Article

Terraces and river incision in great passive margin escarpments: genetic and geochronological aspects

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Terraces and river incision in great passive margin escarpments: genetic and geochronological aspects

Abstract

Fluvial terraces and their depositional tracts are important geoindicators of past environmental conditions and the relief neoquaternary evolution, and in regions of great passive margins escarpments assume different genetic links. This article aims to discuss different causes that generate these geoforms, using techniques of faciological and geochronological analysis and paying attention to general patterns of occurrence and distribution, as well as to particularities, articulating regional characteristics and local controls. For this purpose, dating by Optically Stimulated Luminescence (OSL) and facies analyzes on nine river terraces were performed, integrated with other chronological results, obtaining ages between the terminal Pleistocene and the Holocene. As for genetic links, terraces generated by river capture, transposition of thresholds and vertical notch by tectonic uplift were found, results that expand the knowledge about the sedimentary organization in the great escarpments domain, allowing the correlation with other regional studies.

Keywords: Fluvial depositional levels. Fluvial captures. Vertical notch. Neotectonic control. Optically Stimulated Luminescence.

Terraços e incisão fluvial em grandes escarpamentos de margem passiva: aspectos genéticos e geocronológicos

Resumo

Terraços fluviais e seus tratos deposicionais são geoindicadores importantes de condições ambientais pretéritas e da evolução neoquaternária do relevo, e em regiões de grandes escarpamentos de margem passiva assumem diferentes vínculos genéticos. O presente artigo assume o objetivo de discutir causas geradoras dessas geoformas, empreendendo técnicas de análise faciológica e geocronológicas e atinando para os padrões gerais de ocorrência e distribuição, bem como para as particularidades, articulando as tipicidades regionais e os controles locais. Para tanto, foram realizadas datações por Luminescência Opticamente Estimulada (LOE) e análises de fácies em nove terraços fluviais, interpretadas integradamente a outros resultados cronológicos, obtendo-se idades compreendidas entre o Pleistoceno terminal e o Holoceno. Quanto aos vínculos genéticos, foram encontrados terraços gerados por captura fluvial, transposição de soleiras e entalhe vertical por soerguimento tectônico, resultados que ampliam o conhecimento acerca da organização sedimentar no domínio dos grandes escarpamentos, permitindo ainda a correlação com outros estudos regionais.

Palavras-chave: Níveis deposicionais fluviais. Captura fluvial. Entalhe vertical. Controle neotectônico. Luminescência Opticamente Estimulada.

Terrazas y incisión fluvial en grandes escarpes de margen pasivo: aspectos genéticos y geocronológicos

Resumen

Las terrazas fluviales y sus tramos de depósito son importantes geoindicadores de las condiciones ambientales pasadas y de la evolución Neocuaternaria del relieve, y en regiones con grandes escarpes de margen pasivo asumen diferentes vínculos genéticos. El presente artículo asume el objetivo de discutir las causas que generan estas geoformas, utilizando técnicas de análisis faciológico y geocronológico y considerando los patrones generales de ocurrencia y distribución, así como las particularidades, articulando tipicidades regionales y controles locales. Para ello, se realizaron dataciones y análisis de facies por Luminiscencia Ópticamente Estimulada (OE) en nueve terrazas fluviales, interpretadas en conjunto con otros resultados cronológicos, obteniendo edades entre el Pleistoceno terminal y el Holoceno. En cuanto a los vínculos genéticos, se encontraron terrazas generadas por captación de ríos, transposición de sills y muescas verticales por levantamiento tectónico, resultados que amplían el conocimiento sobre la organización sedimentaria en el dominio de los grandes escarpes, permitiendo además la correlación con otros estudios regionales.

Palabras clave: Niveles de depósitos fluviales. captura de río. muesca vertical. control neotectónico. Luminiscencia estimulada ópticamente.

Introduction

The relief in the great escarpment region of the Brazilian southeast is dissected by channels characterized by strong vertical notch, organized in a drainage network that demands directly to the Atlantic Ocean and in another one that drains toward the interior of the continent, having as its baseline level great rivers that also meet the Atlantic Ocean. They thus form watersheds of strong erosion force formed by the channels closer to the Atlantic baseline level, and a set of watersheds with significant spatial expressions turned to the inland, which form the watersheds of Paraná and São Francisco. Although passive margin relief evolution models referred to in the principle of flexural isostatic equilibrium foresee a more aggressive denudation on Oceanic strains of great escarpments when compared to inland ones (Macedo, 1989; Summerfield, 1991; Gilchrist; Summerfield, 1994; Marent *et al*., 2013), as evidenced by BE dating (Salgado *et al*. 2014; Salgado *et al*., 2016), the role of fluvial captures (Cherem *et al*., 2013; Rezende *et al*., 2013), lithology, and tectonics is also recognized (Saadi, 1991; Santos, 1999; Marques Neto; Perez Filho, 2013) in the evolution of these geomorphological systems.

In face of erosive contrasts, geomorphological evolution tends to differ between watershed that drain to the inland and those that go directly to the Atlantic baseline level (Summerfield, 1991). The tectonic-originated reliefs of the Brazilian Atlantic coast present sill sequencies connected to local baselines formed by differential erosion, but also commonly formed due to tectonic pulses that create local uplifts and block tilting. This relief scaling is very striking in the inland section of these escarpments, where depositional tracts vary from small upper montane alveoli suspended until the plains formed at the regional baseline levels, such as those connected to the Sapucaí, Verde and Grande Rivers.

Terraces are important landscape geoindicators, preserving depositional registers that are often valuable for deduction regarding climate and tectonic control in the evolution of relief (Leopold *et al*., 1964; Schumm, 1977; Christofoletti, 1981; Charlton, 2008). Due to that, terraces have been regarded as a nuclear object of study in many studies that are geochronologicaly set in the Quaternary (Etchebehere, 2000; Oliveira, 2012; Rubira; Perez Filho, 2019). In geomorphological contexts of great escarpments, characterized by active tectonics and accentuated fluvial dissection and incision works, these geoforms can take on different meanings, and are thus valuable to understand the neoquaternary evolution of landscape.

In the context of the Mantiqueira Mountains, terraces persist in the landscape in an incontiguous, yet recurrent, manner, helping to interpret important factors that intervene with the landscape's quaternary evolution. Considering these points, this article seeks to discuss elements that work in the quaternary relief evolution in the inland area of the Southern Minas Gerais' Mantiqueira based on the interpretation of the genesis and age of sediments present in river terraces and their relations with current tectonic-structural controls. For that end, the study investigated depositional archives focusing on their genetic bonds and their relationship to the local and regional geomorphology context, a procedure based on the faciological analysis of sediments from selected stratigraphic sections and on their dating by Optically Stimulated Luminescence (OSL).

Materials and Methods

The materials used for fating were buried fluvial deposits, of vertical or lateral accretion, and organic horizons reworked by overlayed pedogenesis or buried by coverage materials. The materials were collected by a dark PVC pipe to avoid solar irradiance. The pipe was inserted into depositional bodies, always deeper than 1.0 m, with sealed ends to avoid irradiation; likewise, they were firmly wrapped by black plastic and then sent to the lab Datação Comércio e Prestação de Serviços Ltda (Dating Commerce and Service Provision Ltd.), where the trials were conducted. Nine captures for dating were made in different deposits and, after that, their results were compared to those of other OSL dating trails conducted in the area by Marques Neto e Perez Filho (2013) so to obtain a wider spatial coverage with the sample units. The dated deposits were not the only ones analyzed during the study, but they were selected due to their preservation in deep valley landscape and their position in the study area, on the pretext of collecting samples that represent different tectonic-structural contexts. The location and elevation of the analyzed deposits were measured with the Garmin GPS, Etrex model.

On the field, the altimetry of the deposits were also recorded, using as reference the elevation of the capture spot and of the active drainage line, measure at the closest point to the thalweg. Subsequentially, incision rates were measured (Burbank; Anderson, 2011; Rezende, 2018) by dividing the altimetry difference between the deposit's altitude and the active channel by the dated age:

$$Incision\ rate\ \left(\frac{mm}{kA}\right) = \\ deposit\ altitude\ - current\ channel\ altitude\ \div deposit\ age$$

To visualize the terrace position on the deep valley, transversal profiles were designed by using *Google Earth*, an environment in which the UTM coordinates obtained on the field were inserted. Transversal sections were captures in different flight distances due to the convenience of adjusting the presented sections to the deep valley morphology, which makes these extensions different for each representation. Later on, the georeferenced sections were redesigned in a CAD software.

Henceforth, depositional dating objects were interpreted in relation to the geomorphological system they part of, seeking to differentiate terraces formed by structural control, related to lithologic contact or to the notch that cannels promote by crossing a rocky sill, terraces formed by notches due to morpho-tectonic control, and those connected to drainage rearrangements dur to fluvial capture.

Lab dating procedures followed the SAR protocol (Single Aliquot Regenerative Doses) in 15 aliquots. OSL, as it is known, indicates the close time when the sediment was buried by overlaying deposition and the quartz and feldspars isolated from contact with lights, thus trapping electrons inside these minerals' crystal lattice, with the decay of radioactive elements (U, Th, K, Rb) and being able to create free electrons that are trapped in the mineral (Jacobs; Roberts, 2007; Anderson; Anderson, 2010; Bierman; Montgomery, 2014).

As an additional procedure, lab analysis of granulometry, organic matter, and dominant chemical elements (Al, K, P, Ca e Mg) were conducted on the dated materials and on the covering material to better understand the geochemical aspects of the different depositional tracts regarding their organic-mineral composition. The study also analyzed aluminum saturation, base saturation, and the cation exchange capacity (CEC). The trials were conducted in the Soil Lab at the Federal University of Lavras using the Melinch protocol. Due to the significant space the presentation of the report results demands, we chose to not present them in this article's main text.

Lab analyses supported a division of deposits according to the facies that could be identified in the field, categorized in an adaptation of Miall's methodological system (1984, 1986). The found fluvial facies were represented by an uppercase letter indicating the dominant granulometric fraction, followed by one or two lowercase letters that indicate the accessory granulometries and/or specific traits, such as organic horizons and preserved stratigraphic signatures. The prevalence of fine materials (silt/clay) was represented by the letter F (fine), of sand by the letter S (sand), and of gravel by the letter G (gravel). After that, deposits were represented by profiles and correlated to the depositional environment, paying attention to similarities and differences between past and current processes.

Study area

The Mantiqueira Mountains are one of the geomorphological systems most significantly affected by morpho-tectonic control in the whole context of the Brazilian Platform (Saadi, 1991; Gontijo, 1999; Santos, 1999; Ribeiro, 2003; Chiessi, 2004; Morales, 2005; Silva; Mello, 2011; Marques Neto, 2012; Silva, 2023). It corresponds to a set of shear zones of predominantly ENE orientation and NW tilting, forming a continuous horst that, in its southern branch, is aligned to the Atlantic margin of the Brazilian Southeast, along with the graben of the Paraíba do Sul river and to the Sea Ridge horst. These aligned escarpments are Precambrian structures reactivated by the continental rift system of the Brazilian southeast (Riccomini, 1989). Geomorphologically, this region was designed by Gatto *et al*. (1983) as Southern Mantiqueira.

The platform uplift and associated taphrogenic tectonics had created escarpments and significant altitude ranges, with the formation of terraces both for the interior of the continent and the coast side. The drainage that flows to the continental interior is organized in scaled base levels that define a succession of plateau surfaces until the contact with the phanerozoic sediments of the Paraná Watershed. The drained that flows to the Proto-Atlantic meets the general base level running a much shorter surface length, which contributed to a substantial erosive aggression of the watershed that drain to the East, directly connected to the South Atlantic.

In the Brazilian Southeast, this drainage network has led the lowering of the Proterozoic orogenic belts reactivated during the Mesozoic/Lower Cenozoic and promoted the erosive opening of scaled intra-plateau depressions followed by epigenic cuts promoted by direct affluents of the Paraíba do Sul river, according to Paixão *et al*. (2021).

The southern branch of the Mantiqueira Mountains is defined by the most continuous and highest horst, which, in its other side, its dissected by the rivers that flow to the interior of the continent and that, in this region, have the Grande river as their main collecting trunk. Although this watercourse is one of the affluents of the Paraná River, Rezende *et al*. (2018) suggest that the upper Grande river watershed belonged to the São Francisco watershed, having been captured and redirected to the Paraná watershed during the Cenozoic.

Marques Neto (2017) proposed a morphostructural subdivision for the studied area, integrating the existing geomorphologic units, the relief and drainage's structural lineaments, the configuration of the river network, and the geological base. The results indicate a strong control of preexisting structures, especially in the differentiation between the Top Levels and Scaled Levels, which are aligned to the general NE-SW direction (Figure 1). Evidence of morphotectonic control overlaid with structural arrangements were also identified in all subdivisions, besides the river terraces, very visible in these tectonic reliefs, in which they present different genetic bonds, discussed below.

Results and discussion

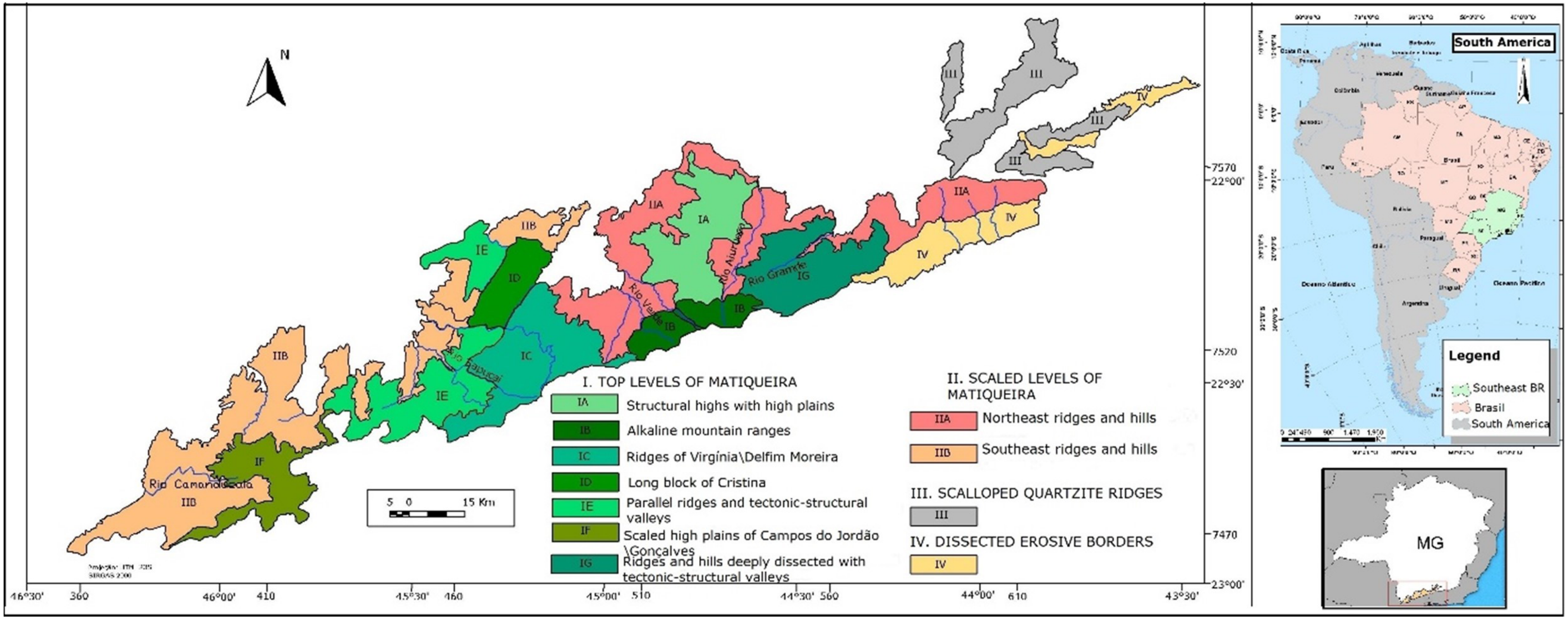
Faciological description and chronology of the analyzed terraces

In general, the analyzed fluvial terraces are located in deep valleys, in the downslope and above active fluvial plains. The presence of terraces was ascertained throughout the whole context of the Southern Mantiqueira, being recurrent in all its morphostructural subdivisions. In some cases, they are fluvial paleo-deposits are rarely have preserved sedimentary structures, they may contain organic horizons related to alluvial paleosols, commonly burred and with overlaid pedogenesis. General information regarding the nine points that were analyzed by dating are summarized in Chart 1. Figures 2 and 3 show the spatialization of capture points and the cross-sections of the investigated depositional environments. Chart 2 shows the details of dating trials.

There were three genetic meanings interpreted for the dated terraces: (1) formation by fluvial capture; (2) notch formed by rocky sills; (3) notch formed by epeirogenic uplifting.

The first terrace of the presented sequence (T1) was dated based on a buried organic horizon (facies Fo), which consists of a paleo-organosol formed at the end of the Pleistocene and distinctly darker than the overlying facies. This material still preserves marks of roots and presents 65 cm of overlying pedogenesis. The deposit reaches a 2-meter unevenness in relation to the local base level, appearing as a former accumulation alveolus currently positioned between two active dissecting lines and recharacterized by linear erosive processes exerted by ephemeral channels. It is currently controlled by a N-S structure.

Figure 1 – Localization and morphostructural subdivision of the Southern Mantiqueira in its Minas Geral portion.



Source: Adapted from Marques Neto (2017).

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Chart 1 – Summary of geomorphologic and chronological information of the dated material.

Sample	UTM	Unit	Alt. (m)	Municipality	Dated material	Depth (m)	Unevenness from the active channel (m)	Age (kA)	Incision rate (mm/kA)	Genesis
T1	397384/7491855	Top levels	1402	Bom Jesus Stream	Buried organic horizon	1.10	2.1	16,400 ± 2,680	128.04	Fluvial capture
T2	611577/7598353	Scalloped quartzite ridges	1197	Lima Duarte	Buried organic horizon	1.05	3.5	23,000 ± 3,440	152.17	Fluvial capture
T3	624432/7575203	Dissected erosive borders	907	Santa Bárbara do Monte Verde	Fluvial deposit	1.25	1.2	22,150 ± 2,200	54.17	Sill transposition
T4	625325/7574537	Dissected erosive borders	915	Santa Bárbara do Monte Verde	Fluvial deposit	1.15	2.7	5,500 ± 1,050	149.09	Sill transposition
T5	458105/7531042	Scaled levels	892	Maria da Fé	Buried organic horizon	1.10	1.07	13,400 ± 850	111.94	Sill transposition
T6	553351/7546514	Top levels	1197	Bocaina de Minas	Buried organic horizon	1.45	3.15	16,000 ± 2,400	196.87	Notch made by tectonic control
T7	453736/7524911	Scaled levels	860	Itajubá	Buried organic horizon	1.15	2.7	2,100 ± 390	1258.7	Notch made by tectonic control
T8	475738/7542814	Top levels	1187	Cristina	Buried organic horizon	1.05	2.4	10,250 ± 1,720	234.14	Notch made by tectonic control
T9	541195/7558453	Top levels	1115	Aiuruoca	Fluvial deposit	1.10	2.7	3,690 ± 360	731.70	Notch made by tectonic control

Figure 2 – Distribution of collection spots in the context of the Southern Mantiqueira Mountains.

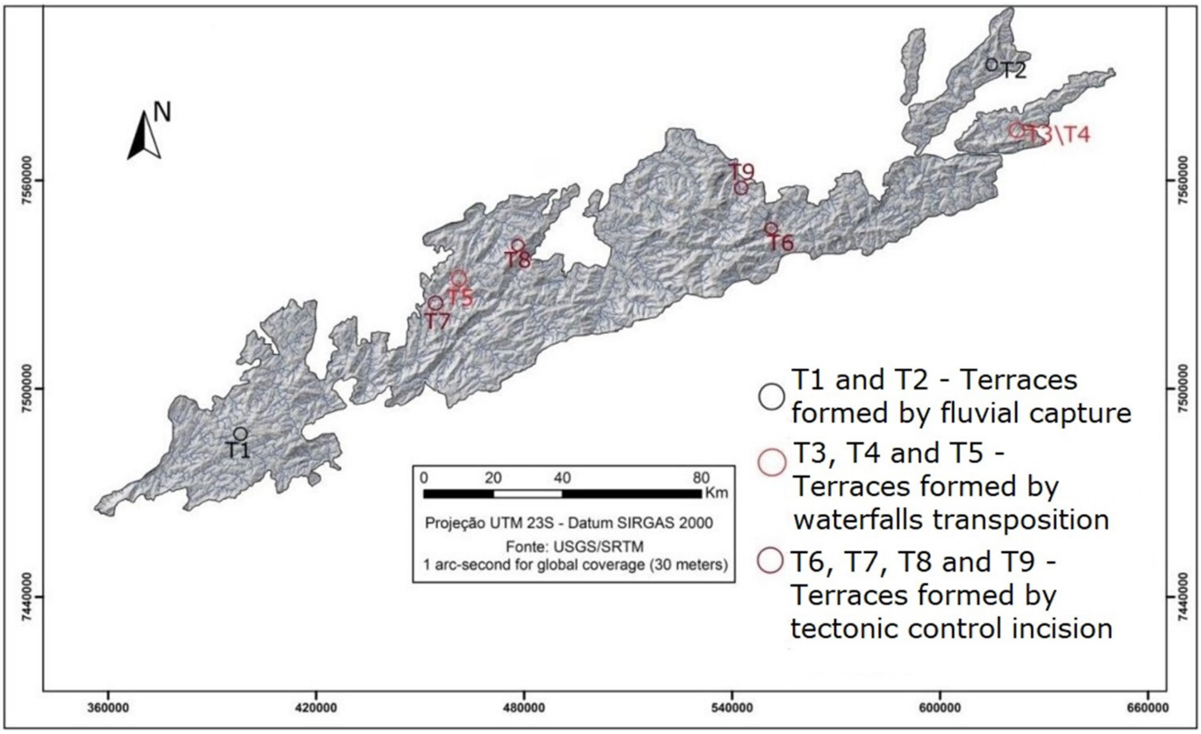

Figure 3 – Cross-sections of the studied depositional environments.

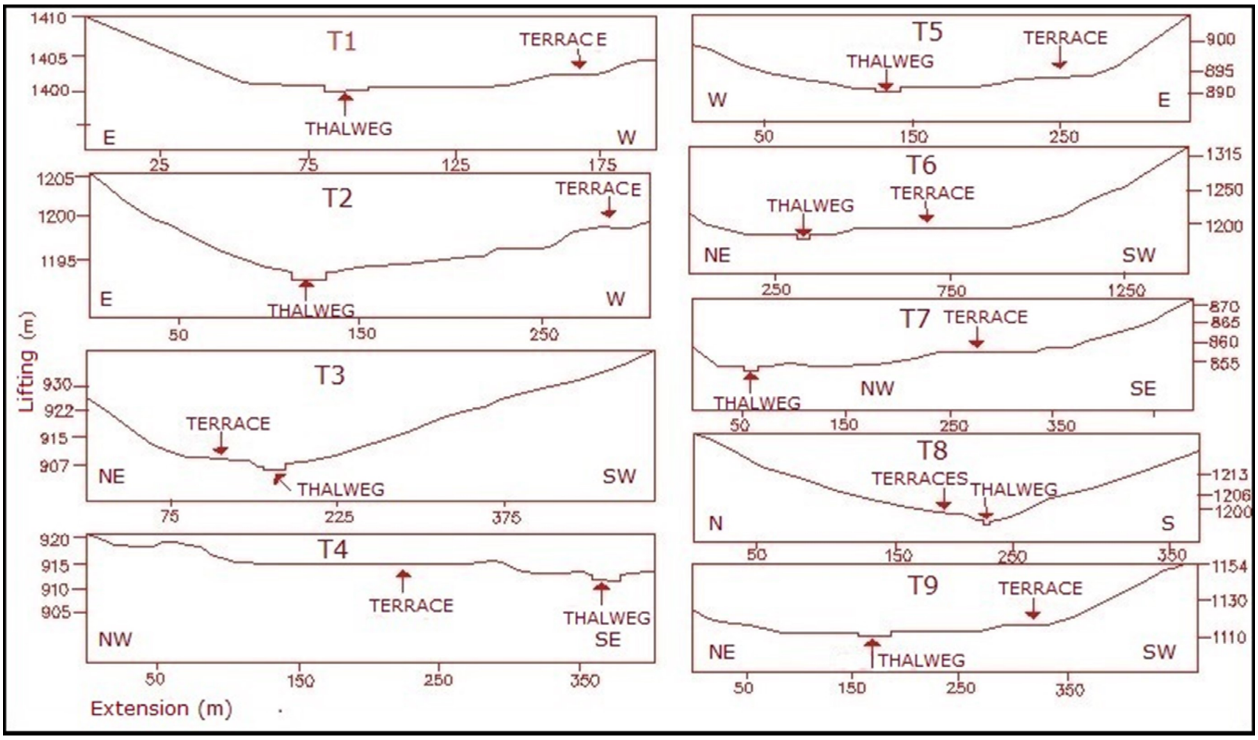

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Chart 2 – Results of dating trials.

Sample	Annual dose (μGy/year)	P (Gy)	Standard deviation	Th (ppm)	U (ppm)	K (%)	Humidity (%)	Age (years)
T1	2,100 ± 240	34.6	3.8	6.275 ± 0.226	2.540 ± 0.356	0.872 ± 0.126	19.0	16,400 ± 2,680
T2	1,070 ± 110	24.5	1.5	5.855 ± 0.211	1.034 ± 0.228	0.217 ± 0.031	20.9	23,000 ± 3,440
T3	2,540 ± 120	53.7	2.5	12.425 ± 0.447	3.510 ± 0.087	0.425 ± 0.062	7.7	22,150 ± 2,200
T4	1,400 ± 200	7.7	–	4.349 ± 0.157	1.126 ± 0.385	0.608 ± 0.088	6.5	– 5,500 ± 1,050
T5	4,430 ± 225	59.3	2.2	12.827 ± 0.555	3.056 ± 0.243	3.056 ± 0.307	19.6	13,400 ± 850
T6	1,920 ± 195	30.7	2.3	10.103 ± 0.364	2.242 ± 0.317	0.573 ± 0.083	32.1	16,000 ± 2,400
T7	1,910 ± 210	4.0	0.6	7.562 ± 0.365	1.541 ± 0.134	0.918 ± 0.261	6.7	2,100 ± 390
T8	2,120 ± 290	21.8	2.1	13.558 ± 0.646	2.716 ± 0.231	0.840 ± 0.442	30.8	10,250 ± 1,720
T9	5,600 ± 225	20.7	1.8	16.109 ± 0.073	6.868 ± 0.343	3.041 ± 0.317	9.0	3,690 ± 360

The organic facies was interpreted here as a buried peatland, with a format that tends to an oblong figure and distributed around 70 meters, in its longer axis, and 25 meters, in its shorter axes, which corresponds to the spatial expression of this upper montane alveolus. Neotectonic deformational efforts have enhanced the slopes and formed transmission functions in a geoenvironment that was formerly a geochemical barrier in an eminently depositional environment. Currently, this deposit is being drained in its profile and eroded in its most emerging portion, thus presenting distinct processes from those prevailing at the end of the Pleistocene.

The next profile – T2 – corresponds to a depositional body located in a discontinuous terrace segment, also in a upper montane environment. The channel is close to the right-margin divide, thus suggesting a tilting of the opposed margin, through which remain exposures of the organic horizons elevated in the alluvial plan, which is currently lixiviated and with overlaying pedogenesis. This spot seems to have seen sediment accumulation in a flood basin, whose depressing is partially preserved, even though it was recharacterized due to the tilting and consequential slope processes.

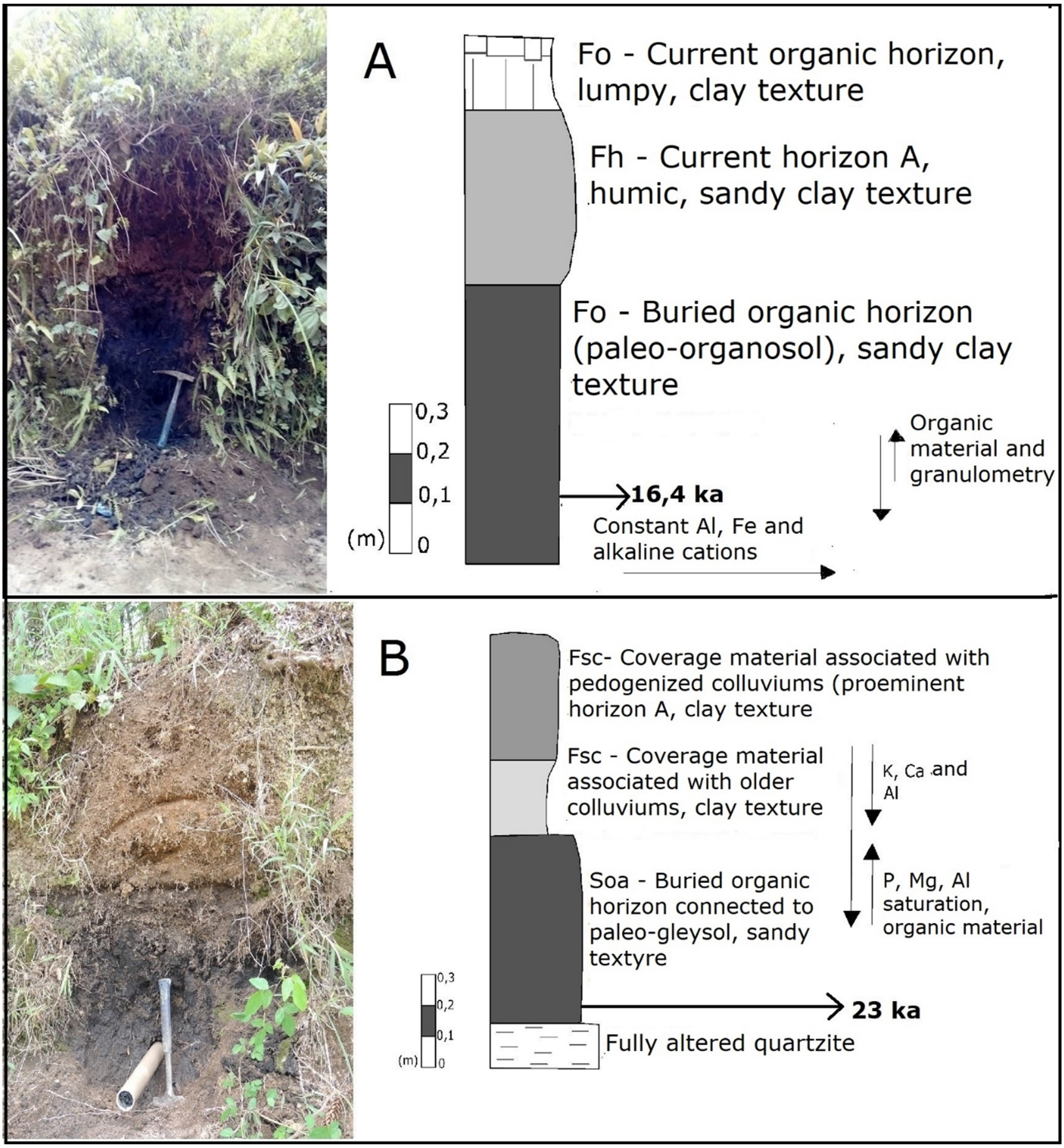
Partly, pedogenetic processes have latosolic organization, forming Latosols associated with Cambisols over organic packages, indicating a full transformation, which, in some spots, are thicker than 1 meter. Consequentially, the level of preservation of organic bodies corresponding to this Pleistocene deposit varies, tending to disfiguration as the overlying lixiviated coverage increases.

Figure 4 shows the sections opened to collection, the faciological description, and dating of the terraces formed by fluvial capture.

The terraces formed by incision after the transposition of erosive sills with no associated fluvial captures are indicated by T3, T4, and T5 (Figure 5). Within this set, T3 presents a sequence of alluvial, colluvial, and organic facies with well-registered contacts, although parallel-plane stratigraphic marks are precariously preserved and have no defined distribution pattern for the organic-mineral substances throughout the facies. Dating was conducted in the Sf basal facies, which had alluvial genesis by vertical accretion, suggested by the parallel-plane lamination. In this depositional body, other sandy facies do not present preserved stratigraphic marks, thus suggesting that they are not lateral fill deposits, such as point bars, but correspond to a set of flood facies truncated by the formation of organic horizons that indicate periods of relative stability. Fining-upward sequence reinforces the hypothesis of vertical accretion.

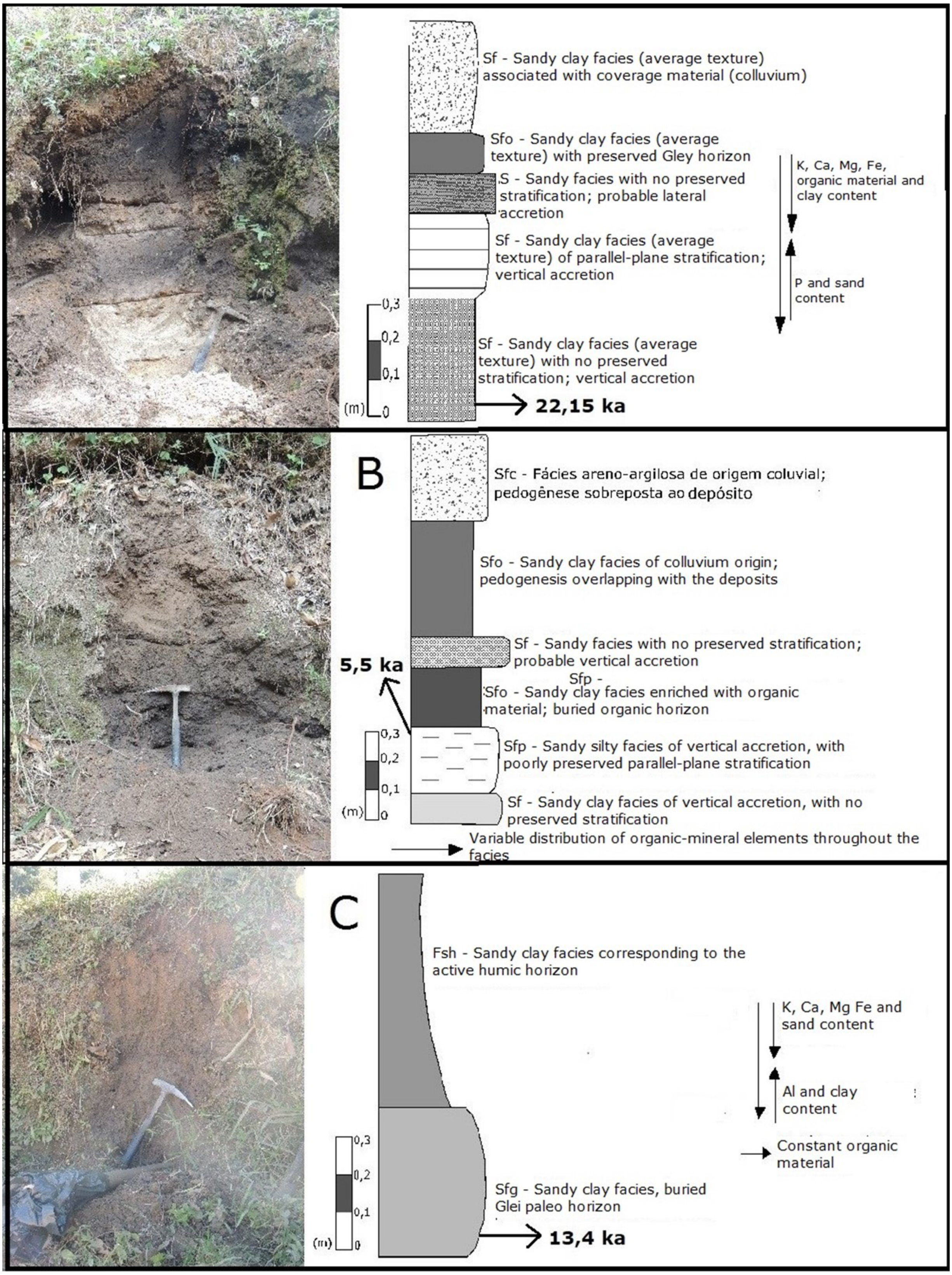
The most basal sandy facies starts being exposed at 1.02 m deep, and it goes gradually defining horizontal marks, although precariously preserved. The depositional sequence is interrupted by a thin organic horizon, underlying another equally thin sandy depositional body that separates a thicker and darker organic horizon in comparison to the previous one. This evidence suggests that it is a newer and less transformed material than the most basal organic facies, whose hydromorphic characteristics are more disfigured. The age found for the basal facies suggests that the deeper organic horizon was also formed in the New Pleistocene, having its evolution interrupted by a depositional tract of side accretion underlying the most emerging organic horizon, probably dating back to the Holocene. In fact, the milder incision indicates a more recent shift in the local base level.

Figure 4 – Terraces that are genetically connected to fluvial capture. (A) T1 –Bom Jesus Stream; (B) T2- Lima Duarte. Localization of the samples shown in Chart 1.



The T4 profile presents similar facies to the previous one regarding the succession of registries of sandy clay texture's vertical accretion, with possible sandier lateral-accretion facies underlying the organic horizon. Dating, however, identified a Holocene age for this package, unlike the previous one, which dates back to the Pleistocene. This depositional body is located 2.7 m above the local base level, more than twice the 1.2 meters observed for the previously described deposit, suggesting a more intense rework, which was possible sheltered in a more prominent unevenness with the fluvial work zone, which allowed for the conservation of more expressive organic horizons that were formed during the Holocene.

Figure 5 – Terraces genetically connected to sill transposition. (A) T3 – Santa Bárbara do Monte Verde; (B) T4 – Santa Bárbara do Monte Verde; (C) – T5 – Maria da Fé.



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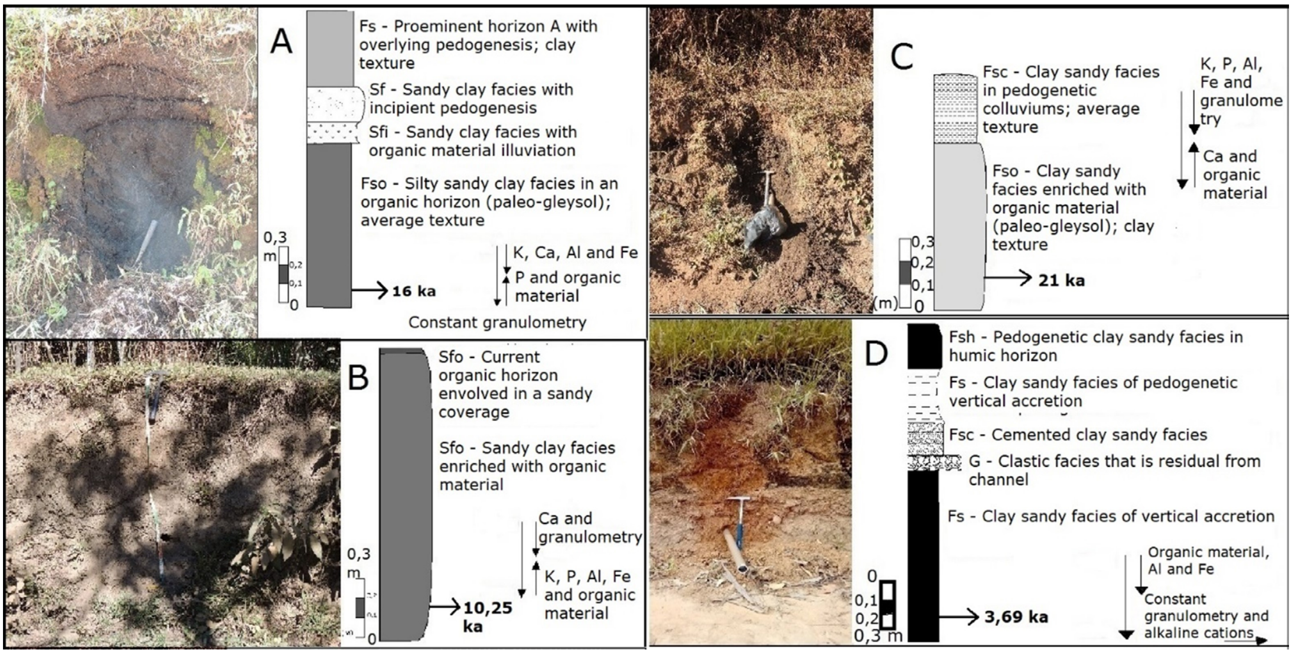
The sampled deposit in T5 also has a New Pleistocene buried organic horizon, with a 1.5-meter unevenness in relation to the local base level. The material is in fluvial terraces genetically connected to the depositional work of the Cambuí stream. It suggests a movement in the horst/graben contact, with deformation of deposits, rocky outcrops in terraces and at the base of the slopes, besides the presence of an inverse fault with overlying immature soils.

The T6 prefile (figure 6) is very representative of the most recurrent facies of the study area: buried organic horizon with overlaying pedogenesis indicating old registry of hydromorphism and soil evolution in old alluvial plains. The upper facies represent active pedogenesis, given by a prominent A horizon, and the two intermediate packages are characterized as an interpenetration zone between past and present pedogenetic processes, as indicated by lab trials and field evidence. At the base, a thick organic package is distinguished as a buried Paleosol with a little more than a three-meter unevenness in relation to the active plain. The terrace is covered by some kind of colluvium material, which recharacterized its inner morphology to a ramp aspect, in which slope processes start to dominate.

The formation of organic horizons also indicates, in this case, a relative past stability, broken out by a probable tilting of the channel's left margin, which migrated toward the divide of the opposite margin, given by a well-marked alignment in normal fault. The package's emerging portion, above the organic material, presents a granular structure that tend to a Latosol pedogenesis and, thus, contrasts with the solid underlying material that has no stratigraphic traits.

Figure 6 – Terraces genetically connected to notch by tectonic control.



Besides the dated deposit, other evidence of recent deformational efforts are connected to the system in well-marked normal fault at the relief's alignment. At the hemi-graben distal to the alignment, a paleo-channel disconnected from the active drainage was found, and it corresponds to the former riverbed of the same channel adapted to the fault, which notched and migrated laterally to meet the divide. The decametric thickness of the line of rounded and subrounded pebbles with subangular accessory clasts indicates a strong water rework. It is, thus, a morphostratigraphic situation in which pedogenesis has transposed the residual charge through an argilluvic structural organization, falling away into subrounded angular blocks. The clastic material has a very homogeneous composition, restricted to quartz grains and feldspathic matrices of gneiss-granite. The adjacent horst, in its turn, shelters parallel suspended valleys disarticulated from the base level, with composed and scaled escarpments cut out in well-marked trapezoid facets.

Following, an organic horizon with a 2.7-meter unevenness from the active plain (T7) was the object of dating. In the *Scales Levels of Mantiqueira*, these registries are rarer when compared to upper montane environments, indicating the presence of subsident blocks, especially in the compartment of the *Southwestern Ridges and Hills* (Marques Neto, 2017), corresponding to the grabens where the Sapucaí river and some affluents are accommodated. The terraces were buried by coverage materials that converge to deep valleys, inducing more recent pedogenetic processes. In this specific case, there is still a pocket of blackened sediment that is already very lixiviated, compacted and hardened. In the upper portion, in contrast, biological activity is more intense, leading to the formation of a current organic horizon of lumpy aspect, flanked by yellow Latosols rich in gibbsite, suggesting that it is a small graben, very evident in the field.

The T8 sample concerns a terrace with wider development at the left margin due to lateral migration. Although the profile presents a very simplified facies ordination (coverage material and buried organic horizon), it is consistent, in the patterns found, with most organic horizons dating from the end of the Pleistocene.

Finally, the T9 deposit refers to a terrace that combines preserved fluvial facies, both from marginal embankments and flood plains and residual channel material. The emerging facies is characterized as a prominent A horizon corresponding to coverage materials that mix pedogenized colluvium with evidence of clay illuviation. Right below it, there is a stratum that also presents pedogenetic meaning, as it defines an incipiently-evolved underlying horizon; from the morphostratigraphic point of view, however, it corresponds to old alluviums that have suffered pedogenesis, with a well-marked mixture of some organic material coming from the overlying horizon A and mineral elements derived from clay complexification and lessivage. Right beneath it, a Bi horizon is truncated by gravel pits corresponding to old residual deposits with an average thickness of 10 cm, supported by rounded pebbles formed by fragments of gneiss and granite. These materials have a 1.5-meter unevenness from the active plain and over 2 m in relation to the thalweg, indicating a strong vertical notch and the formation of marginal embankments. Suggestively, the gravel pit is located in the block that tilted, inducing the migration of the channel to the opposite margin, where the deposits suffered erosion and were not preserved.

The dated material corresponds to paleo-alluviums that were not yet strikingly attacked by current pedogenesis. Dating to the Holocene, they are chronologically related to deposits that were dated in terraces not very far from the Aiuruoca river (between 2850 and 3000 years old) (Marques Neto; Perez Filho, 2013), indicating the frank influence of active tectonics, widely recorded by Santos (1999) in this watershed.

The interpretation of the results obtained along with the geochronological information obtained in other spots (Marques Neto, 2012; Marques Neto; Perez Filho, 2013) was important to understand the most recurring types in the southern branch of the Mantiqueira Mountains.

Relations between the terraces' genetic bond and local and regional geomorphologic organization

In common, the analyzed profiles present the reoccurrence of certain facies, with predominance of clay to sandy vertical-accretion deposits, with signals the strong vertical notch indicated by incision rate regardless of genetic bonds and of the section in which the deposits are. However, lateral migration processes have also left their marks, being very credibly related to fluvial plains whose development is incompatible with the load capacity of generally small channels, which were probably even smaller during the less humid periods at the end of the Pleistocene. Besides these recurrent facies, the organic horizons are also abundantly preserved above local base levels.

The processes of fluvial capture in the region are plentiful, and they can happen due to differential erosion (Paixão *et al*., 2019) or tectonic stimuli (Santos, 1999), reactivating headwaters, re-ranking the water network, and dynamizing the system's erosive organization. Among the analyzed terraces, two of them (T1 e T2) were formed due to capture processes that favor the channel's notch with changes in base level. The T1 terrace registers the capture of a portion of the São Domingos creek's waterhead by the Lavrinha stream, which belongs to the Itaim river basin, sharing a process that has been recurrent in the Camanducaia river basin, where channels were intercepted by affluents of the Itaim river, which reaches a base level that is over 100 meters below the Camanducaia river, making the highest portion of its basin, located at the foothills of the São Domingos Mountains, deeply rearranged by fluvial captures.

The T2 terrace corresponds to a capture from the headwaters of the Conceição river, which used to drain to the Grande river basin, but was abducted by a captor basin that belongs to the Paraíba do Sul river basin, whose reference base level is almost 500 meters lower, established at the passage of the Peixe river. This rearrangement favored the entrenchment of the channel and the abandonment of the organic horizons formed during the New Pleistocene at current terrace levels, dynamizing the retreat of the escarpments by erosive reassemble of the river that indirectly demand from the Paraíba do Sul river.

The lower portion of the the Mantiqueira Mountains corresponds to a set of fault escarpments, fault-inherited escarpments, and hills aligned in terraces whose higher unevenness is formed by top surfaces that reach the interfluvial line with the Paraíba do Sul river basin and by the scaled levels of the western portion. Many sills are thus formed in lithological contacts or by differential block uplifting, factors that also dynamize notches and the formation of fluvial terraces. Terraces T3, T4, and T5 present this genetic bond and figurate as important evidence of tectonic-erosive controls that give rise to a strikingly scaled regional relief.

T3 and T4 terraces are located in the lower portion of Mantiqueira, a submontane zone characterized by dissected erosive borders (Marques Neto, 2017), dissected by the channels that drain toward the Preto River, an affluent of the Paraíba do Sul river. They are two sequences of fluvial facies of the Monte Verde river, close to one another and truncated by paleosols, under the influence of erosive contrast between quartzite and softer lithotypes (schist, gneiss, and charnockite). These terraces preserve sequences of depositional facies, despite the aggressive notch formed in a alluvial plane just above 900 meters but connected to the passage of the Preto river below 500 meters, defining a sequence of terraces and small waterfall formations, with highlight to the Serra Negra quartzite sill downstream to the analyzed terraces. This structure separates upstream sequences of garnet-biotite-gneiss and downstream associations of gneiss and charnockite, belonging to the Juiz de Fora Complex (Soares *et al*., 2002).

In the case of T5, an upstream sill forms the bottleneck of the plain. Besides this control, it was also observed a capture that involved a wide area of the Cambuí stream basin, although the fluvial rearrangement happened within the basin. Anomalous changes in the channel's direction indicate rather significant tectonic influences.

The morphogenetic contexts where the terraces T6, T7, T8, and T9 lie did not present evidence of fluvial capture or structural sill, leaving only the hypothesis related to tectonic control acting on the uplifting and tilting processes of blocks that trigger vertical notch.

At the Grande river basin, the morphotectonic bond was interpreted for two samples, being also observed in other context that were not the object of a more vertical description. T6 sample refers to a Grande river terrace that was developed when the river had already reached the base level in its headwaters, crossing a long extension without intercepting topographic levels or abrupt sills. These materials that preserve organic horizons appear discontinuously in other segments of the fluvial plane of the upper Grande river, and its morphotectonic bond corroborates to the results obtained by Santos (1999) at the region.

The Aiuruoca river, the main affluent of the Grande river in its headwaters, besides having been the captor of a branch of this river in the highest portion of its drainage basin, also presents many features of preserved terraces, some of which have rocky outcrops. The described and dated material (T6) is thus fit to a morphotectonic control that had formed two or even three depositional levels throughout an extended lane of around 1100 meters of altitude, characterized by a low gradient of the channel, and matching a sudden shift in the NE-SW orientation to N-S. Throughout this extension, the orientation shifts are recurrent and happen as overlying structures are intercepted, also presenting shifts to E-W and NW-SE, based on the most general orientation.

At the Sapucaí river basin, a sample contained in top levels (municipality of Cristina, T8) was submitted to dating, as well as another one located on scaled levels (municipality of Itajubá, T7). Concerning T8, we highlight is location on an upper montane valley of the Glória creek of striking E-W orientation with the channel being confined to the fault, with no lateral migration eroding the notches and dominating vertical notches. The expressive vertical dissection is also observed at lower scaled levels, with T7 coinciding with a sudden deviation of the Lourenço Velho river, whose basin was highlighted by Oliveira (2013) due to the expressive tectonic control that works in its drainage area. At the sampled spot, the E-W direction is disfigured by deviations controlled by N-S systems, probably due to the influence of transcurrent faults with movement planes to this direction, even though they have not been found at the field. As for its landscape position, T7 is at the base level of the Lourenço Velho river (around 860 meters), which is kept until the confluence at the Sapucaí river, a level where there are preserved discontinuous terraces of up to two generations in distinct depositional levels.

Neotectonic influences over terrace position and distribution

The faciological analysis showed the prevalence of vertical accretion facies in solid structure, formed predominantly by material decantation in small Pleistocene and Holocene flood basins. The confined aspect of the valleys does not favor the development and stabilization of lateral accretion bars, which are thus restricted at the stratigraphic registry. Although pelitic facies dominate, it is striking that they are truncated by sand and clastic facies, indicating the strong rework present at the system. Pelitic meandering systems with well-developed fluvial plains are consolidated based on the Scaled Levels of the Mantiqueira that demand to the Upper Grande River plateau, as observed by Marques Neto (2012) in the Verde river basin.

Incision rates of the analyzed terraces varied from 54.176 mm/kA (Pleistocene) to 1258.71 mm/kA (Meghalayan), with higher rated observed in Holocene terraces, suggesting the continuity of penecontemporaneous neotectonic efforts and a plausible correlation to both chronologically-related tension fields identified by Silva and Mello (2011) at the region, which can have favored the continuity of notches, possibly catalyzed by the emphasis on post-glacial tropicality. Dislocations that were measured at the field on NE-SW and E-W-oriented faults reinforce the evidence of tectonic control over the Cenozoic evolution of the regional relief. One cannot dismiss, however, that higher incision rates on Holocene materials could be explained by a shorter landscape permanence period of the most recent deposits during the post-glacial period, a time of emphasized tropicality that favors more intense rework when compared to the Pleistocene.

The unevenness between preserved terraces and the current altimetry of active channels varied from 1.2 meters to 3.15 meters. Although the higher unevenness happen in Holocene terraces, the highest value (3.25) was observed for a New Pleistocene-aged deposit. Therefore, active tectonics and the tilting associated with it are elements that hinder a safe altimetric and chronological division among terrace levels, once these effects accentuate fluvial dissection and deposit rework by the river itself, thus enabling different incision rates for chronically-related depositional tracts.

The New Pleistocene and Holocene terrace ages indicate a very active geomorphologic organization, with prevalent erosive reorganizations at slopes and deep valleys, controlled by tectonic and structural factors consorted with the energy increment provided by tropicality. Pleistocene terraces are all adjustable to the Late Pleistocene, and the three Holocene terraces are chronically related to the Northgrippian and the Meghalayan (T7 e T9). New Pleistocene ages and terrace levels from the Lower Holocene (Greenlandian), as well as Northgrippian and Meghalayan deposits, have also been identified by Marques Neto e Perez Filho (2013) in the context of the Southern Mantiqueira and the Upper Grande River Plateau, indicating that older but still preserved terraces, at least more visibly, date back to the Late Pleistocene, having also had successive generations throughout the Holocene.

Usually, the terraces found at the Southern Mantiqueira do not adhere completely to the position of depositional levels and their ages, in the same way it was observed, for example, in the works by Oliveira (2012) at the Pomba river basin (MG), by Dias (2015) at the São Paulo Peripheral Depression, and by Rubira and Perez Filho (2019) at the Santa Catarina coast. The Mantiqueira Mountains have an particularity given by the high relief energy and strong rework at slopes and channels that lead to a discontinuous terrace distribution, which can vary from one to three depositional levels with strong adherence to local hydrogeomorphological factors (figure 7). Although a regional pattern was observed, and discussed here, local controls give rise to the observed variations.

Figure 7 – (A) Alluvial bed with depositional level, recurrent typology at the Sapucaí river basin (Itajubá, MG); (B) Sequence of three depositional levels at the transfer zone of the Lambari river in a segment of marked notch (Cristina, MG); (C) Depositional level in a valley coalescent to the Grande river (Bocaina de Minas, MG); (D) Sequence of two depositional levels suspended in relation to the active sedimentary strip at the Aiuruoca river basin (Aiuruoca, MG). In each picture, the numbers represent different depositional levels.

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These local controls were observed, for example, in the dated material for the Aiuruoca river (T9), chronically related to another sample dated in a similar material deposited by the same same river upstream, which also have recent Holocene age (Meghalayan), fixated at 2,580 years old. However, T9 materials are positioned in a second terrace level, while the upstream deposit lies on a first level, in a more open valley in the context of the Aiuruoca river basin. Further downstream, it is visible that the channel has entrenched itself, forming a narrower and more recent plain and abandoning a slender depositional level, still floodable during more severe floods, indicating distinct controls that determine different positions in the landscape for deposits with similar ages. In common, besides age, these materials underlie gravel pits whose roundness indicates water rework and a recent supply of debris by the slopes connected to these channel segments, notoriously operated during the last two to three thousand years.

The discussed depositional patterns happen throughout the whole southern Mantiqueira in Minas Gerais. It is possible to conclude, however, that the horizons enriched in organic material that refer to old Organosols and Gleysols are more plentiful at the *Mantiqueira Top Levels* and appear in upper montane alveoli much farther than the samples dated here, and which were geochronologicaly approached in other works (Marques Neto, 2012; Marques Neto; Perez Filho, 2013), which have identified chronically-related deposits for different compartments of the Mantiqueira and the Upper Grande River Plateau. At the *Scaled Levels*, despite the registered occurrence of rocky terraces and Quaternary deposits affected by tectonics, the most recurrent presence of longitudinal hemi-grabens gives rise to more continuous and well-defined base levels, with sudden contact among slopes and active plains. Still, in some blocks, terrace levels are formed, such as the materials dated from Itajubá and Maria da Fé. It is also interesting to note the occurrence of these materials in *dissected erosive borders*, a unit that covers the portion of the horst that is in plain erosion exerted by the channels that drain toward the Preto river.

Final Remarks

Fluvial terraces and their depositional archives were shown to be value geoindicators for the interpretation of important aspects of the neoquaternary landscape evolution, enabling measurements and inferences about the role of weather, lithology, and tectonics in the organization of the hydrographic network and in the formation of depositional tracts that were partly preserved in the landscape's superficial and subsurface structures.

The results showed patterns characterized by the prevalence of vertical accretion, recurrent presence of organic horizons indicating periods of relative stability and, in some cases, by the presence of clast-supported bedload. These patterns can occur in all genetic bonds considered among the analyzed deposits, both in the New Pleistocene and in different Holocene times. Depositional registries, therefore, do not indicate by themselves severe changes in the dominant processes of the studied geomorphological system, pointing out that processes of notching, capture reorganization, and hydromorphism have transposed the passage from Pleistocene to the Holocene and remained in the landscape. This finding is very suggestive of a morphotectonic requirement nesting the previously mentioned New Pleistocene and Holocene tension fields in favor of a much prevailing notching. In addition to the structural control that gives rise to differential erosion, neotectonics also influence the cluster of fluvial captures that happen in the Mantiqueira Mountains and other compartments of the Crystalline Plateau of the Brazilian Southeast.

The presented set of results shows, thus, processes that mark strongly the regional geomorphological system, which is very prone to local controls, with genetic and evolutional meanings that are often controlled by altitudinally arranged base levels that scale based on the summit surfaces of the Mantiqueira Mountains, which, in their turn, define a regional pattern. As mentioned in the text, it converges to results from other works that estimate regional tectonics, the role of captures in the evolution of the relief and the age of fluvial terraces, usually dating from the national production between the Pleistocene and the Holocene. As an opportunity, we advise fomenting studies in a detailed scale, thus improving the chronological precision and decoding in an increasingly more meticulous manner the evolution of deep valleys in escarpments with the intrusion of micropaleontological techniques and the densification of faciological and allostratigraphic analyses.

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