Soils of the Lagoa Santa Karst

Luís B. Piló and Selma Simões de Castro

Abstract

Red Latosols are the predominant soil type in the Lagoa Santa Karst High Plains and they can be up to 10 m deep on the high and middle slopes. Representative profiles of the soils have been described morphologically and micro-morphological, granulometrical and chemical analyses have been conducted. Two horizon groups were repeatedly identified in the surveyed toposequences: an upper red horizon and a lower yellow one. In both cases, the granulometric analysis revealed the predominance of a highly clay-like texture. Chemical analyses showed that the soils are acid with a low permeable base totals (S) and low cationic exchange capacity (CEC), indicating soils pedogenetically well evolved. That is corroborated by the Ki relations indicating the presence of kaolinite and therefore a process of mono-sialitization (secondary silicate formation) typical of tropical climates. The source material of both the red and the yellow horizons was correlated to meta-siltites and meta-argillites of the Serra de Santa Helena Formation deposited over limestones of the Bambuí Group. It can be concluded that the karst modeling of the Lagoa Santa Karst High Plains evolved due to a set of inter-relations between the epikarst, the surface karst and the underground karst with various pieces of evidence reinforcing the idea of a connected system in which the soil cover plays a major role.

Keywords

Lagoa Santa Karst • Soils • Pedogenesis • Epikarst

L. B. Piló (✉)
Instituto do Carste e Grupo Bambuí de Pesquisas Espeleológicas, Rua Conselheiro Mata 35/301, Belo Horizonte, Minas Gerais 31010-510, Brazil
e-mail: lbpilo7@gmail.com

S. S. de Castro
Department of Soil Science, Superior School of Agriculture Luiz de Queiroz, University of São Paulo, São Paulo, Brazil
e-mail: selma.castro@uol.com.br

1 Introduction

Well-developed soil is usually composed of the super-positioning of two groups of horizons each one characterized by very distinct mineralogical and structural properties. The upper one nearer to the surface and known as the *solum* is made up of horizons A and B. They are the result of innumerable mineral and structural alterations brought about by various aspects that control their formation, including geomorphological processes and biological activity. An accumulation of humified organic material is frequently found in horizon A. The deeper set also known as the C horizon, horizon of alteration or saprolite, is the result of the progressive alteration of the subjacent rock or sediment of which it conserves at least some of the primary minerals that are still susceptible to alteration and sometimes even maintain the structure of the rock itself (Delvigne 1983).

As regards their formation, the soils that develop on carbonate rock formations differ from soils formed on other types of rock by the notable dissolution of $CaCO_3$, its removal by leaching processes and sometimes, its re-precipitation when it may even form new horizons rich in calcium (Pedro 1976, 1987). In that regard, Lamouroux (1972) stressed that the weathering of limestone rocks occurs through a process of pellicular alteration in which the disaggregation and dissolution of the rocks are conditioned by mineralogy, texture, structure, porosity, and climate. That pellicular alteration process leads to the accumulation of an insoluble residue of the carbonate rock which is normally only found in small quantities in the pure limestones (<10%). White (1988) states that the insoluble portion of limestone rocks mainly consists of SiO_2, Al_2O_3, and Fe_2O_3 and that silica may be present in the form of chert, authigenic, or detritic grains of sand or as a component of other silicates; and that among the silicate minerals most commonly found in carbonate rocks are kaolinite and illite. Aluminum and iron may be present that are adsorbed to clay

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minerals or in the form of hydrated oxides (gibbsite, goethite).

According to Pedro (1976), in the evolution of surface karst landscapes in wet climate conditions, there is a relative accumulation of clays essentially inherited from the limestone rock which liberates them during its alteration. Duchaufour (1968) explains that in that situation of the dependence of the residual product, the limestone-derived soils are very old and consequently they are almost always polycyclic. In his studies of soils overlying limestone formations in Switzerland, Germany, Bulgaria, Pakistan and the former country of Yugoslavia, Ciric (1967) demonstrated that direct relationship of dependence on the type of soils formed on the mode of alteration of the subjacent limestone. The dolomitized limestones or marls (with from 30 to 40% of residues) are associated with mineral soils formerly denominated rendzine but nowadays classified among the chernozemic soils in the Brazilian soil classification system (EMBRAPA 2013) and in the mollisols group in US Soil Taxonomy. Such soils result from the greater intensity of formation and their profiles vary from moderately deep to deep. However, the mineral part of soils that develop over pure limestone rocks (with $\geq 90\%$ of $CaCO_3$) originates from the chemical decomposition of the rock itself in the form of an insoluble residue notably in organogenic and non-carbonate soils with slow formation processes and not very deep profiles.

Nevertheless, in many cases, it may be that there is no genetic relation at all between the *solum stricto sensu* and the subjacent altered material or even with the limestone rock found at the base of the profile. In such cases the material that originated the soils may have been allochthonous, that is to say, the hard rock at the base of the profile was covered by other geological materials of varied origins from which the soil developed (White 1988; Bouyer 2004). Outstanding among such materials are alluvial mud (Olson et al. 1980), volcanic ash (Comer 1974), aeolian sediments (Yaalon and Ganor 1973; Muhs et al. 2007) or metapelite rock settled on top of the limestone (Lund 1837; Boulet et al. 1992). In that regard, the residual (autochthonous) or detritic (allochthonous) origin which gave rise to the soils over limestones rocks have been the object of a long debate that began with the discussion of the genesis of the *Terra Rossa* of the Mediterranean region (MacLeod 1980) and which went on in several countries such as Australia (Foster et al. 2004), Barbados (Ahmad and Jones 1969), Bahamas and Florida (Muhs et al. 1990), China (Feng et al. 2009), Brazil (Lynch 2009) and others. A mixed origin for such soils, that is to say, soils originated by materials that had a co-participation of both autochthonous and allochthonous materials, is another concept that several authors have defended for some time now (Yaalon 1997).

Brazil is a country with a tropical wet (equatorial) and sub-tropical (savannah) climate and it has an extensive area of carbonate rock outcrops estimated by Auler et al. (2001) to cover about 190,000 km^2, most of it covered by soils. In a far-reaching biographic survey, Shinzato (1998) reported great diversity among the soils directly influenced by the alteration of limestones rocks, among them cambisols, vertisols, rendzines, and lithosols. According to the Brazilian soil classification system, the SiBCS (EMBRAPA 2013) the last two are now called *chernossols* (chernozems) and lithólic neosols. Podzols were also reported (*argissolos* in the SiBCS) and latosols which, according to that author, could have been influenced by material of allochthonous origin. However, in addition to the fact that there have been few studies of soils overlying limestone rock, such studies have also failed to contribute much towards a better understanding of the relations between the soils and the karst, especially in regard to morphogenesis versus pedogenesis relations.

Earlier studies of soils in the Lagoa Santa Karst High Plain (Boulet et al. 1992; Piló 1998, 2004; Shinzato 1998, and others) reported a clear predominance of latosols. Latosols are generally correlated with oxisols (American soil taxonomy) and ferralsols (WRB system). In the tropical regions of Brazil, latosols are considered to be geochemically and pedogenetically well evolved with deep, homogeneous profiles, whatever the substrate, and they predominate in more elevated geomorphic surfaces that are smoothed and geomorphologically stable, being mainly located on the highest thirds or tops of slopes (EMBRAPA 2013). The occurrence of cambisols and podzols (*argissolos*) is more limited but they have also been registered for the Lagoa Santa Karst (IBAMA-CPRM 1998; Shinzato 1998).

The aim of this chapter is to present and characterize the soils of the Lagoa Santa Karst High Plains as being an outstanding component of the regional karst as a whole and clearly influencing the genesis and evolution of the surface karst, the epikarst and the underground karst.

2 Study Area

The Lagoa Santa Karst is located approximately 40 km north of Belo Horizonte, the capital of the state of Minas Gerais, in Brazil's southeast macro-region, and it encompasses parts of the municipalities of São José da Lapa, Lagoa Santa, Pedro Leopoldo, Matozinhos, Prudente de Morais, Funilândia and Sete Lagoas. The classic Lagoa Santa Karst High Plain corresponds to the eastern and southeastern sectors of the Lagoa Santa Karst and its landscape is marked by the presence of doline fields and limestone outcrops (Fig. 1). The predominant soils in the area are deep, homogenous latosols, geochemically and morphogenetically

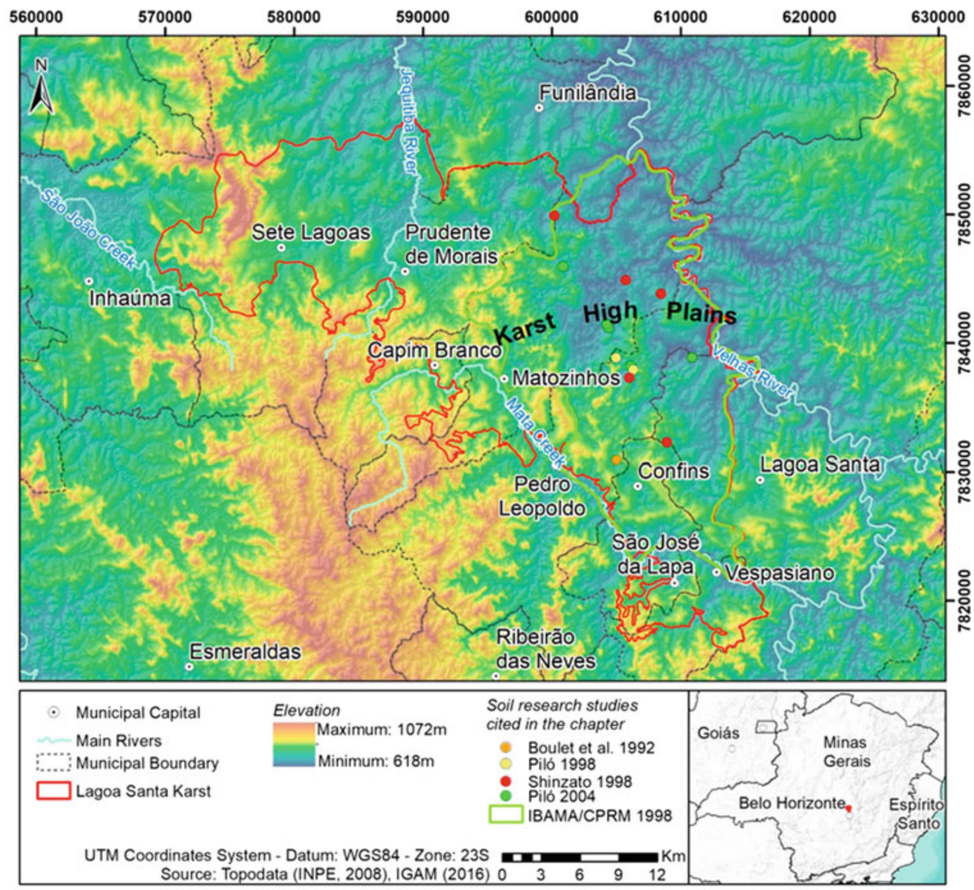

Fig. 1 Location of the Lagoa Santa Karst and the areas of soil research referred to in this chapter

well evolved but little is known about their material of origin and they are very different from the red Mediterranean soils that usually typify karst soils. That is why the attention of this chapter has been devoted to the soils of the Lagoa Santa Karst High Plains.

The regional geology is comprised of two formations of the Neoproterozoic Bambuí Group: the Serra de Santa Helena and the Sete Lagoas formations (Branco and Costa 1961; Dardenne 1978). On the top, there is the Serra da Santa Helena Formation made up of a metapelite sequence consisting of meta-siltites and meta-argillites (Tuller et al. 1992). The Sete Lagoas Formation is divided into two members: the Lagoa Santa Member and the Pedro Leopoldo Member. The Lagoa Santa Member consists of a carbonate sequence predominantly represented by calcarenites. The calcarenites are dark gray limestones with an abundance of calcite. These rocks are usually quite pure with over 95% $CaCO_3$ content (Table 1) and a considerable propensity for karst formation. The Pedro Leopoldo Member is formed by a carbonate sequence of calcisiltites and subordinately, by calcarenites and loams. The calcisiltites are impure limestones, sometimes containing silica (Table 1), with overall gray color with darker intercalations (Tuller et al. 1992). At the base of the carbonate sequence, there are igneous and metamorphic rocks (Auler 1994).

Table 1 Average percentage contents of $CaCO_3$, $MgCO_3$, SiO_2, Al_2O_3, and Fe_2O_3 in carbonate rocks of the Bambuí Group in the Lagoa Santa Karst High Plains (Piló 1998)

Parameters	Members	
	Limestone—Lagoa Santa Member (32 samples)	Limestone—Pedro Leopoldo Member (6 samples)
$CaCO_3$	96.34	67.08
$MgCO_3$	1.37	3.03
SiO_2	0.34	23.0
Al_2O_3	0.25	2.95
Fe_2O_3	0.18	1.75
Total	98.48	97.81

Fig. 2 **a** A doline field formed in the thick latosol cover of the Lagoa Santa Karst High Plains; **b** limestone cliff in which the Sumidouro Cave is located beside the lake of the same name. Photos: Ataliba Coelho

The average annual temperature in the region is 23 °C and relative humidity varies from 60 to 77%. The average annual rainfall is 1,355 mm with a seasonal distribution pattern. The dry season lasts for five months, from May to September and the rainy reason occurs during the southern hemisphere summer, especially in the months of December, January, and February (Nimer and Brandão 1989). That 3-month period registers the highest water surplus and surface, sub-surface, and subterranean runoff activity.

The karst landscape of Lagoa Santa lies in a plateau domain on the interfluvial block between Mata Creek and Velhas River at altitudes varying from 650 to 900 m (Kohler 1989). It displays a well-developed tropical karst with certain specific surface features, thick soil cover and the presence of doline fields (Fig. 2a). On one side of the dolines, limestone rock may come to the surface in the form of limestone cliffs (Auler and Piló 2015). The base of such formations normally coincides with the doline bottom which may or may not be occupied by lakes (Fig. 2b) and in many cases entrances of horizontal caves occur. Outstanding among them are caves with a network or anastomotic pattern showing clear evidence of paragenetic evolution (Coutard et al. 1978; Auler 1994, see Chapter "Caves and Speleogenesis in the Lagoa Santa Karst", this volume).

The caves can be up to 2 km long and inside there are considerable deposits of red and yellow clastic material alternating with stalagmitic crusts that mark the various phases of (clastic and chemical) sedimentation. Important sedimentary facies often bear the remains of extinct Pleistocene fauna species (Lund 1845; Cartelle 2012; Auler et al. 2006).

3 Soils of the Lagoa Santa Karst High Plains

The soils of the Lagoa Santa Karst High Plains were analyzed on the basis of four toposequences denominated Baú I, Baú II, Baú IV (Piló 1998) and Lapa Vermelha—LV (Boulet et al. 1992), in which 17 trenches and 75 boreholes were analyzed. The toposequences were examined to identify the role of surface processes in the lateral differentiation of the soils on the slopes and to observe the relative importance of geochemical and pedological processes in the evolution of the relief, in addition to evaluating whether the pedological covers are in dynamic equilibrium in the current landscape (Boulet et al. 1993; Ruellan and Dosso 1993; Queiroz Neto 2000) and their relations with the limestone substrate. Shinzato's (1998) classical analysis of seven profiles was taken into consideration of as well as the semi-detailed mapping of the Lagoa Santa Karst Environmental Protected Area in which 18 trenches and 40 boreholes were analyzed (IBAMA-CPRM 1998). The locations of the study areas are displayed in Fig. 1.

In the toposequences, the dominant presence was of thick layers of soils up to 10 m deep and consisting mainly of latosols with varying colors, textures, and structures. Two horizons were outstanding and repeated in the toposequences: an upper red horizon and a lower yellow one (Boulet et al. 1992; Piló 1998). The same super-position was observed in several cuts made for the highways that cross the Lagoa Santa Karst High Plains (Fig. 3).

On the tops and high slopes that super-positioning is even more apparent because they are not subject to the influence

Fig. 3 Highway cut exposing the two main sets of pedological horizons of the Lagoa Santa Karst High Plains: the red upper horizon and the yellow lower one

of doline which fosters soil transformations through hydromorphy and nodulation. The red horizons (2.5 YR) can be up to 7 m in depth on the top of the Baú II toposequence, before they make vertical contact with the underlying yellow horizons. In the case of the LV toposequence, the red latosol in the upper third of the slope goes down to a depth of 8 m getting shallower on the downside of the slope (Boulet et al. 1992). In the Baú IV toposequence, the red horizons are not so thick and they make contact with the yellow horizons at a depth of less than 2.5 m (Fig. 4).

It is worth noting in Fig. 4 that the doline truncates the soil but the soil carries on to the downhill side keeping up the same pattern among the horizons in relation to the current topography which indicates that the doline formed after the latosol was developed. Also, beneath the doline there is a notable depression of the limestone substrate. The illustration highlights two interesting features; first, the soil horizons in the doline are concordant with one another and with the topography of the doline, and second, that they are discordant with the topography of the substrate which suggests there may have been a collapse, a common occurrence in the region, and subsequently a progressive sedimentation.

The toposequences Baú I, II, and IV revealed a predominance of very homogeneous latosols with a very clayey texture (over 60% clay content) structured in blocks near to the surface and gradually turning to the fine granulate texture (micro-aggregate) in the red horizons (B1). The yellow horizons are resistant to the auger, structured in blocks and with a strong tendency to be prismatic, suggesting the presence of expansive clays. In the red horizons porosity is intergranular and in the yellow ones, it is fissural and apparently less developed.

Boulet et al. (1992) identified two nodular horizons at a depth of more than 7 m and interpreted them as two stable positions of a former water table prior to the latosol-forming process on top of the yellow horizons in which the nodular horizons were found (Fig. 5). A nodular horizon was also recorded for the Baú IV toposequence, which was continuous and located at the level of contact between the red soil and the yellow soil (Piló 1998), possibly indicating the top of the temporary, perched, epikarst aquifer.

In the lower slope of the toposequence LV, Boulet et al. (1992) reported a thinning of the latosol cover and the rising of the yellow horizon nearer to the surface. That, however, does not correspond to a toposequence differentiation but instead, the present-day topography has been truncated by erosion which has removed the red latosol from the vicinity of the doline (Fig. 5). In the toposequences Baú I, II and IV, the horizons in the lower part of the slope are arranged parallel to the surface and there are no clear signs of erosion or any important differentiation among the brown, red and yellow horizons.

Figure 5 differs from Fig. 4 in various aspects. First, the doline is further down the slope than in the earlier figure and the latosol cover in Fig. 5 is interrupted in the middle third of the slope and disappears which suggests truncation resulting from erosion. The volumes of compacted clay are embedded in a micro-aggregate matrix like those of the latosols uphill which suggests the occurrence of a morpho-pedological adjustment of the cover by reorganization of the material in

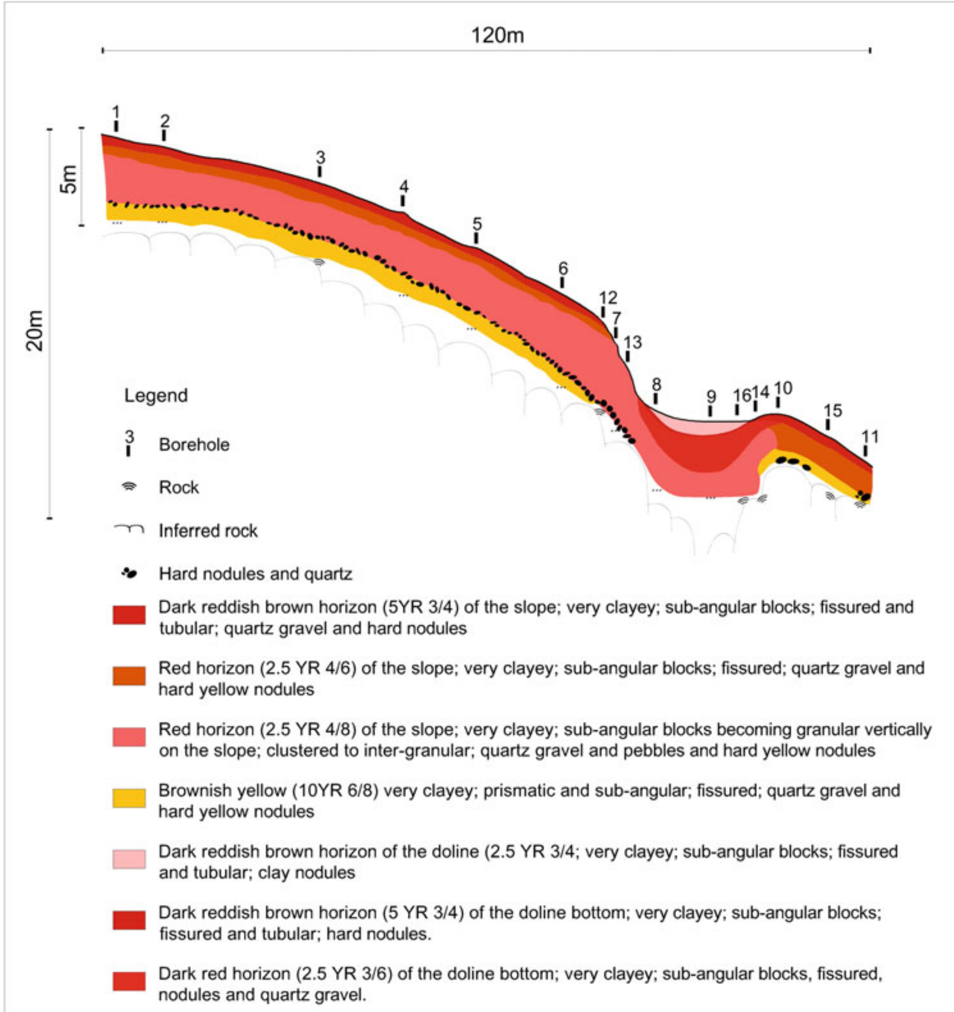

Fig. 4 Baú IV Toposequence showing the red and yellow horizons parallel to one another and to the current topographical surface (Piló 1998)

the light of the erosive truncation it suffered further down where the presence of variegated material on the edge of the doline suggests the material underwent hydromorphy.

The horizons in the bottom of the doline are more complex, more numerous, sometimes concentrated and may present nodules associated with the seasonal presence of the water table. Colors vary from reddish brown, to yellowish brown, to stained and variegated and textures are marked by increased participation of silt and sand. In all the doline bottoms, organic soils (organosols) buried under sediments were found.

Reconstruction using geometry approximation for the horizons surveyed and present in the toposequences showed that they are laid out more or less parallel to the present-day topographical surface meaning that they are concordant among one another and with the surface. According to Boulet et al. (1993), that kind of soil cover with no discordance among horizons that are parallel to the topography of the surface shape of the relief are formations in equilibrium with the prevailing pedoclimatic conditions, that is to say, they have evolved over time in climatically and tectonically stable conditions so that the transformation sequence from the bedrock to the soil surface is maintained. That means their organization reveals continuity in the alteration and pedogenetic processes insofar as they show no evidence of lateral transformation fronts which would result from more significant climate changes or from the downcutting of the base level associated with them or from tectonic events. On the contrary, when there is any evidence of notable differentiation as in the case of the LV toposequence, it is probably due to the influence of erosive truncation phenomena.

The Baú I and II toposequences are examples of a complete vertical transformation system still in equilibrium with the current karst model. The Lapa Vermelha toposequence would seem to show evidence of a small transformation due to the presence of the doline where there is erosive

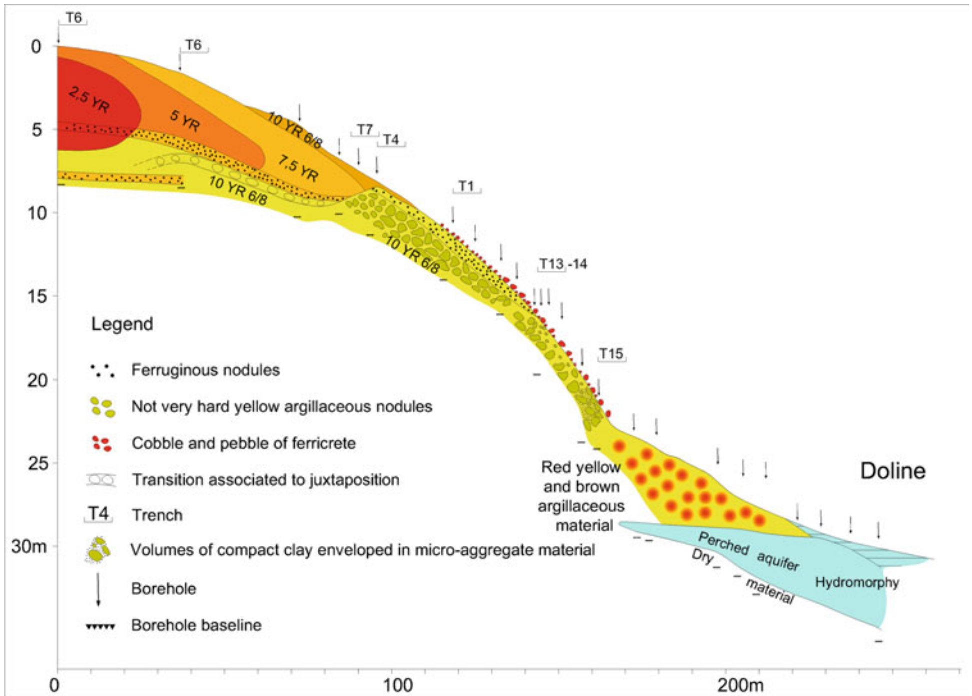

Fig. 5 Toposequence of the Lapa Vermelha. Adapted from Boulet et al. (1992)

truncation halfway down the slope probably due to changes in the underground karst.

4 Micromorphology of the Soils

Observation of the micromorphology of the Bau I, II, and IV toposequences revealed a distribution of porphyric types for all the soils that were analyzed. The superficial red horizons (2.5 YR 4/4 e 4/8) found in the TR-3 and TR-6 profiles are either granular or crumb microstructures with a highly developed pedality (Fig. 6, Table 2). Porosity is predominantly intergranular leading to a high overall porosity (Piló 1998). In the layer from 0.50 to 1.00 m of the TR-6 profile horizon, the presence was observed of iron-clay material lining the pores which is usually interpreted as a sign of illuviation. However, those features only occur locally and do not mean that the horizon as a whole is an illuvial horizon (Fig. 6c).

The microstructure of the yellow horizon of TR-6 is of the angular blocks type with a moderately developed pedality (Fig. 6b). Porosity is predominantly fissural but considerably less developed than that found in the red soils of the surface. In the yellow horizon close to the contact with the underlying rock the micromorphology can be almost solid.

The upper set of red horizons is marked by the predominance of a microstructure that is enaulic (micro-aggregate) and piled, as is typical for red latosols with strong inter-aggregate porosity. Micro-aggregated is the term usually used to denominate the granular structure that typifies latosols but on the microscopic scale it can be spheroid, ovoid or polyhedral and it may stem from various different origins (Buol and Eswaran 1978; Stoops 1983; Stoops and Buol 1985) so accordingly, they have been attributed specific names. The microstructures of the lower set of the lower yellow horizons are predominantly fissured to solid porphyric with fissure porosity (Fig. 6d). According to Ruellan and Dosso (1993), angular microstructures are formed by flocculation and/or concretization followed by splitting. They may have the appearance of blocks, cubes or prisms favored by the presence of 10–30% of argillaceous material.

According to Ruellan and Dosso (1993), the mechanisms that originate the aggregation of pedological material are: (i) flocculation of the constituents, especially clays, associated to the presence of organic material and bivalent cations (Ca^{++}, Mg^{++}) or trivalent ones (Al^{+++}) in the adsorption complex; (ii) cementation of the constituents by organic material, iron, calcium, silica, or biological activity; (iii) fissuring of the flocculated or cemented domains, above all associated to the expansion and contraction of clays in desiccation/humectation conditions that particularly affect the expansive clays.

Thus the red horizons would be of geochemical origin (flocculation and cementation), representing a more evolved stage of pedogenesis, while the yellow ones formed by fissuring represent a less evolved stage. In addition, those

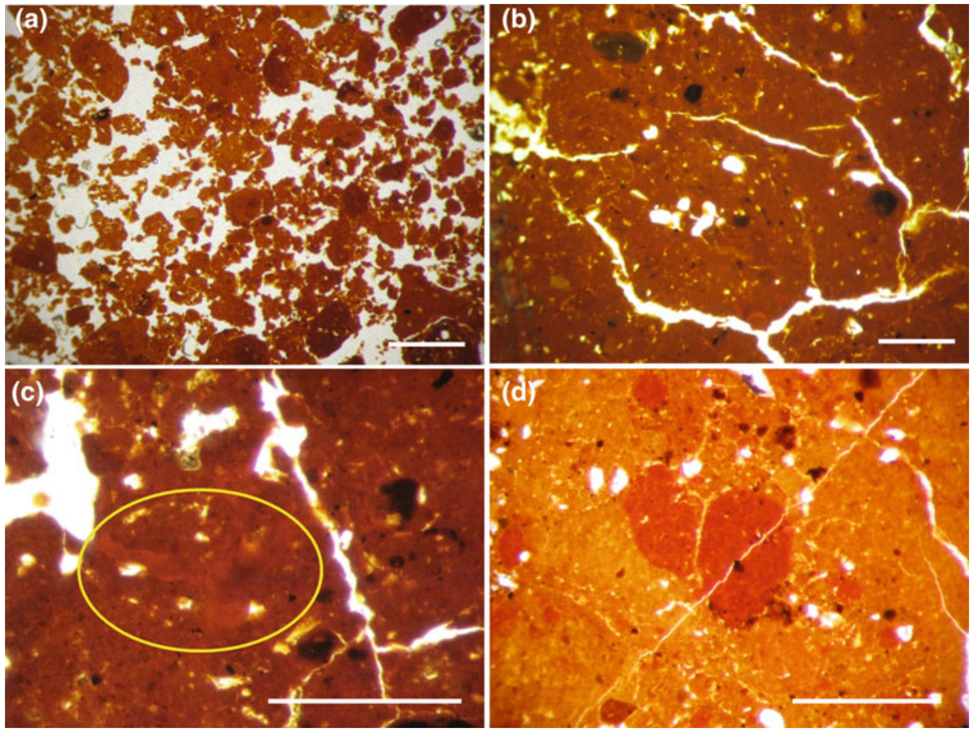

Fig. 6 Microphotographs of soil horizons of the Lagoa Santa Karst High Plains: **a** granular (enaulic) and fragmentary (porphyric) microstructure in horizons **B** and **C**, respectively (TR-3) showing the presence of small polyhedral fragments filling the spaces in a matrix of much larger fragments; **b** porphyric microstructure fissured in sub-angular blocks in the horizon (TR-06); **c** scattered illuvial ferri-argillaceous coating entirely filling a pore in horizon **B** (TR-06); **d** solid porphyric microstructure with poorly developed pedality from the deep part of the yellow horizon. Scale = 500 µm

Table 2 Main microstructure characteristics of the A and B horizons of the red latosol of profile TR-3

Horizons	Depth in cm	Color	Microstructure (pedes)	Pedality	Porosity
A	0–60	Reddish brown (5 YR 4/4)	Fissural, blocks and closed enaulic	Moderately developed	Fissures and channels (25%)
B1	60–100	Reddish brown and Red (2.5 YR 4/4, 4/6)	Dense enaulic and fragmentary porphyric	Highly developed	Closed intergranular/Fissures and channels (35%)
B2	100–180	Red (2.5 YR 4/8)	Small enaulic and fragmentary porphyric	Highly developed	Small intergranular (40%)

characteristics, especially in the case of inter-aggregate porosity, indicate an internal drainage that is faster and more efficient in the red latosols and slower in the yellow ones; a situation which may even lead to the formation of a perched epikarst aquifer draining downhill and that could lead to the formation of nodules. On the other hand, they do not indicate any lithological discontinuity so the possibility cannot be ruled out of there being genetic affiliation among them whereby the yellow ones would correspond to the saprolite material of origin, evolving to become the red soil.

5 Granulometric Composition

Granulometric analysis of the soil samples of the studied toposequences revealed a predominance of very argillaceous soils with a participation of clays of up to as much as 95% (heavy clay). A greater participation of silt fractions only occurs in the soils around the rims and in the bottoms of the dolines and can be as high as 23% at the base of profile TR-9 in which total sand content is 32%, partly constituted by quartz, clay, iron and manganese nodules; these last three constituting the pseudo-sand. No differences in the textures were found between the red set and the yellow set (Piló 1998).

Likewise, Shinzato (1998) reported little variation among the profiles of the Lagoa Santa Karst. The clay contents in the B horizon are quite homogenous and the soils all belong to a single texture class: highly argillaceous (Fig. 7). In profiles P5, P6, P13, and P14, it can be seen that there is a gradual increase in clay content with increased depth but not sufficient to determine any significant textural difference and the form of the curve is similar to that observed in the latosols. In all of the analyzed profiles, the sand fraction

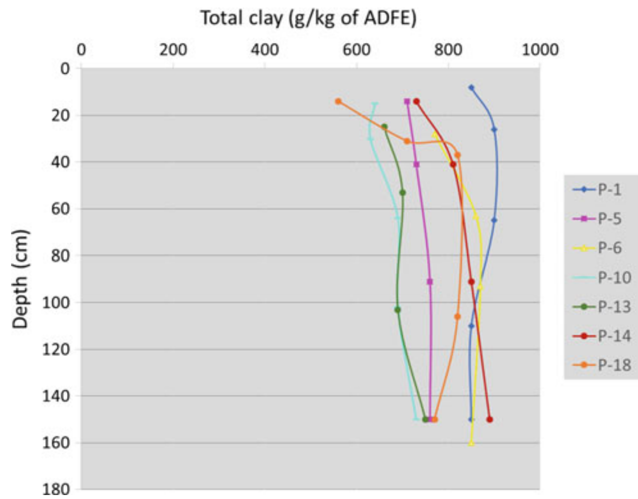

Fig. 7 Clay content variations by depths in the profile analyzed in the Lagoa Santa Karst High Plains (Shinzato 1998)

decreases gradually with an increase in depth. In most of the soils, coarse sand prevails over fine sand.

In the soil mapping undertaken in the Lagoa Santa Karst Environmental Protected Area by IBAMA-CPRM (1998) all the soils identified—latosols, cambisols, podzsols, and gleysol also showed very clayey textures.

6 Soil Mineralogy

Analysis of the resistant materials is based on the principle that minerals like zircon, tourmaline, garnet, anatase, rutile quartz, albite, and microcline do not suffer any expressive alteration during soil formation and are therefore considered to be resistant (Moniz 1972). The occurrence of these minerals and their distributions in the profile have allowed interpretations as to the affiliation of the soils under analysis. That aspect was analyzed in two soil horizons of the Lagoa Santa Karst High Plains: the red horizon and the yellow horizon and the following minerals were identified:

– Red horizon—milky quartz, hyaline quartz, black tourmaline, green tourmaline, limonitized pyrite, garnet, and rutile;
– Yellow horizon—milky quartz, hyaline quartz, black tourmaline, limonitized pyrite, garnet, and rutile.

It can be seen that the red and yellow horizons possess the same assembly of resistant minerals, which only corroborates the idea that those soils developed on top of the same material of origin. It should be stressed that it is a mineralogical assembly that cannot possibly be a residual product of the limestone (Piló 1998) but it is compatible with the meta-siltites and meta-argillites overlying the Sete Lagoas Formation as being the material of origin of the latosols. The same conclusion was reached at by Lund in the mid-nineteenth century (Piló 2002) and by Boulet et al. (1992) and Shinzato (1998).

7 Soil Chemistry

Chemical analysis showed that the soils are predominantly acid with pH values ranging from 4.3 to 5.7 in the high and mid slopes. Acidity is reduced at greater depths and laterally in the downslope direction which is a typical pattern for tropical soils. The soils in the doline bottoms are less acid (Piló 1998). Shinzato (1998) in turn, reported pH values for regional soils in the range of 4.7–6.9. In the studies undertaken by the IBAMA-CPRM (1998), pH was found to vary from 4.8 to 6.3 (Table 3).

Values for soil organic matter (SOM) are higher in the superficial levels and decrease at greater depths as was to be expected. However, the highest values are those of the organic horizons in the doline bottoms where they can be up to 7.6% (Piló 1998). The sum of the permutable bases (S) is very low in the soils and so is the cation exchange capacity (CEC) (Table 3). The values of the latter are less than 15 meq/100 g, indicating the predominant presence of kaolinite. Due to the higher CEC values of the organic

Table 3 Chemical analysis for a typical latosol profile of the Lagoa Santa Karst High Plains according to the IBAMA-CPRM (1998) soil mapping study

Profile	Horizon	pH in H_2O	C (%)	Ca^{++}	Mg^{++}	S	Al^{++++}	H^{+}	T	V (%)	Sat. Al (%)	CEC of clay cmol (+) kg^{-1} of clay
				cmol (+) kg^{-1} of ADFE								
P1 Latosol	A	6.3	1.89	4.74	0.1	4.95	0	2.71	7.66	65	0	–
	AB	5	1.16	0.71	0.02	0.77	0.6	4.01	5.38	14	44	0.2
	BA	5.2	0.96	0.26	0.02	0.31	0.6	8.33	9.24	3	66	5.5
	Bw1	4.8	0.76	0.1	0.01	0.13	0.45	3.55	4.13	3	78	0.8
	Bw2	5.1	0.6	0.16	0.01	0.19	0.25	3.17	3.61	5	57	1.1

Table 4 SiO_2, Al_2O_3, and Fe_2O_3 percentages and Ki and Kr indexes in five latosol horizons in the Lagoa Santa Karst High Plains (Piló 1998)

B Horizons	SiO_2	Al_2O_3	Fe_2O_3	Ki	Kr
45-100 TR-6	34.64	30.91	5.64	1.91	1.71
100-240 TR-6	32.70	30.60	6.70	1.82	1.59
240-300 TR-6	29.80	26.52	6.40	1.91	1.65
40-90 TR-2	35.01	31.11	5.41	1.91	1.72
90-160 TR-2	32.18	29.76	6.84	1.84	1.58

material, the horizons with higher SOM content have somewhat higher S values.

According to Shinzato (1998), CEC values for the clay are lower than 24 cmol (+) kg^{-1} of clay, classifying them as low-activity clays. Furthermore, since the threshold distinguishing latosols from cambisols is 13 cmol (+) kg^{-1} of clay, the soils analyzed are within the range normally accepted for latosols and in concordance with the classification of the Brazilian system SiBCS (EMBRAPA 2013). Similar figures were obtained by the studies of CETEC (1994) and IBAMA-CPRM (1998), as shown in Table 3. In regard to base and aluminum saturation percentages (V% and M%), according to Piló (1998), regional soils can be alic, eutrophic or dystrophic with a predominance of this last.

The relations between silica and alumina in the soils showed Ki values (SiO_2/Al_2O_3) lower than 2 confirming the presence of minerals of the kaolinite group in both yellow and red horizons (Table 4).

Shinzato's (1998) results showed that the mineral fraction of the soils in the region that were analyzed is predominantly made up of argillaceous minerals of the kaolinite group given that the values he obtained for the molecular Ki ratio were close to 2.

In the TR-6 profile (Baú IV top sequence) there were three main horizons namely, a dark red-yellow B horizon (45 cm to 1.0 m), a bright red B horizon (1.0–2.0 m), and a strongly yellowish-brown horizon B (2.4–3.0 m). The oxides percentages and the molecular Ki and Kr ratios are presented in Table 4.

Two red B horizons (2.5 YR) in the TR-2 profile of the Baú II top sequence were analyzed, situated at depths of 40–90 cm and 90–1.65 m. SiO_2 values were 35.01 and 32.18%, respectively. Those figures are very close to the figures obtained for the TR-6 profile. Al_2O_3 values were 31.11 and 29.76%, respectively; again very similar to the figure for the TR-6 profile. Fe_2O_3 figures were 5.41 and 6.84%. Ki values were 1.91 and 1.84 and those for Kr were 1.72 and 1.58, respectively. The Kr values are indicative of the presence of iron oxides/hydroxides.

Those percentages confirm the existence of a mono-sialitization/ferralization environment. An analysis of the overall set of results shows that highly weathered and pedogenized soils predominate in the Lagoa Santa Karst High Plain (Piló 1998) classified according to the SiBCS (EMBRAPA 2013) as red dystrophic and dystroferric latosols in spite of the occurrence in them of cambisols and acrisols (IBAMA-CPRM 1998; Shinzato 1998).

In short, they are not soils derived from the limestone rocks and therefore the red color of their upper horizons does not mean that they are the equivalent of the Mediterranean *Terra Rossa* soils as Sans (1973) and Auler (1988) proposed for the region, but instead, they are derived from the oxic-ferralitization that is typical of sub-humid tropical regions.

8 Age of the Organic Horizons and the Charcoal Present in the Soil

According to Lowe and Walter (1997), sediments that accumulate in lakes and ponds are either of allochthonous or autochthonous origin. The former are partially derived from organic production of the lake ecosystem and partially from rainwater runoff from the slopes of the lakes' drainage basins in which case they include both organic and inorganic materials.

Lakes rich in mineral nutrients have a high rate of organic material production and create eutrophic environments. Deposits formed in such contexts are dark-colored and rich in organic material that is usually of autochthonous origin. In lakes where such nutrients are less present, organic production is low (oligotrophic) and the predominant sediments are allochthonous.

In the case of the Lagoa Santa Karst, the bottoms of the dolines are the main sites of deposition in the dynamics of the karst surface relief as confirmed by the organic horizons to be found buried at the bottom of the dolines.

For sediment investigation purposes, four temporary lakes were selected, namely, Baú, Santo, Sumidouro, and Cerca Grande. The investigation of the sedimentary records in the bottoms of the karst lakes made it possible to obtain seven radiocarbon datings (Table 5). It must be emphasized that the dates obtained represent the average for all the components present in the respective sample after the latter

Table 5 Datings for organic material and charcoals buried in the soil cover of the Lagoa Santa Karst

Sample	Beta number	Site	Material	Depth (cm)	Method	Conventional radiocarbon age
TR-04	103615	Baú	Peat	168	Standard	580 ± 60 yr BP
LAGSANTOB	178557	Santo	Peat	35	AMS	430 ± 70 yr BP
LAGSANTOH	178558	Santo	Peat	145	AMS	810 ± 50 yr BP
LS-115	162531	Sumidouro	Peat	115	AMS	1,570 ± 70 yr BP
LS-275	162532	Sumidouro	Peat	275	AMS	2,630 ± 40 yr BP
CGS0NO.10-OS	159240	Cerca Grande	Peat	50	AMS	2,800 ± 40 yr BP
CGS0 N.11	159241	Cerca Grande	Peat	210	AMS	9,680 ± 230 yr BP
CGS9NO.08	159238	Cerca Grande	Charcoal	125	Standard	2,320 ± 60 yr BP
CGS10NO.09	159239	Cerca Grande	Charcoal	210	Standard	8,690 ± 140 yr BP

had undergone treatment to remove carbonates and roots. According to the information made available by Beta Analytic Radiocarbon Dating (http://www.radiocarbon.com) ages obtained for organic materials pretreated in that way always correspond to the minimum ages.

Two facies were identified in the Cerca Grande Lake (UTM 604423 E – 7841173 S) that were typical of the organic production of a lake ecosystem with datings of 9,680 ± 230 years BP (depth 210 cm) and 2,800 ± 40 years BP (depth 50 cm). Two organic facies were also identified at Sumidouro Lake (UTM 610899 E – 7838879 S) with datings of 2,630 ± 40 years BP (depth 275 cm) and 1,570 ± 70 years BP (depth 115 cm). In the perched lake at Baú (UTM 606160 E 7838200 S) the radiocarbon dating obtained was 580 ± 60 years BP (depth 180 cm). At the Santo perched lake (UTM 600882 E 7845965 N) another two facies were identified with datings of 810 ± 50 years BP (depth 145 cm) and 430 ± 70 years BP (depth 35 cm). Unlike the aspect of the facies in the Cerca Grande, Sumidouro and Baú lakes, the organic levels at the Santo Lake were distinguished by the frequent presence of charcoal showing an allochthonous origin for the organic contribution to the facies records, probably stemming from burning of the vegetation.

During the borings drilled to identify soils around the Cerca Grande Lake (UTM 604295 E 7841465 N) two horizons rich in charcoal were found, one at a depth of 210 cm dated 8,690 ± 140 years BP and the other at a depth of 125 cm dated 2,320 ± 60 years BP (Table 5).

The ages showed that at the beginning of the Holocene there were two lakes occupying dolines. It was found that the bottoms of the dolines are important sites of deposition in the Lagoa Santa Karst and the rate of sediment accumulation varies from 0.02 to 0.29 cm/year. It must be pointed out that those depositing processes are not continuous over time or space and the rates mentioned here are merely referential. It was also found that the soils may have a colluvional contribution as indicated by the charcoals buried at a depth of 2 m at Cerca Grande.

It should be noted that with the occurrence of dolines at the beginning of the Holocene the landscape would have evolved slowly without going through any great erosive processes but certainly, there would have been laminar erosion that would have supplied the material found in the dolines. The latosols would have been developing in a way quite compatible with the tropical climate for at least 10,000 yr BP.

9 Soil and Epikarst Drainage

The epikarst is the upper portion of the carbonate rocks immediately under the cover of unconsolidated material (alterites, soils, sediments, etc.) and is marked by the presence of a network of fissures (cracks) opened up by karst processes (Williams 1985; Pessoa 2005; Ford and Williams 2007). The epikarst corresponds to the vertical extension of the soils (Bakalowicz 2012).

The macroscopic and microscopic analyses of the horizons investigated by Piló (1998) and Boulet et al. (1992) make it possible to propose a hypothetical model for the drainage dynamics of the epikarst zones of the upper and middle slopes of the Karst High Plains: predominantly fast and vertical in the red horizons (rapid hydrolysis) and a slower lateral circulation in the yellowish horizons (slow hydrolysis) in contact with the epikarst. In the case of the lower slopes and the bottoms of the dolines occupied by temporary lakes, both drainage and pedological organizations are usually more complex and there may be nodular levels due to the fluctuations in the epikarst aquifer or levels with ferricrete formations, or truncation of soil horizons caused by erosion, and buried organic horizons as registered by Boulet et al. (1992) and Piló (1998).

The first thing to be pointed out is the micro-aggregated structures of the red horizons, which are typically associated with free vertical drainage. In that context, there is a well-developed (inter-aggregate) structural porosity showing

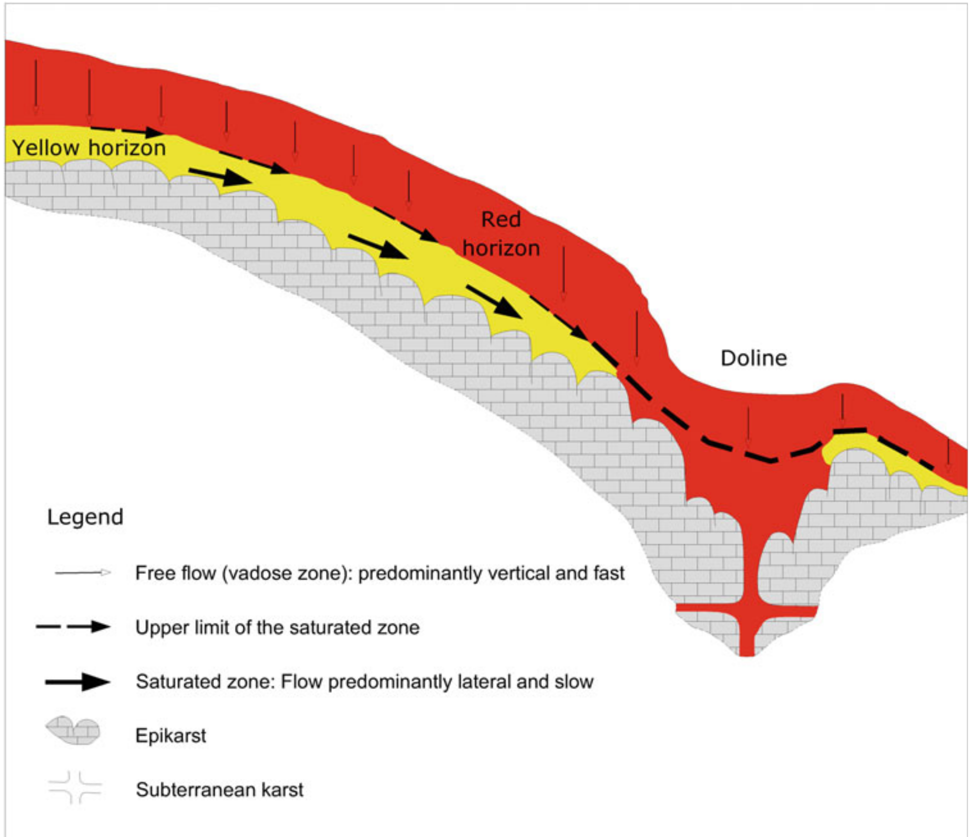

Fig. 8 Simplified model of water circulation in the soils and the epikarst in the upper and middle slopes of the karst High Plains

the possibility of the occurrence of a free internal drainage. The red horizons are also considered to be a favorable environment for the formation of hematite given the more rapid hydrolysis and the effect of ferri-hydrate dehydration processes, all of which tend to support that interpretation. The yellow horizons, on the other hand, have a much more closed microstructure between the sub-angular blocks resulting from the installation of a very fine fissural porosity. As seen above, the micro-morphological analyses clearly indicate that structural differentiation.

In that regard, after the infiltration on the slopes, the red horizons would be responsible for a flow vector that was predominantly vertical, initially associated with capillarity and then to gravity. As infiltration increases, so a fast (vertical) gravitational flow would be established in the red horizons going down to near the level of contact with the yellow horizons which would represent the top of the saturated zone. In those lower horizons, there would be a reduction in the velocity of flow as the level neared the point of contact with the epikarst and that would lead to the formation of a lateral base flow in the downslope direction.

High recharge rates in the rainy season or even resulting from other heavy rainfall events would generate an excess of the recharge water stored in the epikarst and especially in the porosities of the yellow horizons. Once the base of the soil in contact with the underlying rock becomes saturated, especially in view of the poor capacity for drainage into the underground karst, it is possible that a perched epikarst aquifer might form which would usually be of a temporary nature. In that case a slow, predominantly lateral, drainage process would occur over the surface of the rock and be eventually exported through preferential drainage routes usually facilitated by vertical and horizontal cracks that allow for the transmission of water from the epikarst to the underground karst. In the deeper part of the epikarst, the saturated zone may actually enter into contact with the karst aquifer as in the case registered by Pessoa (2005). The flows inferred above are illustrated in Fig. 8.

Ford and Williams (2007) stated that most of the chemical energy involved in dissolving the carbonated rocks is spent near to the surface because of the proximity of the main source of CO_2 production, which is the soil. The same authors report that 80% of the chemical denudation in the watershed takes place within the first 10 m of carbonate rock and the efficiency of the dissolution gradually diminishes as the distance from the surface (and the source of CO_2) increases. Water dynamics in the epikarst represent a mechanism that is essential for the development of the surface karst and the underground karst as well (Bakalowicz 2012). In the Lagoa Santa Karst, large volumes of red and yellow

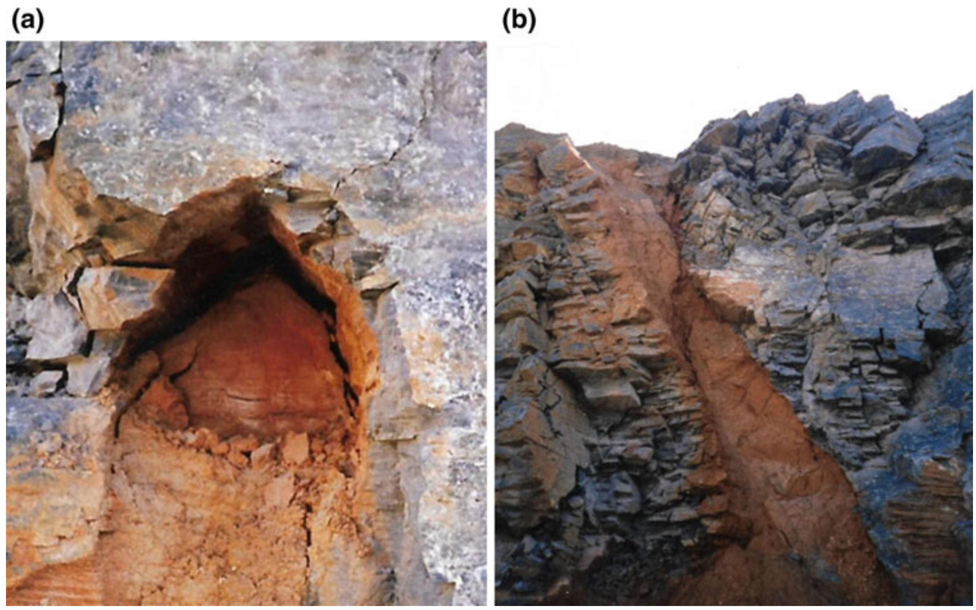

Fig. 9 Sites of mining/quarrying activity exposing red and yellow soils introduced into the underground karst

soils have been introduced into the underground karst, via the epikarst (Fig. 9) directly influencing the paragenesis processes which are frequent in the region's caves and also playing a role in the dominant anastomotic (Palmer 1991) pattern in them.

Because of its soil cover, the observation of the epikarst is difficult. However, the areas where the cover has been removed by limestone quarrying serve as good points for analyzing the epikarst morphology. It is very apparent that the yellow soils predominate in the zones of contact with the epikarst while the red soils are more superficial. However, it is possible at times for the red soils to be in contact with the epikarst.

The larger shapes are measurable in meters and represented by a sequence of residual shapes of the pinnacle type. In the top areas, they form a set that is less individualized and more labyrinth-like. The further down the slope one goes, the more individualized those shapes become. Given that description, the karst is a typical example of a covered pinnacle-type karst (Fig. 10a). The rounded tops of the pinnacles follow the slope of the surface.

Micro-shapes groove the covered epikarst and define four different typologies for the karrens of soil covered karst. Karrens in which the joints are horizontal are the most frequently found showing plan-parallel grooves measurable in

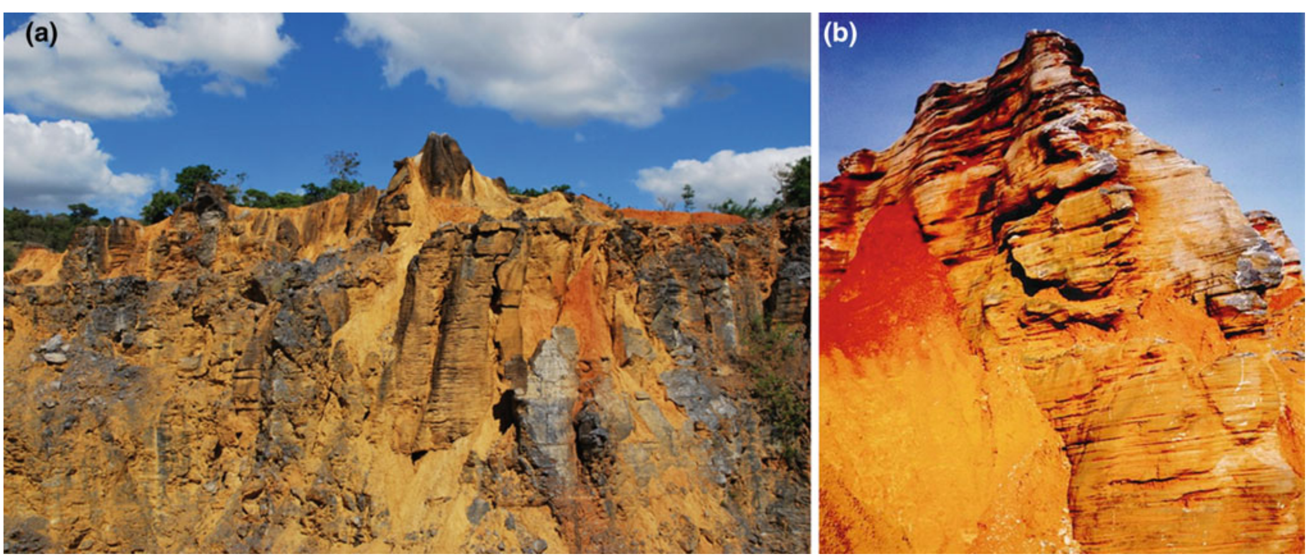

Fig. 10 Epikarst exposed by limestone quarrying showing the main forms elaborated in the sub-surface: pinnacles (**a**) and karrens with horizontal joints (**b**). Figure 10b shows how the karrens are more developed in contact with the red soils

millimeters or centimeters and following the well-marked foliation of the rock (Fig. 10b). Alveolar karrens are made up of small horizontal cavities with sizes ranging from a few millimeters to a few centimeters. Such pockets left by dissolution are usually set out in an East–West direction which is the orientation of the mineral lineation and/or stretch developed in the foliation plane of the rock. It was also found that they usually begin in the horizontal joints. Kamenitzas were also found especially on the tops of the pinnacles. They are closed basins in the rock a few centimeters wide and high.

In the light of the profiles of the soils in contact with the karst's lateral walls, it was possible to show that the karren are more highly developed in the surfaces in contact with the red soils than in those in contact with the yellow soils (Fig. 10b). That is due to less intense hydrochemical dynamics in the contact with the yellow soils and that is corroborated by the microstructure and the porosity micro-morphologically observed in the thin section.

The slow drainage rate in the yellow horizons in contact with the limestone rock is what would be responsible for the elaboration of such a well-developed epikarst relief in the Lagoa Santa Karst High Plain especially in view of the time of residence of infiltration water rich in CO_2.

Those morphologies are indicative of a more dynamic zone of the local karst. In that zone of contact between soil and epikarst, with its great lateral extension, the water circulation is more effective for karst formation than in the superficial zones and is actually the main mechanism lowering the karst relief as well as being the main driver of superficial and subterranean karst dynamics.

10 Conclusions

The soil horizons studied in the toposequences were relatively parallel to the topographic surface with no apparent current (lateral) transformation fronts and therefore represent a system of vertical transformation of the substrate into the soil. Such features have been interpreted as representing a state of equilibrium of the morphogenesis and pedogenesis with the currently stable climatic and tectonic conditions.

Analyses of the macro and micro-morphology of those main toposequence horizons clearly indicate the differentiation of structures between the red horizons and the yellow ones and it can be deduced that the yellow horizons are at a less evolved stage of pedogenesis than the red ones. Furthermore they make it possible to deduce an internal drainage model for the soils in the high and middle slopes: fast vertical drainage in the red horizons (rapid hydrolysis) in the more superficial positions and lateral drainage along the zone of contact between soil and epikarst in the base of the yellow horizons (slow hydrolysis). On the other hand, the analyses also make it reasonable to propose the hypothesis that the red soils originate from the yellow ones and the presence of relics of yellow material in the mass of red latosol tends to corroborate that.

The epikarst relief was found to be well developed and formed by covered pinnacles thus testifying to a karst formation process more expressive than in the surface and underground karst. The current general geometry of the upper and middle slopes of the Karst High Plains reflects the development of the epikarst.

The red and yellow horizons derive from the same material of origin which is the source of the continuous pedological cover on top of the limestone rocks. That material, in turn, corresponds to the alteration and pedogenesis of meta-siltites and meta-argillites of the Serra de Santa Helena Formation which, in the stratigraphic sequence, are situated on top of the limestone rocks of the Sete Lagoas Formation corroborating the reports of various other authors. The altered metapelites evolved into red mono-sialithic/ferralithic (oxidic) latosols by means of a vertical transformation system in the climatic conditions that prevailed in the Quaternary period, especially the Holocene epoch. The dolines are therefore more recent than the latosols that they have truncated, controlled by the underground karst but re-capped by the sediments coming from the lateral removal of the latosols. Thus, the contribution of the limestone is insignificant in the pedogenetic evolution of the region considering that the limestones consist of more than 95% of $CaCO_3$, whereas the clay content of the soils and their mineralogical assemblages are incongruent with those characteristics, especially in such a short time as the Holocene.

Given the expressive introduction of volumes of soil via the epikarst into the underground network, there is an increase in the clastic sedimentary dynamics in the conduits, influencing the morphology patterns of the caves and favoring paragenesis. The materials that fill the cave passages also suggest that their two main sources are the two latosol horizons, which shows that the extinct megafauna remains were deposited along with those materials especially through the bottoms of the dolines. The deeper closed depressions represent the points of greatest hydric flows to the underground karst (accelerated dissolution) with an important introduction of cover material into the underground karst and the configuration of the surface concavity of the slopes (doline formation) and the outcropping of limestone cliffs at the same time as the morpho-pedogenesis of the interfluvium covered by the latosols.

The studies have revealed that the karst modeling of the Lagoa Santa Karst High Plains evolved in the light of a set of inter-relations involving the epikarst, the superficial karst and the underground karst thereby reinforcing the idea of a coupled system with special importance attributed to the soil cover. At the same time, that indicates incompatibility with the idea that the limestone rock is the source material but nevertheless, it does condition an evolution of the surface and subterranean landscapes favored by the contact between the soil and the limestone substrate.

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