Geomorphological Evolution of River Forms in Humid and Semi-arid Tropical Environments

Éverton Vinícius Valezio, Kleber Carvalho Lima, and Archimedes Perez Filho

Abstract Fluvial channels are directly affected by changes triggered by natural and anthropic phenomena, adapting to new conditions in different temporal-spatial rhythms. In order to demonstrate how certain techniques can support the interpretation of the geomorphological evolution of tropical river systems, we selected two rivers in different climatic conditions: Jacaré-Guaçu (SP) in humid tropical regimes, and Itapicuru (BA) in semi-arid regime. By means of aerial photographs, orbital images, aerophotogrammetry by remotely piloted vehicle, description of the deposits, and absolute dating by Optically Stimulated Luminescence (OSL), it was verified that, even in distinct systems, the processes of formation of fluvial terraces were active in more humid conditions, however, in different periods, more current for Itapicuru and older for Jacaré-Guaçu, demonstrated by the morphology of the paleochannels and by the absolute dating. Thus, it is believed that the techniques used for the interpretation of the geomorphological evolution of river systems can improve the studies of landscape evolutionary models in line with considerations of the sensitivity of river systems to absorb, resist, or recover from disturbances in their own temporalities.

1 Introduction

Difficulties inherent to the spatialization of relief are recurrent, given the complexity of representation of the terrestrial model. In fluvial systems, sensitive to natural events

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(tectonics and climate) and, more recently, to anthropic factors, the identification of forms and features is crucial for the understanding of their evolution over time.

The interpretation of changes in river channels and the reconstitution of paleoenvironments are linked to the understanding of fluvial dynamics at the most different scales and environmental conditions, being of great importance the association of current and past processes associated with studies about fluvial terraces, paleochannels, and floodplains in hot and humid (Hamilton et al. 2007; Morais et al. 2020) and hot and dry environments (Norton et al. 2016; Larson et al. 2020).

However, the complex analysis and interpretation of fluvial environments in tropical regions are often hindered by the superficial dynamics of the landscape. Hydrological variations, transformations in pedological cover by slope dynamics, and human action end up masking river morphologies that respond to current and past climatic conditions, as well as enhancing the rate of change that took place at geological scales (Sridhar 2007; Hughes et al. 2015; Lima and Lupinacci 2019).

In this sense, the identification, mapping, and characterization of forms and attributes of the river landscape in these environments can be considered complex steps to be developed, constituting real methodological challenges for the researcher. Traditionally, these steps are carried out through systematized cartographic bases, aerial photographs, satellite images, and field procedures, such as translations in toposequences and stratigraphy of alluvial deposits (Straffin et al. 1999; Bisson et al. 2011; Celarino et al. 2013; Piégay et al. 2020; Molliex et al. 2021).

However, new tools have emerged in recent decades as a way to expand the methodological possibilities and improve interpretations regarding the genesis and geomorphological evolution of river systems. New technologies such as remotely piloted vehicles (RPVs), high spatial resolution orbital images, ground-penetrating radar (GPR), and absolute dating have been added to previously used tools in order to obtain more consistent results.

In the Brazilian scalar context, with the different climatic regimes and their structural heterogeneity, we selected two rivers with distinct process characteristics: Jacaré-Guaçu River and Itapicuru River. In the case of the first one, it is disposed of in the Sedimentary Basin of Paraná, latitude 22º, where the hot and humid regime is dominant. The river is a tributary of the right bank of the middle course of the Tietê River, in the state of São Paulo, constituting one of the main rivers of Brazil, both for its capacity for hydroelectric generation and for crossing the most populous state of the country. As a main mark, the Jacaré-Guaçu has meander typology and preserves, in certain sectors of the river plain, forms of its lateral rambling and incision of the bed, while we still encounter hydrodynamic changes that are no longer present in the river plain (Valezio 2016). On the other hand, the Itapicuru River is located in the northeastern region of Brazil, and crosses several structural units, such as the headwaters plateaus, passing through depression and the tablelands in the lower course. Due to its position in low latitude (11º), there are hot and dry air masses with a predominantly semi-arid climate. The longitudinal structural modifications, added to the climatic and anthropic dynamics, are capable of determining patterns and changes in the typology of the river channel throughout its longitudinal extension (Lima et al. 2021).

Thus, we seek to evidence and discuss aspects of fluvial dynamics in these different environments from the identification of forms and processes, as well as the correlation with absolute dating, aiming to understand the functioning of landscapes in the context of geomorphological evolution at different temporal-spatial scales.

2 Study Area

Running 238 km longitudinally, from the headwaters in Itirapina/SP and mouth in Ibitinga/SP, the Jacaré-Guaçu River is part of a humid tropical system, marked by seasonality, with pedogenesis accentuated by the presence of water throughout the year, which quickly decharacterizes the sedimentary deposits from fluvial action (Celarino and Ladeira 2017). The average precipitation of 1402 mm in the upper, 1391 mm in the middle, and 1257 mm in the lower course (IPT 2003), with higher outflows between the months of October and March, links to the higher average annual temperatures in this period 22 °C (Costa 2005). Another fundamental characteristic for understanding the functioning of the river is the lithological heterogeneity along its course and by the transition of geomorphological compartments: from the sandy-basaltic Cuestas to the Paulista Western Plateau, following in the NW direction until the middle course and W until its mouth (Fig. 1). Regarding the geological substratum, the Botucatu and Serra Geral formations are highlighted (Riccomini 1997). The Mesozoic formations vary along the river, alternating meandering alluvial sectors on the sandstone formation of Botucatu and sectors with less lateral migration (in bedrock embedded in the Serra Geral basalts).

The Itapicuru River is 567 km long, whose sources are located in the northern portion of the Diamantina Plateau and crosses the Sertaneja Depression and the Coastal Tablelands until it flows into the Atlantic Ocean (Lima 2017). The topographic variation occurs longitudinally, with low altitudes on the coast, gradually increasing upstream, until reaching more than 1200 m of altitude. Similarly, the spatial variation of the climate is longitudinal (SEI 1999), with humid to sub-humid climate on the coast, sub-humid to dry, semi-arid, and arid climate in the central portion of the drainage basin. In the western sector, in turn, the orographic effect in the transition between the depression and the plateau favors the formation of wet areas in altitudes above 900 m. The lithological and structural variety is significant, whose tectonic domains include the São Francisco Province, composed of syenitic and granitic suites, felsic volcanic rocks, volcanic arcs, orthogneisses associated with granitoids, igneous rocks, among others, dating from the Archean-Proterozoic. The Tucano Central sedimentary basin is of Cretaceous age, composed of the Marizal Formation (associations of sandstones and conglomerates with shales and limestones), São Sebastião Formation (medium to fine sandstones with coarse levels at the base and intercalations of siltstones, argillites, and shales) and Islands Group (medium to coarse sandstones alternately, with intercalations of shales and siltstones) (Kosin et al. 2004).

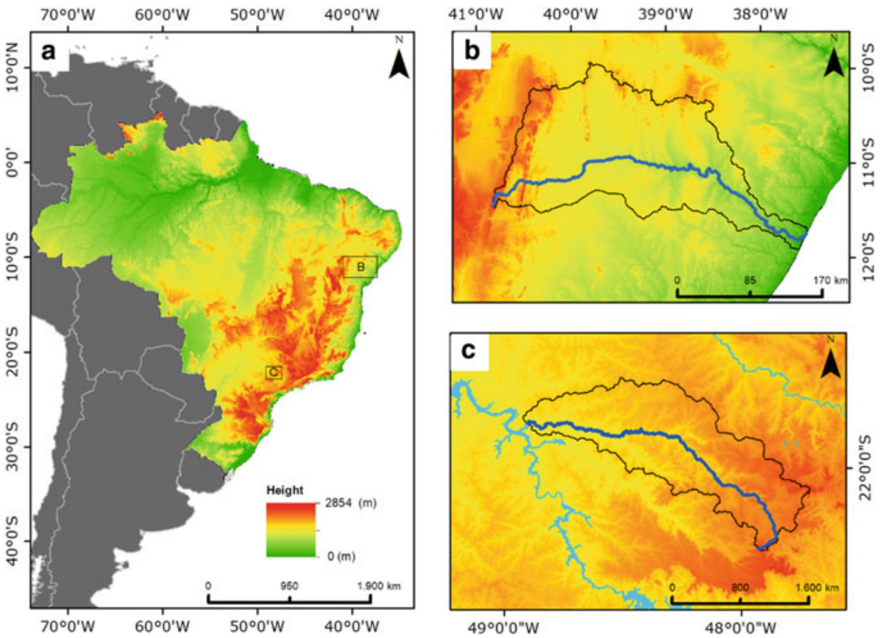

Fig. 1 Location of the study areas. **a** topographic and latitudinal variation of the hydrographic basins in the Brazilian territory. **b** Itapicuru River watershed, Bahia State; **c** Jacaré-Guaçu River watershed, São Paulo State, and its outlet on the Tietê River

3 Materials and Methods

The geomorphological mapping of the fluvial plain of Jacaré-Guaçu and Itapicuru rivers was performed by means of stereoscopic pairs of aerial photographs of the years 1962 and 1975, respectively, both in 1:25,000 scale. From the same, was used for the two cases, orbital images from the Rapideye satellite with spatial resolution of 5 m orthorectified, and images from the CBERS 2B-HRC satellite, with spatial resolution of 2.7 m. In a complementary manner, the SRTM (*Shuttle Radar Topography Mission*) digital elevation model was used, with a spatial resolution of 30 m. For the Jacaré-Guaçu River, an RGB aerophotogrammetric survey was conducted by remotely piloted aircraft (DJI Phantom 4 Advanced), with GSD of 4 cm/pixel and planimetric errors of 11.53 cm and altimetric errors of 29.65 cm, generating orthomosaics, DTM and DEM for an area of approximately 13 km^2 in the middle course of the river.

Fieldwork was carried out for control point inference, translations, and description of sedimentary and pedological profiles at low terrace and floodplain levels. Absolute dating by Optically Stimulated Luminescence (OSL) was used to estimate the formation time of the fluvial plains and embedded forms, correlating them to climatic and/or tectonic factors. Ages were estimated by the SAR (Single Aliquot Regenerative-dose) protocol, as per Murray and Wintle (2000) and Wintle and Murray (2006).

The protocol was used for all samples collected, differing only in the number of calibration curves. Fifteen aliquots were established for the samples of the Itapicuru River and 25 aliquots for the Jacaré-Guaçu River, given the temporal difference of sample collection (years 2014 and 2019, respectively).

Dating by OSL and the use of remotely piloted aircraft have been widely used in Brazilian geomorphological studies in the last ten years. Tools already used for the evolutionary interpretation of the landscape, such as aerial photographs, satellite images (although now with better spatial resolutions), and the descriptions of the forms and their constituents tend to remain, although the results may lose significance when not linked to new technologies and possibilities of analysis. We emphasize that new methodologies should be increasingly incorporated to overcome the limitations imposed by the already consolidated techniques, widely used in geomorphological studies in Brazil.

4 Results

4.1 Jacaré-Guaçu River

On the Jacaré-Guaçu alluvial valley, two levels of low terraces were identified: Level T1, about nine meters above the riverbed, which is preserved in the landscape in the middle and lower course, developed in alluvial environments over sandstone rocks of the Botucatu Formation; and Level T2 elevated about twelve meters above the current level of the fluvial channel. The T2 level, identified by photographs dated 1962, is in a more advanced erosion process, losing its genetic-morphological characteristics. The T1 level, more preserved and easier to access, is characterized by an abrupt transition between sandy material (preponderantly medium sand and fine sand), with millimeter-sized granules and pebbles, and oxirection marks associated with roots, classified, overlaid by fine material (>50% clay and silt compound), oxirreduction marks up to 90 cm deep and medium to large lumps in the first 20 cm (A horizon), clear transition to B1, with light lumpy structure (30–45 cm depth), and plastic and sticky, apparently massive B2 horizon with lumpy structure—associated with modern roots—when manipulated (Fig. 2). Part of level T1 is covered by peat bog, part of which has already been anthropically remobilized. Level T1 was dated by OSL at 140 cm depth, dating 7920 ± 1440 BP (Sample MDT1), in the innermost portion, and 7670 ± 1220 years BP (Sample BT1), in the border portion.

The DEM, DTM, and orthoimagery indicated the presence of upper meander loops in amplitude, width, and length in both low terrace levels of the Jacaré-Guaçu River, differing morphologically and morphometrically from the current and recently abandoned meanders (Figs. 3 and 4). Furthermore, translations confirmed the difference in depth between the meanders sustained on the terraces and the present ones, besides the associated deposits, coarser (coarse sand to blocks) in the older ones, and more sandy-clayey in the modern loops. The scars of the past processes and their presence

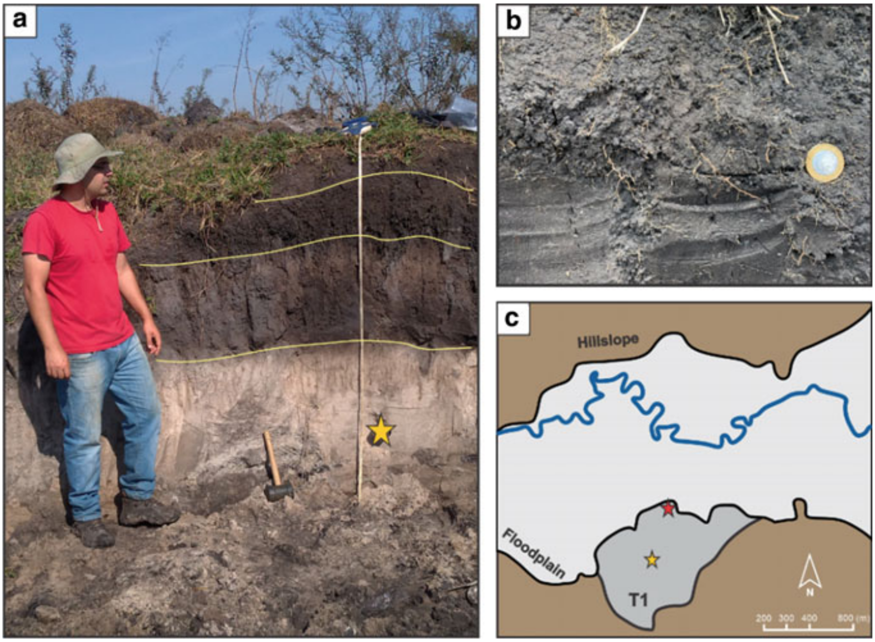

Fig. 2 Low terrace level (T1) in the middle course of the Jacaré-Guaçu River. **a** Sedimentary material constituting the low terrace, with subdivision in horizons; **b** Transition from the A to B1 horizon, highlighting the lumpy structure of the superficial part; **c** Location of the sample collection points for dating by OSL. Point in the middle portion of the terrace MDT1 (yellow star) and in the border portion BT1 (red star)

in the landscape allow morphometric comparison between the forms and, consequently, between the patterns established still in the Middle and Lower Holocene in relation to modern characteristics (differences in land use and vegetation) (Fig. 4).

Meander alteration processes typical of deconfined channels in the middle course, with significant cutoffs, reducing both the sinuosity of the sector (2.20–1.85) and the total length (404 m); and in the lower course, especially in the post-confinement sector of the river by the Serra Geral Formation, with four cuts, rotation and enlargement processes, causing the channel to reduce its sinuosity from 2.65 to 2.08 and its length from 5417 to 4259 m, between the years 1962 and 2012. In this second sector, it was possible to identify the presence of settling basins, abandoned meanders, and scrollbars, in addition to, as in the middle course sector, the asymmetric position of the fluvial channel in its fluvial plain (arranged on the right bank).

Another factor addressed in the mappings was the retraction of the riparian vegetation due to the advance of sugar cane and orange plantations, facilitating the erosive process of level T2, heading toward level T1.

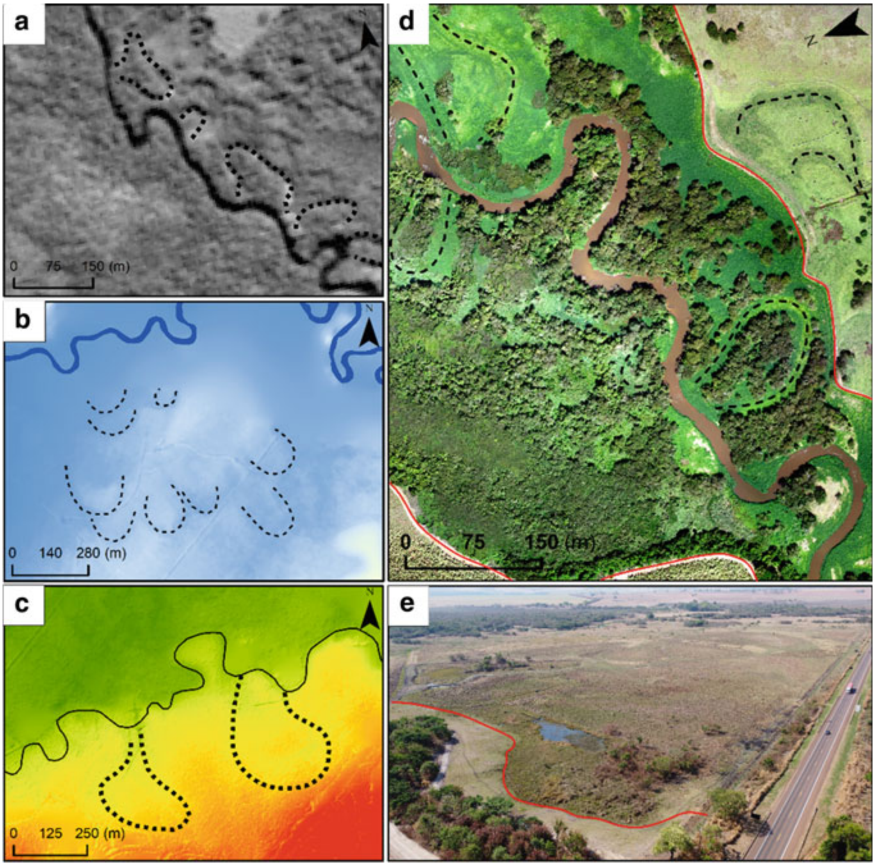

Fig. 3 Current, recently abandoned, and past meanders of the Jacaré-Guaçu River are identified by RPV and CBERS2B images. **a** Jacaré-Guaçu River and centennial-scale abandoned meanders identified by CBERS2B satellite; **b** Intermediate-level floodplain meanders identified by RPV DTM; (C) Lower terrace (T1) paleomeanders identified by RPV DEM; **d** Current river channel, recently abandoned meanders, and subdivision between meander belt and possibly new low terrace level formation made by RPV orthomosaics; **e** Aerial drone image of the division between low terrace (T1) and floodplain/new low terrace level

4.2 Itapicuru River

The orbital products used in the identification and mapping of the terrace levels and floodplain of the Itapicuru River contributed significantly to the understanding of the fluvial dynamics since they allowed the visualization of features indicative of these dynamics. The granulometric analysis of the profiles and the absolute dating by OSL favored the understanding of the dynamic behavior of the river during the Holocene to the current time scale.

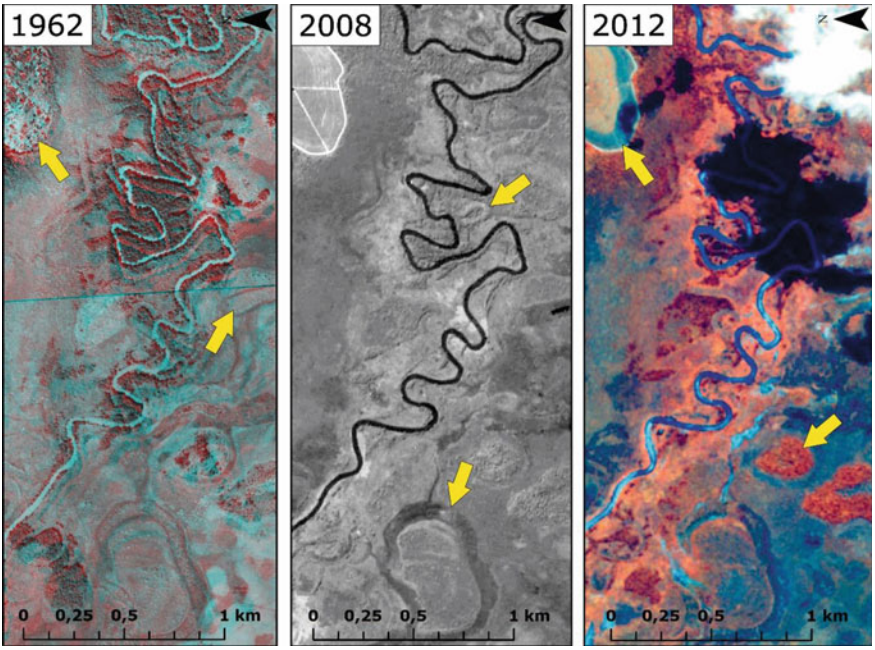

Fig. 4 Overlay of the products used for the lower Jacaré-Guaçu River—3D aerial photographs, Cbers-2B, and Rapideye—to vectorize the river at different times and identify alluvial valley forms and processes. (1962) Arrows indicating land use and former river bed (stereoscopic pairs); (2008) arrows indicating difference in size and morphology between meanders at low terrace level (T1). At bottom, arrow indicating larger size meander, and at top, recently abandoned meander (CBERS2B-HRC); (2012) false-color composition highlighting areas of riparian vegetation in shades of red, with arrows indicating difference in use between periods (upper arrow) and riparian vegetation in stronger shades of red at low terrace level (lower arrow) (Rapideye image, false-color composition 5-4-3 RGB)

The terraces occur discontinuously along the valley, and in the sections with strong lithological and structural control, terraces do not occur. In the crystalline basement, up to two levels of terraces occur: [i] the terraces of the pre-littoral section, associated directly with the general base level of the hydrographic basin, the Atlantic Ocean; [ii] the terraces of the inland crystalline sector are associated to the regional base levels as the anticlinals and synclinals of the Itapicuru Greenstone Belt. In the sedimentary sector, the terraces present up to four levels (Fig. 3) and have relations with the Inhambupe fault system, which limits the sedimentary basin with the precoastal crystalline sector.

The oldest terraces (T4 and T3) are positioned about 30 and 20 m, respectively, above the current river level. They are terraces whose surface cover material presented a muddy sand and sand texture, with absence of stratification (Fig. 5). These levels presented OSL ages of ~ 22,100 years BP (T4) and ~ 9,800 years BP (T3), and are currently in a dissection process. The T2 level occurs only in two sectors. The spatial

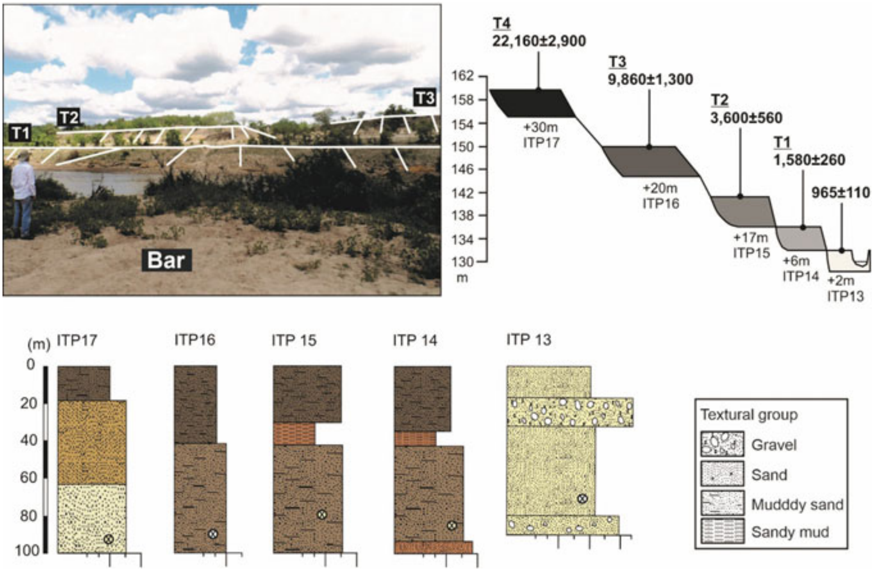

Fig. 5 Representative reach of the Itapicuru River in the sedimentary sector with four terrace levels and sidebar in the floodplain, with OSL ages chronologically consistent with topographic position

pattern identified in the mapping demonstrated that in the sedimentary sector, the T2 levels constitute the most preserved surfaces of the terraces. They present a muddy sand texture with sandy mud texture intercalations. The ages obtained are positioned between ~ 3,000 and ~ 2,000 years BP. In the pre-littoral crystalline sector, T2 level is remnant, occurring in two fragments with age ~ 8,000 years BP and muddy sand texture. The T1 level occurs in all sectors, being narrower and with ages around ~ 2,000 and ~ 800 years BP. They show predominantly muddy sand texture along with the profiles, interspersed by sandy mud or muddy mud texture units. Paleochannels of drainage occurs on the surface of the terraces (Fig. 6), indicating changes in the hydrological pattern in this time interval.

Alluvial plains occur discontinuously along the Itapicuru in the form of pockets. However, they are well developed in parts of the sedimentary sector, where they present features such as dykes, lateral bars, and abandoned channels (Fig. 4), indicative of the current dynamics of the Itapicuru. Dike deposits evidence of sandy-textured allostratigraphic units interbedded with muddy sandy-textured units whose OSL ages are ~ 570 years BP. The lateral bars are composed of sandy deposits interspersed with gravelly units and clayey layers and are representative of deposition in the bar itself or of bedrock that migrated by avulsion. They indicate the lateral migration of the Itapicuru River by oscillations in river discharge over the last 800 years, according to the OSL ages.

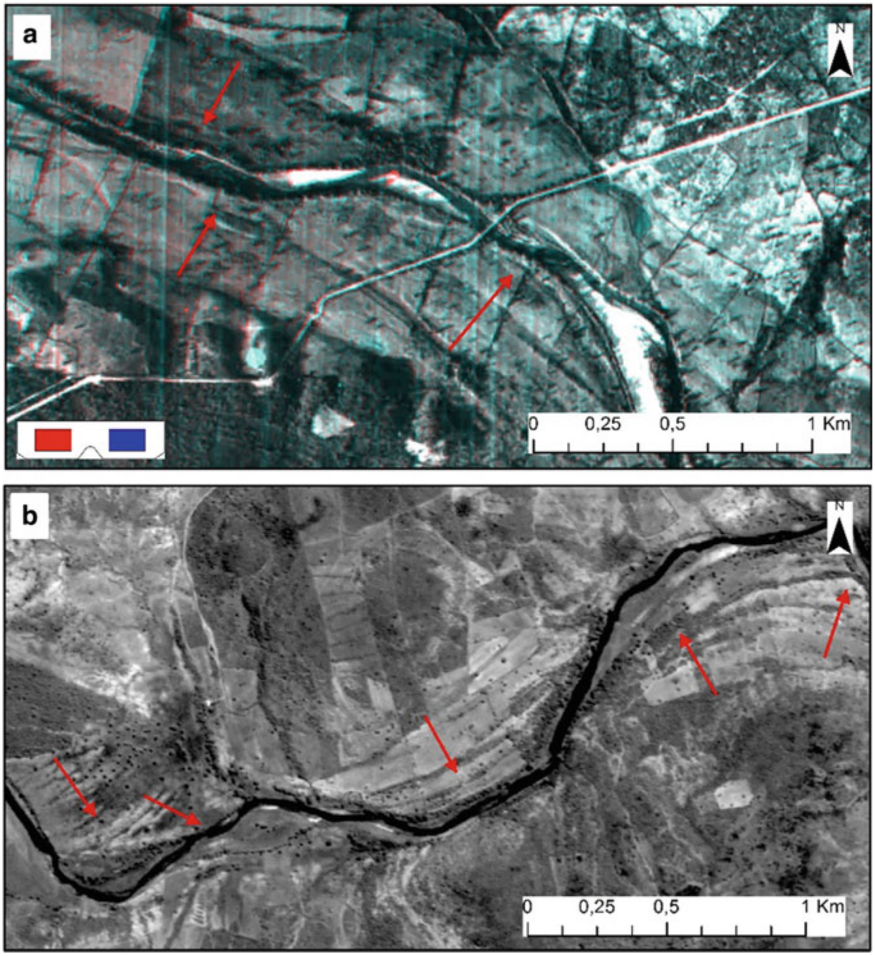

Fig. 6 Sections of the Itapicuru River with indications of lateral migration dynamics in the last 2000 years: paleochannels with preferential direction of river migration at T1 levels; and lateral bars in the floodplain, identified in stereoscopic pairs of aerial photographs (**a**); paleochannels at T1 levels and abandoned beds in the floodplain with preferential direction of migration, identified in Cbers-2B images (**b**)

5 Jacaré-Guaçu and Itapicuru: Holocene Evolution

The identification of the forms by the use of the different techniques allowed, in plant, the recognition of landscape patterns by the images and the connection of the forms to the processes, with previous understanding of the functioning of the alluvial valley in these different environments.

The constituent materials of the T1 level indicate a change in the energy pattern of the Jacaré-Guaçu River, associated with possible lateral migration, when the level becomes filled by overbank deposits, such as the clays and silt that dominate the surface horizons, and the chemical alteration of organic matter into peat in depressed areas of the former floodplain (Corrêa et al. 2016). Deposits correlated to periods of higher transport energy (blocks and pebbles), present in the former riverbeds at the low terrace level, would be linked to the river incision process and the abandonment of the former floodplain. The absence of sedimentary structures in the overlying sandy package may indicate the rapid transformation of deposits into soils by chemical and biological alteration in warm and humid environments (Celarino and Ladeira 2017), contrasting with the Itapicuru River profiles.

The forms arranged in the river plain are also uncharacterized by climatic conditions, as well as by flood flows and new conditions of use, which resignify the hydrological role of the river plain. Added to this is the reduction in sinuosity in the last 50 years, contrasting with the morphology of the abandoned channels at low terrace level, which are essentially sandy and less sinuous. Both reductions in sinuosity indicate a change in the processes and behavior of the river, with emphasis on the passage from an intermediate sinuosity to a smaller one in the lower reaches, and are also interpreted as a consequence of the self-organization of the river in relation to the new energy balance (Langbein and Leopold 1970; Timár 2003).

The absolute ages of the T1 low terrace level reinforce the transition of environments around ~ 8,000 years BP, as reinforced by another dating (OSL and ^{14}C) at the same plateau in the area (Valezio 2016; Cheliz and Gianinni 2020). The shape mapping and geochronology of these low terrace cover materials combined indicated the periods of river incision and lateral migration throughout the Holocene. As present in Fig. 3D, in the dating of the distal floodplain (not yet properly refined) and verified in the field, there is the possibility, in the recent period, of a new incision of the Jacaré-Guaçu riverbed and transformation of the present extensive floodplain into a new low-level fluvial terrace.

The paleochannels still preserved were identified by the orbital and non-orbital images, and those of the Jacaré-Guaçu River are morphologically and morphometrically different from the current ones, pointing to different hydraulic conditions. In addition, the asymmetry identified in the Itapicuru River and Jacaré-Guaçu River would be linked to processes of tectonic order, capable of influencing the erosion or pleasanting of the alluvial valley (Leeder and Alexander 1987; Latrubesse and Kalicki 2002; Kane et al. 2010), such as the presence of low terraces preponderantly on one of the banks.

In the Itapicuru River, the variation in the textural groups of the terraces indicated changes in the fluvial energy pattern over time achieved by absolute ages (Lima 2017; Lima et al. 2021). However, more significant variations were identified only in the recent deposits, which correspond to the marginal dykes and lateral bars. According to Tricart (1958) and Tricart and Silva (1968), significant changes occurred in the regional climatic pattern during the Holocene, which contributed to the intense deposition of coarse material at the bottom of the Itapicuru valley in the dry phases. Abandonment of the floodplains through channel incision would have occurred during the wet phases. The OSL ages obtained in this research demonstrated that the T2 and T1 levels were elaborated in a more recent time period than the one previously proposed, that is, during the Upper Holocene. Regional paleoclimatic models pointed out the current condition of semiaridity established in the last 4000 years (De Oliveira et al. 1999; Auler et al. 2004; Novello et al. 2012), but with the occurrence of small humid intervals observed mainly in the higher sectors of the Chapada Diamantina.

Thus, it is believed that the formation of the older terrace levels, T4 and T3, may have been triggered by changes in regional climatic conditions, as highlighted above. The levels of T2 and T1, in turn, may have been elaborated under conditions similar to the present ones; however, oscillations in river discharge as a result of increased precipitation upstream of the Itapicuru at decadal intervals would have been responsible for the intense lateral migrations of the river, as visualized in the orbital products. During regional wet events of the last two thousand years (Novello et al. 2012), it is possible that river dynamics were characterized by vertical incision simultaneously occurring with lateral migrations (Tofelde et al. 2019) at short time intervals (Limaye and Lamb 2016).

Over the last 800 years, lateral migration of the Itapicuru would have predominated until the current period, where evidence of this dynamic has been observed in the deposits of the sidebars and in the mapping carried out. However, this dynamic occurs in a spatially restricted manner as the current floodplain is narrow and discontinuous along the channel (Lima 2017). In several sectors, the T1 levels are in an advanced stage of lateral erosion with undermining at the base of the terraces and flooding of the bed, as a result of current anthropic interventions that favor greater vulnerability of the banks of the beds and the scarps of the T1 levels.

The techniques used to obtain the results, from aerial photographs to remote sensing, added to the dating, showed that the records of changes in the fluvial landscape of both rivers are Holocene. These characteristics identified for both rivers, given the application of the chosen methodologies, can be replicated for the study of fluvial environments in different climatic contexts, linking the identification, description, chronology, and interpretation of different levels of evolution of fluvial geomorphological systems.

6 Final Considerations

The work illustrates how the combination of different methodologies allows the interpretation of the geomorphological evolution of different river systems. The similarities of the techniques employed also opened space for adaptations of use for each type of environment, given the relationship of the forms and processes to be influenced by different dynamics, although on a long-term scale, the processes that triggered the formation of the terrace levels were based on variations in humidity and temperature. Both the morphology of the old meanders in the humid tropical sector and the river deposits in the hot and dry tropical sector demonstrate that hydrodynamic variations are still recorded in the landscape.

With different evolutionary pictures, attested by the absolute dating, the rivers responded to the extrinsic alteration factors according to the past and present regional characteristics. While the river is present in the state of São Paulo, the action of the humid tropical climate is preponderant in the configuration of the fluvial plain in the eight thousand years BP, having its last process of abandonment in the Upper Holocene, the river present in the state of Bahia has still preserved along its course four levels of low fluvial terraces, with sectors with greater tectonic imposition and with marked characteristic of the climate variations in the Holocene, having established itself more recently in hot and dry tropical climate.

Even with two fluvial units, their distinct environmental configurations, and complexity of geomorphological responses to different regional stressors over time, we can analyze and discuss them from the perspective of forms and processes. Semi-arid environments arranged in the same territory of humid tropical climates, as is the case of Brazil, reveal the potentiality of studies of integrated river systems still to be explored.

The fusion of techniques for better apprehension of the landscape should still be expanded with the arrival of new methodologies. The popularization and cheapening of more advanced procedures, without leaving aside established techniques, are and will be crucial for research to be further refined and deepened for the interpretation of these increasingly complex natural systems.

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