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Research Article

The geochemistry of the pedogenized coverings of the Dissected Plateau of the Uruguay River – States of Santa Catarina/Rio Grande do Sul, Brazil

Geoquímica das coberturas pedogenizadas no Planalto Dissecado do rio Uruguai – Santa Catarina/RS, Brazil

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Abstract: Superficial deposits constitute an important sedimentary record with data that may be indicative of current and past environmental conditions. With the aim of analyzing the degrees of weathering affecting pedogenic surface formations and establishing relationships between pedological and geomorphological factors in the genesis and transformation of natural landscapes, this study investigated physical and geochemical evidence of 22 weathering mantles (pedogenized coverings) in Volta Grande, an upper valley stretch of the Uruguay River on the border between the states of Santa Catarina and Rio Grande do Sul, Brazil. Sedimentary and pedogenic materials were sampled from lower and middle/upper slope positions. Morphological descriptions of pedological profiles, particle size analyses, and ^{14}C and OSL dating analyses substantiated the analyses of these materials. The study also resorted to geochemical analyses (Ki and STI indices) of pedogenic horizons representative of the study area's weathering mantles, geomorphologically represented by the Dissected Plateau of the Uruguay River. The results indicate that, regarding the context of active morphogenesis of the upper Uruguay river valley, the studied pedogenized coverings show a low degree of weathering in the soil profiles sited at lower and upper slope positions, including hilltops and alluvial plains. This situation is consistent with the context of pedological rejuvenation during the entire Holocene, without, however, significant morphological and textural differentiation from the predominantly silty clay deposits.

Keywords: Uruguay River; pedogenesis; weathering rates; paleoenvironment.

Resumo: As coberturas superficiais constituem importante registro sedimentar que contém dados potenciais como indicadores das condições ambientais atuais e pretéritas. Com o objetivo de analisar os graus de intemperismo das formações superficiais pedogenizadas e estabelecer relações entre fatores pedológicos e geomorfológicos na gênese e transformação da paisagem natural, neste trabalho foram investigados indícios físicos e geoquímicos de 22 mantos de intemperismo (coberturas pedogenizadas) da Volta Grande, trecho do alto vale do rio Uruguai na divisa entre os Estados de Santa Catarina e Rio Grande do Sul. Foram amostrados materiais sedimentares e pedogenizados em posições de baixa e média/alta vertente. As análises foram baseadas na descrição de características morfológicas de perfis pedológicos, análises granulométricas, datações de ^{14}C e LOE e análises geoquímicas (índice Ki e STI) de horizontes pedogenéticos representativos do manto de intemperismo da área de estudo, representada geomorfologicamente pelo Planalto Dissecado do rio Uruguai. Os resultados obtidos demonstraram que no contexto de morfogênese ativa do alto vale do rio Uruguai as coberturas pedogenizadas apresentam baixo grau de intemperismo em posições de baixa e alta vertente, incluindo os ambientes de topo e planície aluvial. Tal situação é condizente com um contexto de rejuvenescimento pedológico ao longo de todo o Holoceno, sem, no entanto, diferenciação morfológica e textural significativa das coberturas predominantemente argilo-siltosas.

Palavras-chave: rio Uruguai; pedogênese; índice de intemperismo; paleoambiente

1. Introduction

Features and evidence related to regolith deposits and pedological coverings, such as their spatial distribution, the nature of their constituent sediments and the associated relief forms thereof have been resorted to as important principles in numerous studies seeking to interpret past environmental conditions of continental landscapes (BIGARELLA and MOUSINHO, 1965a,b; PAIN and OLLIER, 1996; THOMAS, 2000; 2008; GODARD; SIMON-COINÇON and LAGASQUIE, 2001; MELO et al., 2005; LEOPOLD and VÖLKEL, 2007; GUERRA and PAISANI, 2013). The sediments themselves and their organization reflect modes of operation of occurring processes which can provide clues about how these sediments behaved in the past in what regards the existing weather conditions and erosion, and how such a behavior proceeded (BIGARELLA and MOUSINHO, 1965a,b; PEDERSON, PAZZAGLIA and SMITH, 2000). It is broadly recognized that climate changes led to erosion and sedimentation alterations in the Pleistocene-Holocene transition, producing distinctions in the sedimentary package formed at bottoms of valleys in several places on various continents (STRAHLER, 1974; PAIN and OLLIER, 1996; STEVAUX, 2000; THOMAS, 2000; MELO et al., 2005; CHAMPAGNAC, VALLA and HERMAN, 2014). In many places, this transition was marked by large floods, incision and deposition of coarse sediment; but as the Holocene climates stabilized and fluctuations of runoff reduced in amplitude, meandering rivers developed floodplains with thick overbank silts and clays (THOMAS, 2000, p. 23).

The fluvial stretch of Volta Grande in the upper Uruguay River has attracted great attention, from an archaeological point of view, because older dates of land occupation have been estimated for the state of Santa Catarina and for the southern region of Brazil in what regards the first human settlements in the South American continent. The ^{14}C dates calculated from sediment collected from the Uruguay River banks in western Santa Catarina indicate an approximate age of 12,000 cal. yr BP, situating in time the oldest so far known human settlement in the area, in the Pleistocene-Holocene boundary (LOURDEAU et al., 2014; 2016; SANTOS et al., 2021). Together with an archaeological interest, through research partnerships, there emerged an interest in investigating evidence that could clarify the paleoenvironmental context. In this vein, this study presents results and interpretations based on physical and geochemical analyses of materials and pedogenized coverings, pedogeomorphologically characterizing the slopes in the upper valley of the Uruguay River and the Dissected Plateau of the Uruguay River, in western Santa Catarina and northwestern Rio Grande do Sul, Brazil. This study primarily aimed to analyze the degrees of weathering of surface formations and establish relationships between pedological and geomorphological factors regarding the genesis and transformation of the natural landscape.

Several authors have, at least implicitly, supported the idea that the soils on the top surfaces of the Brazilian Plateau, with more intensely weathered materials, are older than the soils found in the lowered compartments. Motta et al. (2002) characterized the pedogenized coverings of the South American Surface, as coined by King (1956), near the city of Goiânia, state of Goiás, Brazil – Central Plateau – as very clayey Oxisols and with very low weathering rates (Ki index), thus attesting that old planation surfaces are related to deep and highly weathered pedological coverings. The exploratory soil association survey of the Dissected Plateau of the Uruguay River, to the south of Laranjeiras do Sul, covers expressive areas of Oxisols which almost always occupy the most conserved positions in the relief (RADAM, 2018, p. 450). It is also worth noting that the older the weathering mantle, the finer its texture is (HARDEN, 1982), and generally quite clayey, as is typical of highly weathered soils.

The geological-geomorphological context of the upper Uruguay River valley, considered in this study, is the one that results from the Mesozoic basaltic lava flows that occurred during the "South-Atlantian Event", with a climax between 133 and 129 Ma (RENNE et al., 1992; MARQUES and ERNESTO, 2004). The post-flow context was the initial scenario for the development of weathering mantles originated from basalt in the southern portion of the Paraná Basin (RIFFEL et al., 2016), emcompassing as well western Santa Catarina and northwestern Rio Grande do Sul.

These pedogenized weathering mantles are the result of several changes in the landscape from the interaction between geological-tectonic, climatic, geomorphological and pedological factors. Discerning to what extent each of these factors is more or less important in the genesis and transformation of weathering and relief mantles is the real challenge in what concerns the knowledge about the evolution of terrestrial landscapes. Clearly, there is a consensus on the idea that soil-mantled landscapes are the result of the balance between pedogenesis and erosion, which are two of the most important processes in shaping such landscapes (BÜDEL, 1957; DOSSETO; BUSS; SURESH, 2012).

2. Study Area

The analyses and interpretations carried out in the present study drew on pedogenic sediment samples collected from the region of Volta Grande, meandered by the Uruguay River in its upper course, on the border between the States of Santa Catarina and Rio Grande do Sul, Brazil (hydrographic region of upper Uruguay River). On the banks of the river, in an alluvial plain area, there are archaeological sites that attest to two pre-colonial settlements in the area: the oldest related to peoples belonging to hunter-gatherer groups (lithic materials) and the most recent belonging to the Tupi–Guarani archaeological tradition (ceramic materials) (LOURDEAU et al., 2016; CARBONERA et al., 2018; SANTOS et al., 2021). The sediments analyzed in this study (Figure 1) were sampled from pedogenized coverings sited at upper, middle and lower slope positions, between 200 and 500 meters of altitude.

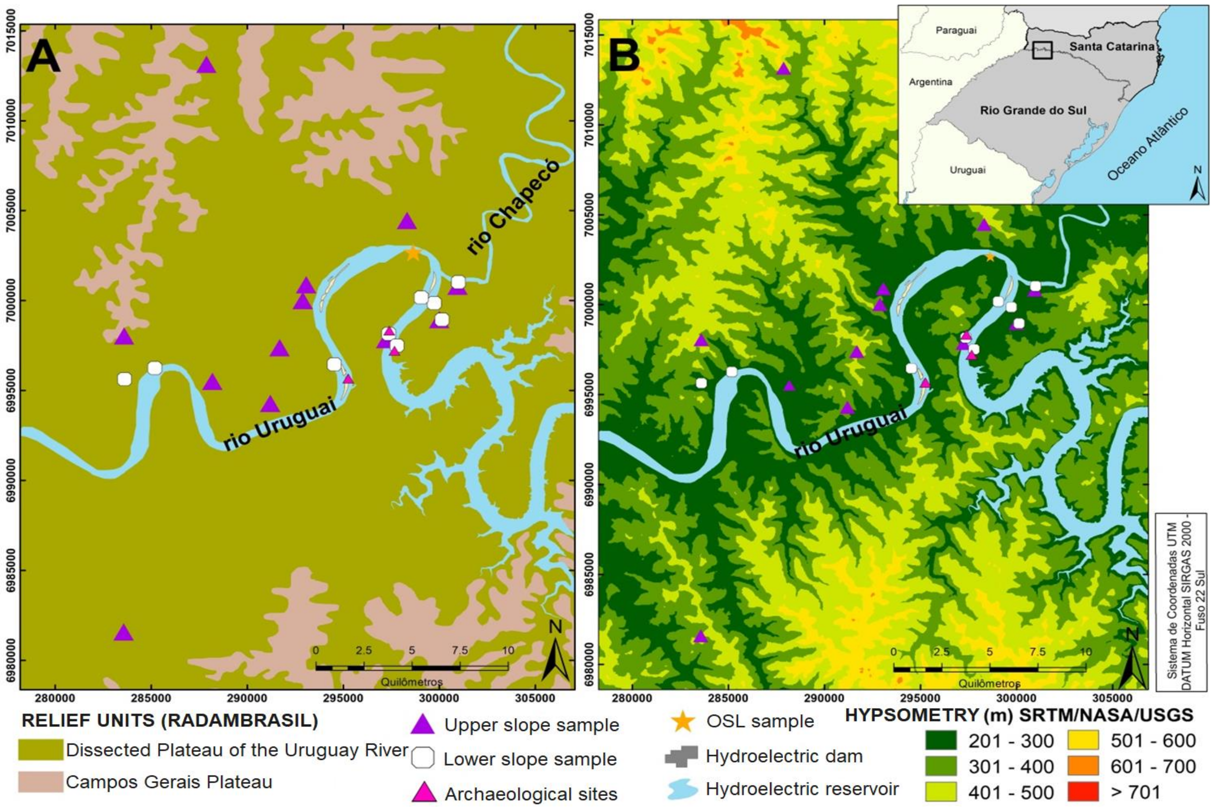

Figure 1. Geomorphological (A) and altimetric (B) context and location of the samples collected in the Volta Grande region of the Uruguay River.

Geologically, the entire area encompasses the Serra Geral Formation (Early Cretaceous) with basalts belonging to the Paranapanema Formation, with gray microgranular texture, changes in brownish red columnar joint faces, thick vesicular horizons filled with quartz (ammethyst), zeolites, carbonates, celadonite, native copper, and barite (CPRM, 2014). According to Dias and Parisi (2007), the various lava flow sequences have great textural and, mainly, compositional uniformity.

In structural terms, basaltic rocks are quite fractured, presenting main fault/joint systems according to the N – W and NE – SW directions, verticalized or with strong dips related to tectonic processes. The large NW, NE and EW tectonic alignments developed since the end of the Mesozoic Era are widely recognized in the literature for the central-southern region of Brazil (SANTOS et al., 2008). As regards drainage, these fractures tend to condition straight watercourse stretches and accentuated elbows (ENGEVIX, 2000). Such fracturing tends to influence weathering intensity, which acts more deeply along the local faults/joints, forming deeper soils (ENGEVIX, 2000). Still in the realm of lithology, another aspect worth stressing is the spheroidal weathering of basalt, common in the study area, which, as a rule, is associated with a dense and regular pattern of fractures (DIAS and PARISI, 2007).

From a geomorphological perspective, the study area is inserted in the geomorphological domain of the Meridional Plateau (MONTEIRO, 1968) or the Araucárias Plateau (IBGE, 2003a), locally marked by incised and steep valleys that configure the lowered geomorphological unit called the Dissected Plateau of the Uruguay River (RADAM/IBGE, 2018), in an active process of morphogenetic elaboration (BERTOLINI; DEODORO and BOETTCHER, 2019). The altimetric upper level of the study area is given by the surface of the geomorphological unit of Campos Gerais Plateau (IBGE, 2003a) (Figure 1), which comprises of elevated surfaces of flat or slightly convex tops, supposedly associated with remnants of old planation surfaces (KRÖLING et al., 2014).

These surfaces are, in general, above 400 m in altitude. The geomorphological unit of the Dissected Plateau of the Uruguay River internally also presents convex tops above 400 meters in altitude, steep slopes, and embedded valleys with an incision depth in the order of 171 to 250 meters (IBGE, 2005). The base level represented by the Uruguay River in the area is at about 220 meters of altitude. Its alluvial plain is discontinuous with stretches that are sometimes more restricted or even non-existent, and sometimes more extended. The accentuated and steep sites of unevenness that separate one plateau compartment from the other, especially along the Uruguay River valley, are pointed out as erosive escarpments by IBGE (2003a) in an updated version of RADAM BRASIL geomorphological mapping.

The average annual rainfall of the study area is 1732 mm, according to an Environmental Impact Assessment carried out by the Foz do Chapecó HPP (ENGEVIX, 2000), which used data from the rainfall station in the municipality of Palmitos, SC, Brazil. The average annual temperature is 19.1 °C in Volta Grande, with a maximum of 31.5 °C in the coldest month (July) and a minimum of 8 °C in the hottest month (January) (ENGEVIX, 2000).

In general, pedological coverings pertaining to the Dissecado Plateau of the Uruguay River can be characterized as shallow and moderately to extremely stony (EMBRAPA, 1998). Coverings of higher surfaces and altimetric levels pertaining to the Campos Gerais Plateau have greater depths and higher clay contents, being classified as oxidic coverings (EMBRAPA, 2014; OLIVEIRA; SOARES; PONTELLI, 2019). Fields of basalt boulders in high slopes and in the body of soil are also not uncommon. Almeida et al. (2018), regarding three toposequences originating from basalt in western Santa Catarina, attested to clayey fractions mineralogically represented by kaolinite, followed by variable proportions of smectite with or without aluminum hydroxide interlayers, goethite and/or hematite and very little or nothing of gibbsite.

The exploratory soil survey conducted by the RADAM BRASIL Project (1980s) showed that along the Dissecated Plateau of the Uruguay River there are soil associations in which eutrophic Inceptsols, eutrophic Entisols, and (purple and brown) Oxisols stand out, the latter occupying the top portions in this geomorphological unit (EMBRAPA, 1998; RADAMBRASIL/IBGE, 2018, p. 450).

2. Materials and Methods

The empirical approach underlying the pedogenic sediment analysis drew on collection of representative samples from the weathering mantle (pedogenized coverings) sited at lower slope positions, including river plains, and upper slope areas, including hilltop surfaces, supposedly representative of alteration mantles that are ancient and deep. A total of 26 samples were analyzed with regard to: horizon/pedological layer, thickness, particle size, %SiO_2, %Fe_2O_3, %Al_2O_3, %TiO_2, %MnO, the Ki, Kr and STI indices, and orthometric altitude. Particle size and geochemical analyses were performed with samples taken from the average depth of each of the studied horizons. The altitude measurements taken with GPS at the surface of the relevant pedological profiles were corrected according to the geoid undulation model (MAPGEO, 2015) that provides the factors to convert altitudes given by GNSS receivers (GPS) to obtain orthometric height values resulting in altitudes compatible with the terrestrial gravity. To compare the means for the main oxides and rates mentioned above, the statistical Student's t test was applied for independent samples and at a significance level of 0.05, upon previous verification and data normality test using the Shapiro-Wilk's test. The tests were conducted in Excel® using the Real Statistics Resource Pack add-in.

For the particle size analysis, 20 g of TFSA and sodium hydroxide (NaOH) at a concentration of 1.5 mol/L were used as a deflocculant, followed by reciprocating agitation for 16 hours. The pipette method was used, and calculations were made according to Ruiz (2005).

As soils evolve, their mineral composition begins to depend more on the weathering environment than on their source material composition. For this reason, the associations of clay minerals in soils are considered indicators of the degree of their development (KAMPF; CURI; MARQUES, 2009, p. 351). In this regard, analyses of the fine fraction samples were carried out using the sulfuric acid attack method to determine the percentages of Fe, Al, Si, Ti and Mn, as well as analyses of the stages of evolution and weathering of the soil profiles from which these samples were taken. Basically, the sulfuric acid attack method consists in solubilizing soil samples with H_2SO_4, aiming at the determination of molecular relationships (Ki and Kr), which allows for the evaluation of soil weathering stages (DONAGEMA et al., 2011). The sulfuric extract produced with this ionic strength allows assuming that only secondary minerals (clay minerals, oxides, and hydroxides) are dissolved, and thus the percentages of Fe, Al, Si, Ti are close to those of the colloidal fraction of the soil (DONAGEMA et al. 2011, p. 140). The samples were analyzed at the ESALQ/USP laboratories in the city of Piracicaba, state of São Paulo, Brazil. For SiO_2, determination was based on extraction by $NaOH_2O$ solution and gravimetric analysis; for Al_2O_3, EDTA-complexometry; for TiO_2, the colorimetric method through organic matter oxidation; for Fe_2O_3 and MnO, extraction by sulfuric acid attack (H_2SO_4 50%).

The Ki index is calculated as a function of the values, expressed in %, of SiO_2 and Al_2O_3, according to Eq. (1):

$$Ki = \%SiO2\ x\ 1{,}70 / \%Al2O3 \tag{1}$$

The Kr index is calculated as a function of the values, expressed in %, of SiO_2 and Al_2O_3 + Fe_2O_3, divided by their respective molecular weights, according to equation a Eq. (2):

$$Kr = \frac{\%\frac{SiO2}{0{,}6}}{\%\frac{Al2O3}{1{,}02}} + \left(\frac{Fe2O3}{1{,}60}\right) \tag{2}$$

The Ki and Kr values, considered as weathering rates, represent the quotient of the division of a highly mobile element – silicon – in relation to two others with low mobility – aluminum and iron (LEPSCH, 2011). Therefore, values equal to or less than 2.0 for these indices are indicative of advanced weathering stages. And values greater than 2.0 are indicative of less advanced weathering stages (MELFI and PEDRO, 1977; LEPSCH, 2011). Ki values greater than 2.0 also indicate the occurrence of 2:1 clays, such as montmorillonite and vermiculite, and Ki values below 2.0 indicate that part of the aluminum in the soil is free in the form of oxides, demonstrating a process of weathering that has been active for a long time (LEPSCH, 2011). Additionally, still regarding weathering, the silica-titanium index (STI) was calculated. It is an index that measures weathering based on the rates of the least mobilized elements of the weathered material (silica and titanium). The lower the value of this index, the greater the degree of weathering (TABOADA et al., 2016).

Radiocarbon ages were determined from coals found in the middle of the pedological covering of the alluvial plain at the archaeological site, on the right bank of the Uruguay River (ACH-LP-7), corresponding to point P2 (Table 1). Such coals are associated with horizontalized and non-remobilized archaeological levels (LOURDEAU et al., 2016). The ^{14}C samples were collected from a depth that ranged between 0.35 and 1.65 meters from the surface. The dates were calculated at the Climate and Environment Sciences Laboratory in Gif-sur-Yvette, France, for the ACH-LP-07 site. The dates were calibrated using the OxCal software (Bronk Ramsey and Lee, 2013) according to the IntCall13 calibration curve (REIMER et al., 2013).

The study also performed optically stimulated luminescence (OSL) dating of alluvial sediments located on the left bank of the Uruguay River (298,653 long UTM/7,002,672 lat UTM) downstream of the 14C samples. For such OSL dating, the sample was collected at a depth of 2.85 meters below the current surface of the plain. Dose rate was estimated by gamma spectrometry with an HPGe detector and ultralow-background shielding. Equivalent dose was determined by the SAR protocol in quartz multigrain aliquots. OSL measurements were performed in a Lexsyg Smart reader equipped with a beta radiation source (Sr/Y) with a dose rate of 0.118 Gy/s. The preparation of quartz aliquots involved: (i) wet sieving to acquire the 180-250 μm fraction; (ii) attack with H2O2 to remove organic matter, attack with 10% HCl to remove carbonates; (iii) density separation of heavy and light minerals (LMT = 2.75 g/cm3) and separation of quartz (LMT = 2.62 g/cm3); (iv) attack with 38% HF for 40 min to eliminate the outer layer of the remaining grains of quartz and feldspars. The equivalent dose of the sample was calculated using the Central Age Model (CAM). Only aliquots with a recycling ratio between 0.9 and 1.1, recovery less than 5% and no contamination by feldspar (IR signal) were considered to calculate the equivalent dose. The dose recovery test was performed on the sample (5 aliquots, pre-warmings of 220 °C and 180 °C, administered dose of 15 Gy). Photoemptying was done in a Lexsyg Smart reader. The ratio between calculated and administered doses was 1.00 ± 0.01.

3. Results and Discussion

3.1. Dating by ^{14}C and OSL

The ^{14}C dating analyses of the pedogenized coverings near the archaeological sites on both riverbanks attests to ages ranging from 12,000 cal yr BP to the present. Regarding the right bank (site ACH-LP-07 – Figure 2), calibrated dates (2^{δ}) were obtained, ranging between 11,500 – 11,250 cal yr BP and 9,560 – 9,470 cal yr BP. Based on the approximate 2-meter thickness of the fluvial portion sampled from the right bank, dates were grouped into different periods, namely: 12,000 to 11,400 years; 11,400 to 11,000 years; 11,000 to 10,400 years and 10,400 to 9,400 years. However, from a particle-size and morphological perspective, there are no significant differences along this portion's thickness, except for the surface sandy levels, signaling the last floods in the channel. Such homogeneity suggests that, at least in this stretch of plain close to the archaeological site, the pedogenetic process of the weathering mantle in fact took place, on an equal footing to the hydrological regime of the Uruguay River, without major disturbances during the Early Holocene. Radiocarbon ages from undisturbed archaeological levels truly indicate the chronological correlation of said pedological covering with the Early Holocene (LOURDEAU et al. 2016).

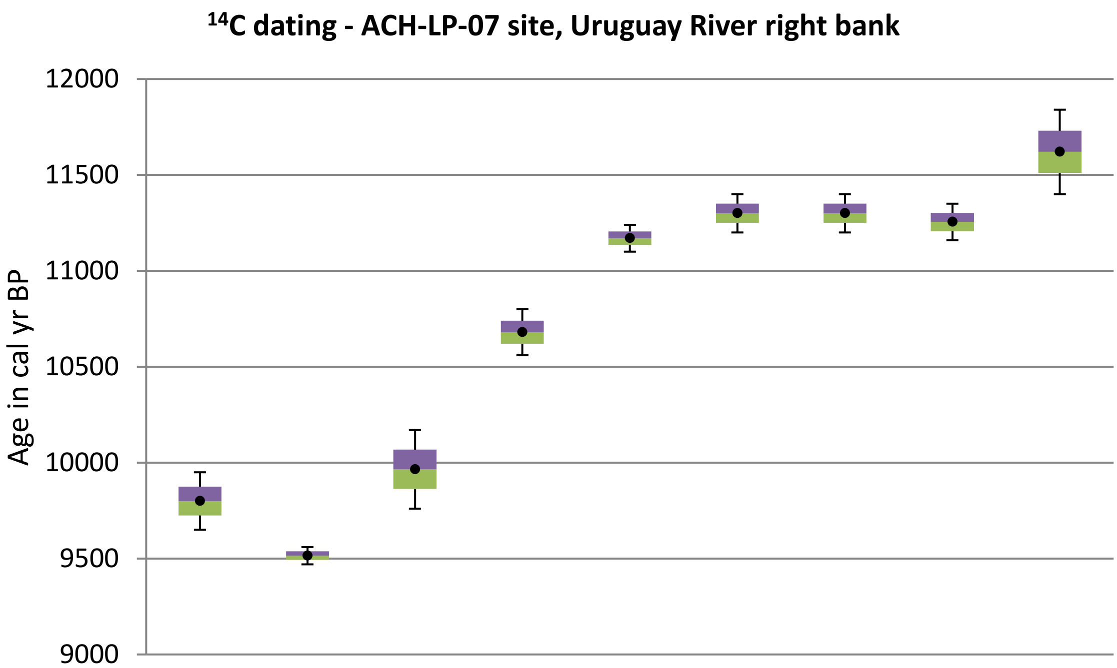

Figure 2. ^{14}C dating analyses of the right bank of the Uruguay River near the archaeological site ACH-LP-07 (municipality of Águas de Chapecó, SC, Brazil).

The OSL dating of quartz grains in the Uruguay River plain attests to an age of 16,169 ± 1,145 years, traditionally associated with a cold and dry climatic period (IRIONDO and GARCIA, 1993; GUPTA, 2011), corresponding to the Last Glacial Maximum. Therefore, it should be considered that the pedogenized covering of the studied plain demonstrates a process of progressive pedogenesis (PHILLIPS, 1993) influenced by erosion and intermittent fluvial deposition, under conditions of a climate colder than the current one, and prior to the Pleistocene/Holocene transition to present days.

All the ^{14}C dating analyses performed attest to the constituent nature of the sedimentary package of the Uruguay River plain that occurred over the last 12,000 years, therefore dating back since the Pleistocene-Holocene transition. The OSL dating extends this temporality yet keeping it within the dry and cold climatic phase associated with the effects of the Last Glacial Maximum. The lack of clear differentiation in morphological and textural terms in the pedogenized sedimentary package tends to indicate a rather continuous process according to a low hydrodynamic energy fluvial regime that did not leave marks of major changes in the sedimentary record of the Uruguay River plain in the region of Volta Grande.

3.2. Particle size, geochemical and weathering analyses

Ten pedogenized lower slope coverings were considered in the study, totaling fourteen samples. Of these fourteen samples, eleven were collected from an alluvial plain environment and two from a position outside the greater bed. The latter two, although of a different nature, did not represent a change in the t test for comparison between the means of the analyzed parameters, which is why they were treated within the same set of lower slope samples. The sediments are relative to horizons B and BC for the plains, and horizons A and AB for the samples outside the alluvial plain, varying within an altimetric range between 209 and 233 m. For the upper slope position, twelve pedogenized coverings were sampled, varying between 229 and 473 meters in altitude, totaling, in this case, fifteen samples related to pedogenic horizons B, BC and C (Table 1).

Table 1. Morphological and textural data of the analyzed samples

Slope Position	Point (site)	Horizon/ Depth (cm)	Orthometric altitude (m)	Sand (%)	Silt (%)	Clay (%)	Textural Soil Classification - USDA
Lower slope and alluvial plain	P1	B1 60 - 77	226	15,75	38,76	45,50	Clay
		B2 78 – 300+		9,94	46,84	43,22	Silty clay
	P2	B1 31 - 76	225	47,23	13,58	39,20	Sandy clay
		BC 158 - 190		42,39	12,78	44,83	Clay
	P7	B 213	225	18,06	48,54	33,40	Silty clay loam
	P6	B2 101 – 140	228	11,84	56,06	32,10	Silty clay loam
		B3 141 - 190		16,34	80,90	2,76	Silt
	P13	B 110 - 120	212	12,82	22,16	65,02	Very clayey
	P28	BC 70 - 80	233	12,19	79,2	8,61	Silty loam
	P36	B 70 - 80	222	9,30	34,20	56,51	Clay
	P61	B1 70 - 137	230	0	52,22	47,78	Silty clay
		B2 200		3,01	38,48	58,52	Clay
	P80	A 10 - 20	231	42,22	33,51	24,26	Franca
	P81	AB 20 - 25	209	21,47	47,62	30,92	Clay loam
Middle/upper slope and hilltop	P3	B 10 - 56	229	4,19	31,8	64,01	Very clayey
	P37	BC 34 - 105	265	12,14	42,11	45,75	Silty clay
	P27	BC 21 - 38	248	30,53	50,13	19,34	Silty loam
	P15	B 60 - 70	284	19,77	39,82	40,41	Clay
	P20	B 36 - 105	261	14,31	15,93	69,76	Very clayey
	P32	AC 0 - 45	400	46,52	27,5	25,98	Loam

	C1 46 - 70		45,44	26,84	27,72	Clay loam
	C2 71 - 140		56,35	22,26	21,39	Sandy clay loam
P59	B 120	473	16,14	23,77	60,10	Very clayey
P73	BC 75 – 140	417	16,21	38,56	45,23	Clay
P82	B 5 - 15	404	27,78	23,99	48,23	Clay
P108	A 0-5	245	9,77	34,74	55,49	Clay
P110	B1 30-70	365	23,55	19,22	57,24	Clay
	B2 71 - 128		18,53	21,18	60,28	Very clayey
P111	B 50-60	408	10,76	29,82	59,42	Clay

The textural classification of the samples allowed recognizing pedogenized weathering mantles of fine texture, with a predominance of clay and silt (Figure 3).

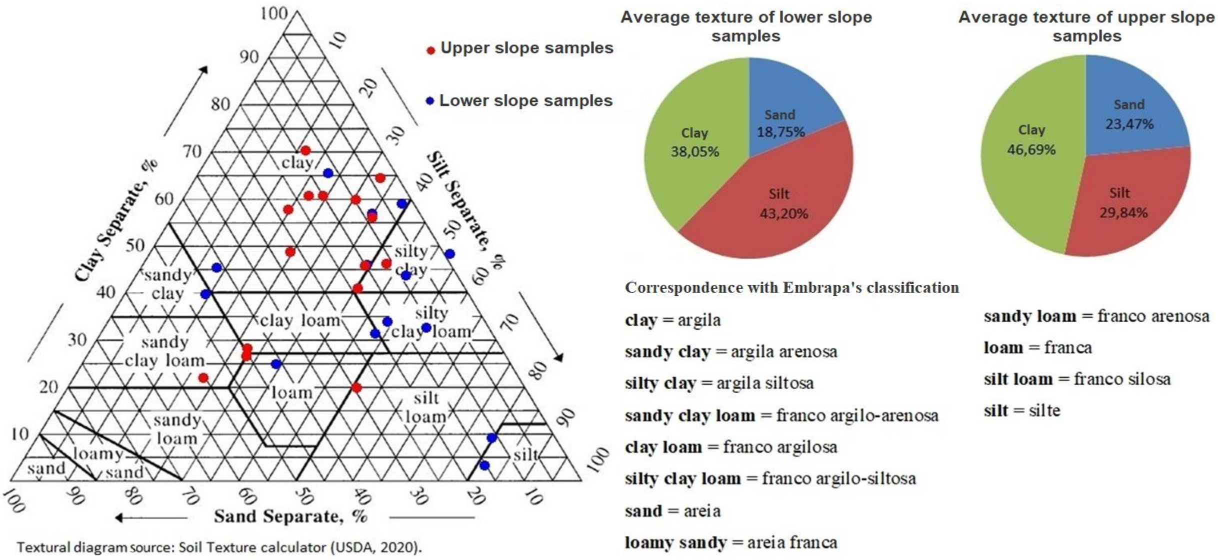

Figure 3. Textural diagram and average texture of the lower and upper slope sample sets – Dissected Plateau of the Uruguay River

Silt stands out with a higher average proportion in the set of lower slope samples, while in the set of upper slope samples it is clay (Figure 3). Such a higher proportion of clay in the upper slope samples points to mantles that underwent a greater deal of weathering, in comparison with the lower slope samples. The significant presence of silt in coverings derived from mafic rocks, such as basalt, is common (RESENDE et al., 2011). The role of flooding in the channel can particularly influence the accumulation of silt in certain bank stretches, depending on the relief and speed of regression of water into the channel. The lower slope pedological coverings in Volta Grande can be understood as mixed colluvial-alluvial (especially within the alluvial environment) and eluvial-colluvial (outside the alluvial environment), with a predominance of clayey textures for the upper slope samples and a relative greater heterogeneity for lower slope samples due to the relocation and transport of materials by overland flow and river runoff.

Gravels and pebbles (fraction > 2 mm) are particularly common in middle- and upper-slope weathering mantles and have a lower degree of rounding as greater the particle size is, and sometimes greater concentration at different depths in the weathering mantle and ease of dismantling in the preparation of air-dried fine earth (ADFE), hence a material of low strength and from recent matrix rock alteration. In sandy fractions, the presence of magnetic minerals with a dark color and metallic shine (magnetite/titanomagnetite) is considerably common.

The geochemical analyses, mainly the ones representative of soil horizon B of the studied pedological coverings showed very similar mean Ki values for the set of upper and lower slope samples: an average of 3.69 for the lower slope samples and an average of 3.25 for the middle/upper slope samples. Only two upper slope samples presented Ki values smaller than 2.0 (equal to 1.6), indicative of a covering under a more advanced stage of weathering. However, given the predominance of Ki indices above 2.0, it can be said that the top- and bottom-valley coverings prove to be young and little weathered, although there may still be remnants of older coverings in the landscape attested to by Ki values below 2.0. The proximity of the middle/upper slope coverings to the basaltic rock corroborates the assertion that they are young (Figure 4). The Ki variation for the lower slope samples was 2.85 between the lowest and the highest index, while for the middle/upper slope samples it was 3.35. Still concerning the middle/upper slope samples, it is worth stressing that those referring to hilltops, equal to or above 400 meters of altitude, presented Ki values greater than 2.0, except for the two points previously mentioned.

Figure 4. Basaltic rock close to the surface, under a pedogenized colluvial covering at a hilltop position at about 400 meters of altitude

The Kr index, in the same way as the Ki index, demonstrates the degree of weathering of a given material. However, Kr regards the sum of the proportions of the two least mobile elements, aluminum and iron, and not just aluminum as in the Ki index. The arithmetic mean for the lower-slope sample set was 1.90; while for the middle-/upper-slope sample set the mean was 1.78, with standard deviation less than 0.5 for both data sets (Table

2). There was no statistically significant difference between the Kr and Ki means between the lower and middle/upper slope samples, as per the Student's t test.

Attesting to the same trend as that of the Ki index, the STI index did not show any significant difference between the means of the two sample sets, with a mean of 57.3 for the lower-slope sample set, practically equal to the mean of 56.6 for the middle-/upper-slope sample set, with standard deviations of 7.93 and 7.31, respectively. The grouping of pedogenized materials (horizons B) in the alluvial plain context showed less variation as regards the STI index, demonstrating a more homogeneous pattern when compared with that of the hilltop and upper slope samples (Figure 5).

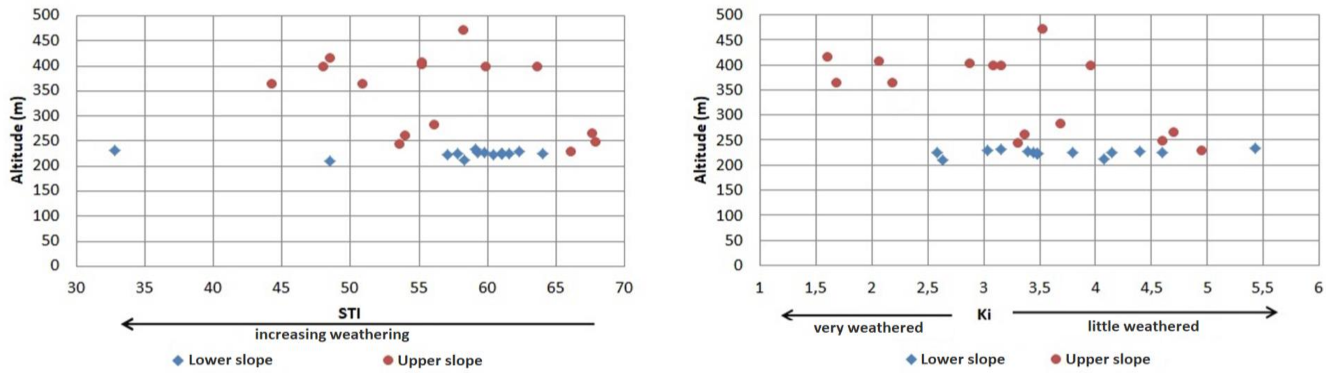

Figure 5. Relationship between the STI, Ki indices and altitude

The Fe_2O_3 and SiO_2 contents in weathered sediments (Table 2) presented a slightly higher mean for the middle/upper slope samples when compared to such contents for the lower slope samples. However, they were not significantly different from a statistical point of view, neither regarding the TiO_2 contents, which were also very close for both sets of sediments. The difference between the means of Al_2O_3 for the lower and upper slope samples was significant, according to the t test at a significance level of 0.05, being 11.33% for the lower slope samples, and 13.54% for middle/upper slope ones, without the occurrence of outliers. Such oxides are indicators of less mobile elements in the weathering profiles. Al_2O_3 proved to be the only distinctive oxide between the two sample sets according to altitude, suggesting that the upper slope samples may be remnants of older coverings. However, the other geochemical parameters do not allow drawing this type of conclusion. This situation is consistent with a context of rejuvenation of the pedogenized coverings on the hilltops and slopes of the Dissected Plateau of the Uruguay River. In this regard, it is hypothesized that the soils of summit surfaces (hilltop) feature regressive pedogenesis (PHILLIPS, 1993) in a close relationship with active Holocene morphogenetic conditions, and probably even prior to that, given the deepening of the valley. The topographic segmentation of such extensive slope sectors in the study area, together with said active morphogenetic conditions, meant short-distance relocations of materials in the upper and middle slope portions, constituting colluvial deposits formed from previously weathered sediments.

The low rates of weathering, attested by both the Ki and STI indices, are indicative of a poorly advanced pedogenetic process in the context of the lowlands and slopes of the Dissected Plateau of the Uruguay River. These indices do not allow, however, to distinguish the nature of the pedogenetic process at different altitudes on slope scale. When considering steep slopes, common elongated ramps and the potential erosive energy involved in this system, one can only assume that there was a relocation of little weathered sediments to the middle and lower slopes, a situation consistent with an active and morphogenetic condition and in full development. This condition agrees with the fact that drainage networks drain predominantly into rocky beds and play the role of an active incision, from the smallest channels to the larger ones, as pointed out by Bertolini, Deodoro and Boettcher (2019). Taking the pedogenized fine sediment package from the right bank of the Uruguay River as the time frame of the Pleistocene-Holocene transition, one can understand this process as a rather continuous event of alluvial deposition, and constitution and thickening of the pedogenized covering that has occurred since at least the beginning of the Holocene.

Table 2. Geochemical data of the analyzed samples

Point (site)	Slope position	Horizon/ Depth (cm)	% SiO_2	% Al_2O_3	% TiO_2	% Fe_2O_3	% MnO	Ki	Kr	STI
P1	Lower (plain)	B1 60 – 77	27	12,08	3,55	17,25	0,15	3,8	2,09	61
		B2 78 – 300+	29,5	12,08	3,04	17,48	0,14	4,15	2,27	64
P2	Lower (plain)	B1 31 – 76	17,9	8,84	3,04	15,08	0,07	3,44	1,73	57,8
		BC 158 - 190	20,3	13,38	2,45	14,83	0,02	2,58	1,59	61,6
P7	Lower (plain)	B 213	26,2	10,44	3,29	17,43	0,09	4,27	2,17	61,1
P6	Lower (plain)	B2 101 – 140	24,3	12,18	3,72	18,8	0,14	3,39	1,8	59,3
		B3 141 - 190	26,4	10,2	3,56	18,3	0,12	4,4	2,16	59,8
P13	Lower (plain)	B 110 - 120	25,3	10,53	3,87	19,86	0,14	4,08	1,95	58,3
P28	Lower (plain)	BC 70 – 80	29,8	9,33	3,71	19,98	0,68	5,43	2,41	59,1
P36	Lower (plain)	B 70 – 80	25	12,23	4,44	22,95	0,19	3,48	1,66	57,1
P61	Lower (plain)	B1 70 - 137	24,5	12,02	3,46	15,16	0,25	3,47	2,02	60,4
		B2 200	27,8	15,6	3,34	12,64	0,2	3,03	2,1	62,3
P80	Lowe	A 10 – 20	16,2	8,75	11,88	21,43	0,32	3,15	1,29	32,8
P81	Middle/ Lower	AB 20 - 25	16,9	10,93	5,81	16,82	0,24	2,63	1,39	48,5
	Arithmetic Mean		24,08	11,33	4,23	17,72	0,20	3,69	1,90	57,36
	Standard Deviation		4,50	1,87	2,34	2,79	0,16	0,79	0,33	7,93
P3	Middle	B 10 - 56	34,8	11,94	2,91	22,91	0,04	4,95	2,34	66,1
P37	Middle	BC 34 - 105	33,4	12,08	2,51	22,04	0,11	4,7	2,28	67,6
P27	Middle/ Upper	BC 21 - 38	33,1	12,23	2,45	20,36	0,14	4,6	2,35	67,9
P15	Upper	B 60 - 70	26,1	12,03	4,82	27,56	0,1	3,69	1,57	56,1
P20	Upper	B 36 - 105	23,1	11,69	5,06	25,91	0,1	3,36	1,46	54,0
P32	Upper	AC 0 - 45	18,4	10,15	6,02	20,37	0,3	3,08	1,42	48,0
		C1 46 - 70	24,9	13,44	3,69	19,67	0,16	3,15	1,71	59,9
		C2 71 - 140	28,4	12,18	3,06	20,28	0,08	3,96	2,02	63,6
P59	Upper	B 120	29,6	14,29	4,87	19,41	0,15	3,52	1,98	58,2
P73	Upper	BC 75 – 140	14,3	15,21	5,16	15,49	0,1	1,6	1,02	48,5
P82	Upper	B 5 - 15	25,5	15,11	5,49	18,68	0,14	2,87	1,69	55,2
P108	Upper	A 0 - 5	25,2	12,99	5,72	9,09	0,09	3,3	2,4	53,6
P110	Upper	B1 30 - 70	14,8	14,97	7,79	12,24	0,27	1,68	1,16	44,2
		B2 70 - 128	20,1	15,71	6,18	10,28	0,19	2,18	1,61	50,9
P111	Upper	B 50-60	23,2	19,12	4,87	9,89	0,08	2,06	1,63	55,2
	Arithmetic Mean		24,99	13,54	4,71	18,28	0,14	3,25	1,78	56,60

Standard Deviation	6,32	2,23	1,52	5,73	0,07	1,05	0,44	7,31

5. Conclusions

The geochemistry of the main oxides found in the pedogenized coverings of the western region of Santa Catarina, in the context of the upper valley of the Uruguay River and the Dissected Plateau of the Uruguay River, attests to soils with a low degree of weathering both at top and bottom valley positions, within an altimetric range between 200 and 500 meters of altitude.

The characterization of the geomorphology and pedogenized coverings of the Dissected Plateau of the Uruguay River allowed confirming that the thickness of the weathering mantle in the Volta Grande valley is heterogeneous, mainly when comparing the lower and upper slope portions. The sediment coverings on the plain of the Uruguay River are, in general, discontinuous, about 5 meters deep, and of fine grain size, while the coverings on middle/upper slopes, including hilltops, tend to be shallow or barely deep, and gravelly to very gravelly.

On the lower slopes, such coverings are conditioned by the fluvial action and by the depth at which the sound rock is found. Such depth and its variation are a result of the spatiality of the balance between erosion and pedogenesis, which then is conditioned by the rather extensive segmentation of the middle and upper slopes. Such segmentation allowed, as per recent geomorphological developments in the area, the accommodation of small colluvial coverings on the middle slopes. The long-term evolution of these coverings is related to the denudational action of morphogenetic agents and appears to be consistent with a structural influence still unknown but capable of providing energy to the system in order to sustain erosion and denudation of old coverings and progressive and prevailing renovation (since at least the beginning of the Holocene) of the weathering front. This way, in general, one can speak of soils being formed in alluvial and lower slope environments and being thinned on hillsides and tops.

In the context of the alluvial coverings of the Uruguay River and the archaeological sites associated with them, the sedimentary data demonstrate that there were no changes in the deposition system to a point that abrupt contact zones are marked in the weathering mantle and associable with very different deposition environments. Such depositional system seems to have been governed by a low-energy fluvial system, materializing stratigraphic sequences with diffuse contact surfaces (SANTOS, 2018; SANTOS et al., 2021) over the last 11,000 years.

Finally, the observations and analyses carried out allowed understanding that:

• In terms of relative age, based on geochemical data, there exist recent coverings both at the highest and lowest topographic positions. However, hilltop coverings in horizon B tend to be older – with a higher $\%Al_2O_3$ mean compared to that of lower slope coverings. This situation suggests that hilltop coverings are remnants of a broader and deeper covering, such as those at higher elevations of the Basalt Plateau in the same region, for instance in the municipalities of Erval Grande - RS and Chapecó - SC, Brazil (OLIVEIRA; SOARES; PONTELLI, 2019).

• The above situation denotes a context of rejuvenation of the pedogenized hilltop coverings of the Dissected Plateau of the Uruguay River, in a context of active morphogenesis and subsurface renewal of the weathering front.

• The low rates of weathering are indicative of recent pedogenesis in the entire compartment of the Dissected Plateau of the Uruguay River, consistent with an active morphogenetic condition and in full development since at least the Holocene.

• As regards climatic conditions, it was not possible to clearly distinguish, within the pedostratigraphic context of the plain, changes that could be related to abrupt Holocene climatic transitions because of the predominance of silty clay deposits undifferentiated as to their depth.

• Most of the volume of the Uruguay River floodplain in Volta Grande is composed of fine sediments (clay and silt) with fluvial and colluvial action in its genesis.

• Radiocarbon dating analyses indicate a pedological covering developed in the floodplain, from the Pleistocene/Holocene transition to present days.

• The weathering rates measured through the Ki and STI indices are consistent when showing little weathered coverings in the dissected valleys of the upper Uruguay River.

• Within the scope of the Dissected Plateau of the Uruguay River, the degree of weathering and the low development of pedogenic horizons of hilltop coverings, with the presence of planation surface remnants, are not consistent with surfaces of 400 – 500 meters in altitude. It seems more reasonable to suppose that the development and transformation of the valley's superficial deposits underwent different rates of decomposition of the parent material and erosion of the weathering mantles.

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