do David - 1	30 05 13.00	51 08 50.00	27	1
02	Beco do David - 2	30 05 13.00	51 08 50.00	45	> 5
03	Beco do David - 3	30 05 13.00	51 08 50.00	?	> 1
04	Morro da Agronomia	30 04 32.00	51 08 28.00	> 5	> 4
05	Parque St Hilaire (Figueira Bonita)	30 05 40.21	51 06 12.72	~ 80	>3
06	Parque St. Hilaire (Estrada do Viveiro)	30 05 47.70	51 06 23.50	~ 100	> 5
07	Parque Saint Hilaire (Afogada)	30 05 20.70	51 06 06.80	?	3
08	Parque Saint Hilaire (Muitos Buracos)	30 05 15.40	51 06 04.60	> 30	> 12
09	Parque Saint Hilaire (Dos Orixás)	30 05 37.91	51 05 35.56	~ 45	2
10	Parque Saint Hilaire (Da Picada)	30 05 45.20	51 05 45.60	~ 37	> 2
11	Beco do Malacara	30 04 34.52	51 00 40.39	> 55	2
12	Beco dos Cunha	30 06 13.43	51 02 33.50	> 30	3
13	Fazenda Refúgio	30 07 23.00	51 03 44.00	> 60	2
14	Campo de Aviação	30 06 16,53	51 03 20,66	> 30	2
15	Sítio do Alessandro	30 08 39.03	51 02 37.82	> 20	2
16	Sítio do João Carlos	30 09 51.73	50 59 43.89	> 20	1

These two processes do not apply to the above-presented areas with karstic features. Both lithotypes with karstic features of the study area (sandstones and weathered plutonic rocks) are homogeneous and strongly cohesive due to high percentages of clay minerals or a medium lithification degree. Soluble minerals, open gullies at the surface and impermeable horizons are absent; the horizon of the water table is located well beneath the tunnels. In addition, karstic features in such lithotypes are very rare, being spotted only in some locations. We have examined, through the last years, hundreds of huge anthropogenic outcrops (excavations) both in sandstones and in weathered plutonic rocks. At those outcrops, we have never seen tunnels and craters as found in the study area, suggesting that these features do not constitute a possible geological weathering process in such terrains, whatever the slope of the hillsides. Therefore, they have to relate to a very special origin.

The possibility to link the karstic features to former burrows of present-day organisms also have been considered. In this region, burrows made by several organisms can be found: some ant species, a species of small owl, woodpeckers, termites, and armadillos. Ant nests constitute elliptical hollow spaces with a width of 40 cm and a height of 25-30 cm, which occur to depths of up to three meters. The hollows are connected to neighboring hollows of the same type and to the surface by very tiny tubes. Owl burrows are very short and superficial, with depths of less than 40 cm. Woodpeckers excavate 10-15cm wide horizontal burrows on vertical outcrops, whereas termites may build up a deep (6m) network of hollows and large (50cm) but low (5cm) interlinking tunnels. This system of chambers and tunnels usually cover several hundred square meters. Tunnels of modern armadillos, on the other hand, never are dug vertically down the terrain, because rainwater will turn the shelters immediately uninhabitable, filling them with water. None of these actual burrows seems to relate to the described karstic features.

The development of the karstic features from palaeovertebrate tunnels, on the other hand, explains these features in a very convincing manner. The depth of the original tunnels and its original shapes, despite the absence of digging marks on the walls and the roof, identify the tunnels as such.

The development of the karstic features occurs with the biogenic impact on the tunnels. The existence of an underground tunnel, whatever its size and origin, represent a weak point in the structure of the lithotype at this particular place. When the root of a shrub or a tree hit the roof of a tunnel, for example, a link to the surface is formed and, after the death of the plant, water uses the way of the root to penetrate into the tunnel. In several palaeovertebrate tunnels, we have seen water dripping or even draining from roots that hang from the roofs. After the constitution of this waterway, erosion widens it with time, forming a cylindrical hole or a crater.

If the plant is very big (e.g., a tree), not only a single way down is opened, but the entire structure of the whole rock above the paleovertebrate tunnel is completely destroyed (broken) by the network of strong and long roots. With time, the weight of the tree collapses the broken rock into the tunnels and meteoric water washes the detritus down the tunnel, opening craters. The trees than remains somehow “hanging” inside the crater or at one side of the crater, as seen in several spots in the Saint Hilaire Park. Erosion widens the craters and the tunnels become partially or entirely clogged with sediments. This seems to be the main process for the formation of karst-like features at these spots. The absence of such features in terrains of mudstones and shales suggest that the impermeable clays prevent the formation of craters.

Some spots of the karstic features suggest the parallel action of tunnel erosion, despite several characteristics of both described lithotypes that hamper this process. Ongoing research aims to clarify and detail the action of the tunnel-destroying processes, based on a larger number of occurrences and more different lithotypes.

7. CONCLUSIONS

The presence of palaeovertebrate tunnels in Southern Brazil, excavated in many different kinds of geologic materials, induces the generation of karst-like features when inorganic processes and biogenic action (e.g. tree roots) slowly destroy these tunnels through time. Karstic features align over the former tunnels and are composed mainly of craters of different sizes, with diameters of up to 10 meters and depths of up to 4 meters. Sometimes the former palaeovertebrate tunnel is unrecognizable due to collapsing and clogging, being identified only through the existence of several holes and craters on hillsides of very gentle slopes. The action of tunnel erosion (piping) associated to some of the tunnel-destroying processes is very probable; its extent will be studied with more research on these features.

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