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KARREN ON LAMINAR CALCARENITIC ROCK OF LAGOA SANTA (MINAS GERAIS, BRAZIL)

ŠKRAPLJE NA LAMINARNEM KALKARENITU LAGOE SANTE (MINAS GERAIS, BRAZILIJA)

Martin KNEZ[1], Tadej SLABE[1] & Luiz Eduardo PANISSET TRAVASSOS[2]

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Martin Knez, Tadej Slabe & Luiz Eduardo Panisset Travassos: Karren on laminar calcarenitic rock of Lagoa Santa (Minas Gerais, Brazil)

The form of the karren is dictated by the horizontal laminated beds and fissuring. They are dissected by characteristic rock forms that are traces of their development and current shaping. The permeable contacts between laminae and the vertical fissuring of the rock fostered a distinctive three-dimensional development of karren and with it unique forms.

Keywords: karst, karren, rock relief, Lagoa Santa, Brazil.

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Oblika škrapelj je v dobršni meri posledica vodoravnih laminiranih plasti in njihove razpokanosti. Razčlenjene so z značilnimi skalnimi oblikami, sledmi njihovega razvoja in današnjega oblikovanja. Prepustni stiki med laminami in navpična razpokanost kamnine pa so omogočili izrazit trirazsežni razvoj škrapelj in s tem svojevrstno obliko.

Ključne besede: kras, škraplje, skalni relief, Lagoa Santa, Brazilija.

INTRODUCTION

The Environmental Protected Area of Lagoa Santa Karst (APA Carste de Lagoa Santa) was created by Federal Decree No. 98.881 in 1990. It was created due to the significance of its karst features and prehistory on the national and international levels and the necessity for its protection. The area of 356 km^2 is among the most endangered in Brazil due to anthropogenic pressures such as waste disposal, water pollution, and overgrazing (Kohler & Karfunkel 2002; Travassos *et al.* 2008; Travassos 2009).

The protected area is located thirty kilometers north of Belo Horizonte, the capital city of the state of Minas Gerais. It includes sections of the municipalities of Lagoa Santa, Pedro Leopoldo, Matozinhos, Vespasiano, Funilândia, and Prudente de Morais as well the entire municipality of Confins (Fig. 1).

Besides its natural importance, the karst in the region holds a record of prehistoric human occupation in Brazil with an estimated age of 12,000 years B.P. as well vestiges of Pleistocene mastofauna. Scientific studies of this karst were started in the 19th century by the Danish naturalist Peter Wilhelm Lund, who was responsible for first introducing the fields of archeology, paleontology, and speleology in the Americas.

The karst area (Fig. 2) developed on a plateau with altitudes that vary from 650 to 900 meters above sea level. It is also important to note that the karst plateau is

[1] Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia, e-mails: knez@zrc-sazu.si, slabe@zrc-sazu.si

[2] Pontificia Universidade Católica de Minas Gerais, Environmental Studies Laboratory Av. Itaú 555, Bairro Dom Cabral, BR - CEP 30730-280 Belo Horizonte, Minas Gerais, Brazil, e-mail: luizepanisset@gmail.com

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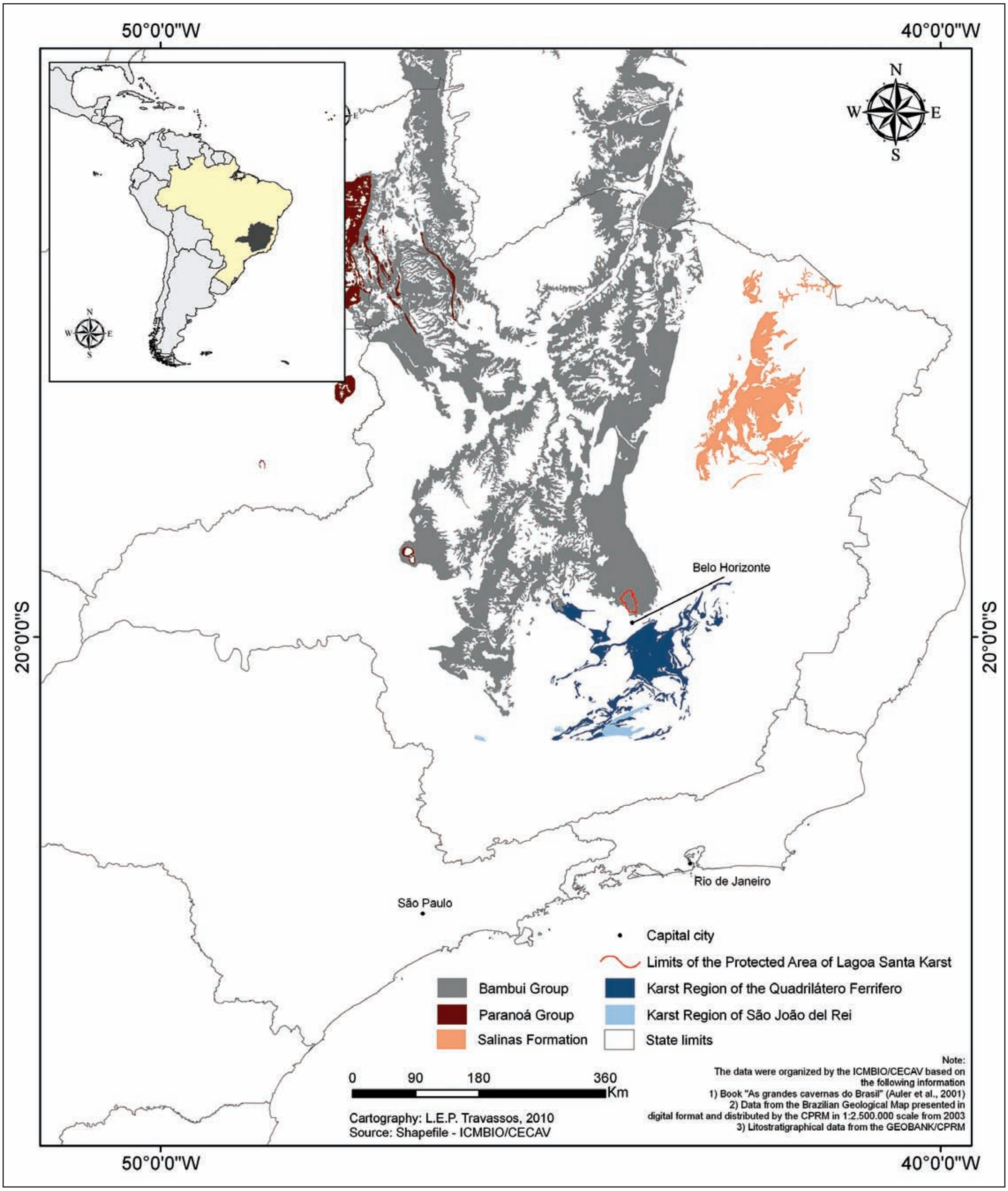

Fig. 1: Location map of the research area and the main speleological provinces of Minas Gerais.

covered with a thick pedological cover and, as in many karst regions, its main features include dolines, uvalas, poljes, karst outcrops, and caves. The poljes and uvalas often become temporary lakes. A variety of karren can be identified on the outcrops. This study was done at the outcrop surrounding the Lapinha Cave in Sumidouro State Park (Figs. 3 & 4).

According to Berbert-Born (2000), the average temperature in the area in July is around 23 °C, with a median minimum of around 11.2 °C in the historical

Fig. 2: Lagoa Santa karren (Google Earth 2010).

record from the last period of 30 years. From October to March, the average temperature is around 29.6 °C. Relative humidity ranges around 60% and 77% during the driest and most humid months respectively. The average annual precipitation is around 1,380 mm. The dry period extends for about five months from May through September with less than 7% of the annual precipitation, characteristic of a typical tropical precipitation regime with a great concentration of rain in summer and drier winters (Patrus 1996).

Cerrado (Brazilian Savannah), semideciduous seasonal forest, and deciduous seasonal forest are the main types of vegetation in the region (IBGE 1993). The Cerrado is restricted to remnant areas in regeneration or in transition from tropical forests to Cerrado. In dolines and around rock outcrops, semideciduous seasonal forest is the main vegetation form. A deciduous seasonal forest develops over limestone outcrops and is locally called "mata-seca" or "dry-forest" (Piló 1998). Important factor of rock disintegration is also biological weathering.

The unique and large karren that dissects the surface of karst outcrops is distinctive and as such deserves detailed study and description.

LITHOLOGICAL PROPERTIES OF THE ROCK

MACROSCOPIC DESCRIPTION

The dark grey to black rock (N2 to N5, Munsell Color 2009) gives a macroscopic impression of homogenous finely laminated and only slightly fissured carbonate rock in a predominantly horizontal position (Fig. 5). Despite the often strongly expressed homogeneity where single laminae are barely visible on the karstified surface, we can also observe less homogenous sections laterally that are only apparent as the consequence of long-term exposure to the atmosphere and precipitation. The contacts of individual laminae in a calcarenitic segment of laminae groups several dozen centimeters thick located below overhangs and on rock that has been covered by soil until recently are greatly erased. The rock reacts strongly to a 10% HCl acid solution.

Tab. 1: Calcimetric data for rock from Lagoa Santa karst.

CaO (%)	*MgO (%)*	*calcite (%)*	*dolomite (%)*	*total carbonate (%)*	*CaO/MgO (%)*	*insoluble residue (%)*
54.62	0.48	96.27	2.21	98.48	113.00	1.52

MICROSCOPIC DESCRIPTION

The alizarin colorant dyed the entire thin section red, which almost entirely proves the presence of calcite only (Tab. 1).

The mineral grains in the rock are arranged in a predominantly horizontal direction in alternating micrite, sparite, and microsparite laminae or sections. Micrite laminae or sections, which change laterally and horizontally in thickness and the size of mineral grains, dominate in some parts of the rock, and sparite laminae dominate in other parts. The thickness of micrite laminae ranges between 45 μm and 3 mm, most frequently being between 200 and 450 μm. The diameter of grains in the micrite laminae rarely exceeds 40 μm, and only exceptionally do individual grains reach 100 μm in diameter. The majority of micrite grains are well under 40 μm in size. Micrite laminae continuously alternate with sparite laminae. The average thickness of the sparite laminae is thinner than the micrite laminae and ranges between 100 and 250 μm, the thinnest reaching around 45 μm, and the thickest 1.5 mm. The average diameter of grains in sparite laminae is between 20 and 45 μm. The diameter of the largest grains, found mostly in thicker laminae, reaches up to 300 μm, and the diameter of the smallest grains in thin laminae is 15 μm.

Compared to sparite laminae, micrite laminae display a more uniform parallel course and only occasionally wedge out laterally. Sparite laminae, on the other hand, in most cases display a very uneven course, "jumping" into one another in a vertical direction, wedging out, varying greatly in thickness, often appearing as pseudocalcite veins, and the like.

Based on the distribution and size of the grains measured in thin sections, the rock was named calcilutite (Tucker 2001), micrite to sparite according to Folk (1959), and mudstone to grainstone according to Dunham (1962).

MICROTECTONICS

A macroscopic examination of the rock could be expected to reveal tiny calcite veins in places. However, the thin sections surprisingly did not display a single vein.

CALCIMETRY

The sample is carbonate rock with an almost 100% proportion of total carbonate (Tab. 1). The two percent of dolomite shown by the calcimetric analysis is found in the form of individual hypidiomorphic grains inside thicker (400 to 900 μm) sparite laminae. In the thin sections it was not possible to clearly determine the one and a half percent of insoluble residue identified by the calcimetric analysis. We assume, however, that these are individual fine micrite grains (less than 40 μm in size) inside micrite laminae or sections. In the area of the studied karren, the total carbonate is around 4.5% higher than stated by Berbert-Born (2000).

SHAPE OF KARREN AND ITS ROCK RELIEF FORMS

The outcrop of carbonate rock with vertical and overhanging walls towers several dozen meters above the surrounding impermeable surface (Fig. 4), which lowers quicker because of selective erosion. The top of the outcrop is horizontal or stepped, formed along the more or less horizontal contacts in carbonate rock (Fig. 3). They are crisscrossed by vertical fissures along which cracks (kluftarren or grikes; Goldie 2009, p. 89) developed that are frequently overgrown. At the foot of the hollowed carbonate rock, a network of periodically flooded foot caves of smaller diameters developed (Travassos & Kohler 2009, p. 288). Above them rise overhanging walls, originally shaped at the contact with the sediments that surrounded the limestone outcrop and today transformed by characteristic traces of three-dimensional karren formation. The central section of the limestone mass is perforated by old caves that reflect the periods when the limestone was surrounded by impermeable rock to a higher level and the caves were often filled with fine-grained sediments, which is evident from the dominance of above-sediment rock forms.

Currently the upper part of the outcrop is being transformed three-dimensionally largely by the precipitation that falls on its top and percolates vertically through the rock along fissures, flows through tubes along the contacts in the rock, and creeps and trickles down the walls. The partial overgrowth of trees and shrubbery has a further significant effect.

The karren was briefly described in a doctoral thesis by Kohler (1989) and by Berbert-Born (2000) in his presentation of the geological and paleontological features of Brazil. Both authors underline the importance of the horizontal layers of rock in its formation.

SUBSOIL ROCK FORMS

On parts of the top, which is overgrown with relatively dense vegetation, there are subsoil rock forms, subsoil channels and cups. They dissect the more or less horizontal tops of the karren and the gently sloping sections of their walls.

The subsoil channels (Fig. 3-1; Sweeting 1972, p. 89; rundkarren, Ford & Williams 2007, p. 329; Slabe & Lui 2009) were formed when they were filled with soil or weathered debris or when their bottoms were covered while the surrounding rock was exposed. In most cases they have the characteristic shape of an inverted Greek letter omega. They can have several levels or stories. Weathered debris frequently occurs only at the bottom of channels where it contributes to deepening and widening them. In most cases the channels developed from tubes that were exposed when the upper parts of the rock dissolved and disintegrated. At the edge of the top, often at the end of the channels, funnel-shaped subsoil notches formed that reach up to one meter in diameter. Wall channels (wandkarren, Veres 2009, p. 237) occur beneath them as well as beneath

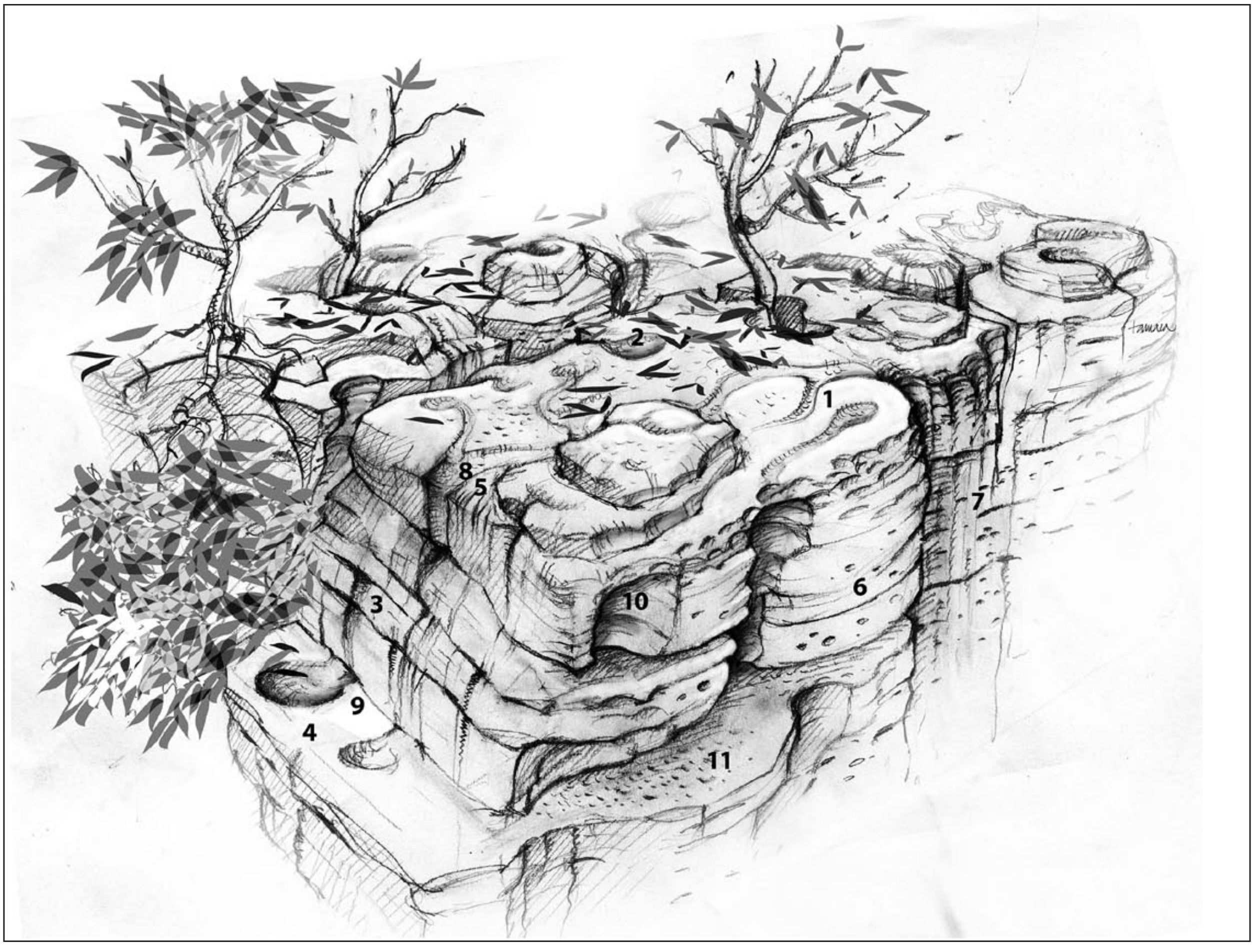

Fig. 3: Karren on laminated rock: 3-1. subsoils channel, 3-2. subsoil cup, 3-3. network of tubes along contact, 3-4. subsoil cup or kamenitza, 3-5. rain flutes, 3-6. notches along contacts, 3-7. vertical jaggedness, 8. half-funnel shaped notch at the end of channels, 9. channel from the inter-laminae tube, 10. ceiling pocket, 11. pits, formed by water trickles.

Fig. 4: Karren wall.

channels that reach the edge of the top. On overhanging walls these widen downwards in a half-bell shape. A web of channels can cover the smaller tops entirely (Fig. 6), which indicates that the water flows over the edges. Subsoil channels start to further reshape the rock and rainwater rock forms when formerly denuded karst experiences new overgrowth (Jennings 1973, p. 50; Slabe 2005). The same process is characteristic of the karren as well since we can observe the traces of recurring denudation and overgrowing processes with the filling of channels.

Subsoil pits and cups (Fig. 3-2) occur on horizontal surfaces under the thin layers of porous soil and weathered debris that cover the rock in patches or entirely (Slabe & Liu 2009). The pits are one to five centimeters in diameter, and the cups are larger. They occur due to the percolation of water through the soil and weathered debris to the rock. As a rule, they form on weak spots in the rock. The water moistens the sediment in the pits, rounding and enlarging them as a rule when the rock is surrounded by fine-grained sediment or soil. Their cross sections are therefore circular, or elliptical along fissures. Cups are most often found side by side or connected. Subsoil tubes (cavernous karren, Szeni 2009,

Fig. 5: Fissured and laminated rock.

Pits and cups also occur under the moss, lichen, and algae that cover the rock in places and often dissect the bottoms of subsoil channels.

As a rule, the surface of subsoil rock forms is smooth if the composition of the rock is uniform. The great magnification (several thousand times) of a scanning electron microscope reveals tiny fracturing that is the consequence of the more rapid dissolving of rock along weak spots in the rock at the contact between the diverse particles that compose it (Slabe 1994). The smoothness or roughness of the rock is influenced by its composition and fracturing. Here, the lamination of the rock and dissection along contacts is a particularly important factor.

Fig. 6: Subsoil channels.

p. 110) can evolve from subsoil cups, especially on fissured or porous rock. Solution pans can evolve from subsoil cups where the rock is denuded. Gams (1971, p. 33) described this type of development of subsoil cups and called them "covered solution pans." A special type of subsoil cup forms under newly occurring weathered debris (Fig. 7). With the overgrowth of denuded surfaces, rotting vegetation piles up on the rock that retains moisture and accelerates the corrosion of the rock. At first the cups are shallow with gently sloping walls. They range from a few centimeters to several decimeters in diameter. Some have channels that drain the surplus water. On sloping surfaces their upper parts are semicircular and wide and they narrow downward.

TUBES ALONG CONTACTS IN THE ROCK

Networks of tubes developed along distinct contacts in the rock at many levels (Fig. 3-3). Water from the surface of the karren and from deep subsoil cups and solution pans flows through them and percolates along the fissures. In most cases their diameters reach up to five centimeters. They are semicircular indentations in the lower laminae of the rock. Their networks, which are only visible in cross sections on the walls, are often dense, covering the entire surface of the contact or just parts of it in some spots. The roots of trees growing on top of the karren often find a way through them and accelerate their biocorrosive dissolving. The dissolving and decomposition of the thin laminae cause the tubes to gradually become exposed and reshaped under weathered debris or by rain. Below the tubes there are wall channels (Fig. 8), and cups (Figs. 3-4 & 9) form when there is a gently sloping or horizontal surface below them. Water flows to them along channels from the tubes. On denuded surfaces they are shaped by rainwater into a composite form with a solution pan. Some tubes are partly filled with flowstone.

ROCK FORMS CARVED BY RAINWATER AND WATER TRICKLING AND DRIPPING DOWN THE WALLS

Rain flutes (Figs. 3-5 & 10; rillenkarren, Ford & Wlliams 2007, p. 326; Lundberg & Ginés 2009, p. 185) are found on denuded sections of inclined walls, and rain pits (Lundberg & Ginés 2009, p. 169) and solution pans (kamenitzas, Cucchi 2009, p. 139) on gently sloping areas. Due to occasional filling with weathered debris, parts of the karren become covered by vegetation and the solution pans acquire a composite form between a subsoil cup and a solution pan.

Fig. 7: Subsoil cups.

Fig. 8: Wall channel.

The tops are also crisscrossed by exposed subsoil channels along which water runs to the edges of karren. They undergo a transformation where they are directly reached by rainwater. It appears that as a rule they are frequently but only temporarily filled with weathered debris of plant origin and therefore retain the rounded features of subsoil rock forms.

The walls are jagged longitudinally along the contact of laminae. The creeping of water down vertical and overhanging walls causes the formation of narrow, up to ten-centimeter long notches (Fig. 3-6) with elliptical cross sections, often located side by side along poorly permeable contacts in the rock. The vertical jaggedness of the walls (Fig. 3-7) is the consequence of the water converging on them from the dense network of subsoil channels on the tops of the karren and inter-laminae tubes ending on the walls at several levels. The walls are therefore crisscrossed by a network of semicircular vertical channels, mostly one to twenty centimeters wide and only a few dozen centimeters long, usually extending to a lower-lying network. From here on, the wall is further shaped by the water running from the network. Due to the merging of numerous inflows, the water shapes the wall farther down. An overhang forms above the outlets from inter-laminae tubes when the corrosion of the rock below them is faster. Half-funnel shaped notches (Fig. 3-8) can form at the ends of the channels at the top rim of the wall. On gently sloping and stepped walls, channels (Fig. 3-9) lead from the inter-laminae tubes and meander variously according to the inclination of the surface and the fissuring of the rock. These channels can also be further shaped by rainwater.

Ceiling pockets (Figs. 3-10 & 11) are found on the upper sections of overhanging walls. They occur due to water percolating through fissures and subsequently spreading across the ceiling. The diameter of the lower part of the pockets and their depth reach up to 0.5 meters. Due to gravity watering, the axes of the pockets are vertical. Composite pockets develop when several inflows of water are involved in the process of their formation. Franke (1975) determined that the diameter of pockets is proportional to the volume and aggressiveness of the inflowing water. With a larger inflow, the diameter increases, and with greater corrosive power the increase in diameter is less rapid and the pocket deepens faster. Dreybrodt & Franke (1994) determined that when water reaches a cave, it regains CO_2 from the air and its aggressiveness increases. A test with plaster at the Karst Research Institute ZRC SAZU helped explain the manner of their formation. Water percolated from a hollow at the top of a plaster cylinder with a flat bottom through a vertical bore 1.5 mm in diameter. After two hours a pocket formed with a diameter of five millimeters and a depth of two millimeters. After another hour, the depth increased by one millimeter while the diameter remained the same. The bore began to widen and the pocket continued to deepen only around the mouth of the bore where a two-millimeter wide and three-millimeter deep concave top formed.

Fig. 9: Solution cup.

Fig. 10: Rain flutes.

Fig. 11: Ceiling pockets.

Plaster is quite soluble (1.4 g per liter) and therefore the bore widened rapidly. The flow changed from laminar to turbulent and pits started to form in the bore. In other tests, the inflow of water was reduced to prevent the bore from widening too fast. The plaster was covered with a sponge from which water percolated evenly to the bore.

Fig. 12: Pits, formed by water trickles.

Single drops of water appeared at the lower end of the bore. A pocket formed that widened and deepened evenly. After two days, when the test was interrupted due the widening of the bore, the pocket was 25 millimeters wide and 7 millimeters deep. The widening of the pocket to a 50-millimeter surface around it was also observed. The interior surface of a pocket is smooth. On ceiling surfaces inclined at less than a 30° angle, narrower pockets up to one centimeter deep formed. They ended in wider flutes in the direction of inclination. The majority of the water that percolated through the bore flowed off along them. These pockets had a steep upper edge.

Pits (Figs. 3-11 & 12) form on sections of walls below overhangs from which water trickles and drips on them. On gently sloping sections the pits are semicircular and larger ones have wider lower parts. On more inclined surfaces their lower side is open. Their diameters measure from one to ten centimeters and in most cases they lie side by side. They form when water hollows the rock with trickles of diverse intensity or drops of diverse size. Larger pits caused by larger trickles contain sand that additionally erodes the rock and water remains in them for longer periods.

We tried to illustrate the process of the formation of such pits with a test dripping water on plaster from the height of 1.2 meters. First, a semicircular pit one centimeter in diameter developed. The drops hitting its bottom splashed so the circumference of the pit was smooth and the surface around it was finely pitted due to the water sprayed on it from the pit. As the pit began to grow, its bottom widened as a result of the wall being undercut by the drops splashing from the bottom. During tests when the dripping on the plaster was heavier, more frequent, or even consolidated into a trickle, water was retained in the pits that dissected the walls and eventually carved runoff channels. Vertical pits with steep upper walls and gently sloping lower walls also formed on inclined plaster surfaces. The decisive factors in the formation of pits are the pattern and amount of dripping water landing in them, the height the water falls, and the inclination of the surface on which they develop.

CONCLUSION

To a great extent, the form of the karren is dictated by the laminated beds with horizontal plane lamination and by its fissuring. Thin-layered karren that form on the surface as a rule have flat tops while subsoil karren are pointed (Knez & Slabe 2010). They are dissected by characteristic rock forms that are traces of their development and current shaping. In Lagoa Santa, the permeable contacts between laminae and the vertical fissuring of the rock fostered a distinctive three-dimensional development of karren and with it unique forms. Tubes developed along the contacts through which water flows periodically and shapes the walls below them. Ceiling pockets occur below fissures in overhanging walls, and water dripping from fissures hollows out pits. The tops covered by vegetation are dissected by networks of subsoil channels filled with weathered debris that developed from inter-laminae tubes when the upper laminae of the rock dissolved. Exposed parts of the tops with flutes, rain pits, and solution pans are being reshaped by rainwater.

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Figure 3 drawn by Tamara Korošec.

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