

Fluvial Morphometry Applied to Studies of Drainage Rearrangement Processes in the Iron Quadrangle—Brazilian Atlantic Plateau, Southeastern Brazil



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Abstract The work seeks to illustrate the applicability of morphometry in the investigation of processes of drainage rearrangement and relief configuration in the Iron Quadrangle, one of the compartments of the Brazilian Atlantic Plateau. To this end, the studies were concentrated in the Conceição River basin, a tributary of the Upper Doce River, southeastern Brazil. Indices that point out drainage migration processes and that allow inferences about the lithostructural and morphotectonic control of the hydrographic network were applied, namely: RDE (Declivity-Extension Ratio), FABD (Drainage Basin Asymmetry Factor), and FSTT (Transverse Topographic Symmetry Factor). In a complementary way, aspects of the morphology and geometry of the drainage were surveyed using satellite imagery. The results show evidence of model evolution from first-order *knickpoints* and channel migration as a result of structural rearrangements. An old tributary of a neighboring watershed (Barão de Cocais River) would have been pirated by a direct tributary of the Conceição River, indicating greater denudational aggressiveness of this basin.

1 Introduction

The dynamics of the drainage network is one of the main vectors of configuration and transformation of the relief. Its mechanisms involve different processes that include rearrangements of the position and routes of springs and watercourses and, consequently, the reorganization of hydrography at the watershed level. These modifications can be conditioned by the climatic framework, in terms of the dynamics of the hydrological cycle and balance at different scales, and by the geological framework, in terms of different levels of rock resistance to denudational processes, the degree of lithological deformation, the density and characteristics of lines of weakness (structures) and also the tectonic dynamics, as well as by anthropic factors that may interfere with the stability of river systems (Magalhães Júnior and Barros

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2020). In any case, changes in the relationship between denudational and depositional processes of a river system, internally and comparatively about neighboring systems, can generate pictures of greater or lesser erosive “aggressiveness”, with acceleration or decrease of processes of remnant erosion, retreat of headwaters and connection-disconnection of hydrographic arteries. Diversions and relatively quick changes of direction of fluvial segments can also result from physical-environmental dynamics and lead to drainage rearrangements. Commanding these transformations from the regulation of fluvial processes, the base levels of different scales of action are essential elements in the approach of the theme.

Drainage network rearrangement processes comprise a traditional focus of geomorphological studies internationally (Vieux 2016; Roberts 2019; Schoenbohm 2019; Struth et al. 2020; Hooshyar et al. 2020). However, there is a usual difficulty in obtaining robust field evidence to underpin investigative processes, such as fluvial deposits that indicate changes in transport capacity/competence or even changes in position/location of watercourses. Not coincidentally, most of the evidence addressed comes from the parallel analysis of the geometry and organization of hydrography, as well as morphology, from the application of geoprocessing and remote sensing techniques (Cherem et al. 2009; Wilson et al. 2012; Wu et al. 2019; Oyedotun 2020). The techniques of treatment and analysis of aerial images have been evolving rapidly in recent decades, opening the range of options for application in geomorphological studies, including those related to morphometry, as in the case of Digital Elevation Models (DEM) and Terrain Models (TTM) whose development was driven by the research efforts of SRTM—*Shuttle Radar Topography Mission* (Brubacher et al. 2012; Ibanez 2012).

Although Brazil has, in relative terms, few works on the subject, there has been significant development in scientific production in recent decades, particularly those referring to evidence of drainage rearrangement in large watershed dividers (Cherem et al. 2013; Salgado et al. 2018; Silva et al. 2019; Nascimento et al. 2019; Paixão et al. 2020). The application of morphometric indices and comparative techniques for investigating denudation rates in neighboring basins, such as ^{10}Be isotope analyses, has been contributing to this scenario (Salgado et al. 2004; Varajão 2009; Cherem et al. 2012; Salgado et al. 2012).

The Iron Quadrangle (QF) is one of the most studied geological domains of the Brazilian Atlantic Plateau (eastern portion of the country), a fact aided by its mineral wealth such as iron and gold. However, the region still lacks studies and information on the evolution of its drainage network and the role of fluvial processes in the configuration of the relief. On the other hand, some research already points to evidence of spatial derangement processes of the regional hydrography in the QF, particularly in the Maracujá and Ribeirão Preto river basins (Salgado et al. 2007; Magalhães Júnior et al. 2012; Barros et al. 2019; Costa et al. 2018; Magalhães Júnior 2020; Lopes et al. 2020). The case of the Ribeirão Preto basin, located in the Upper Rio Doce basin, is particularly rich as it involves hydrographic, morphological, and sedimentary evidence. Medina et al. (2005), Fabri et al. (2008), and Barros (2012) raised hypotheses of fluvial capture in the area, but there is a need for further research and survey of evidence for its confirmation. In this context, the present work seeks

to illustrate the applicability of morphometry in the study of evidence of drainage rearrangement in the Ribeirão Preto basin, signaling the possibilities of studies on the evolution of the fluvial network and the relief configuration in the Iron Quadrangle and the Brazilian Atlantic Plateau.

2 Study Area

The study area is located in the Brazilian Atlantic Plateau, Southeastern Brazil, particularly in the Iron Quadrangle domain (Minas Gerais state)—Fig. 1. The Preto stream is a left margin tributary of the Conceição River, a tributary of the Doce River, having its headwaters located in Serra do Gandarela—the eastern topographic divisor of the QF, specifically in the Conceição do Rio Acima district, municipality of Santa Bárbara/MG. The Conceição River also presents headwaters in the same region, known as the Conceição River Anticline Valley and where a large part of its valley is situated. The springs outcrop at the foot of the crest of the Ouro Fino

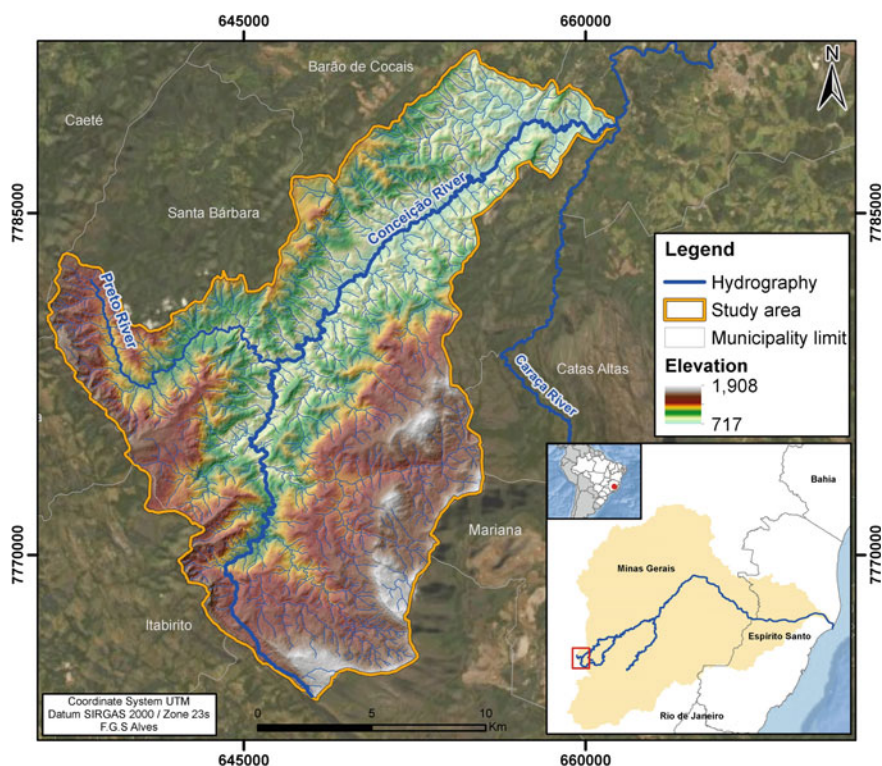


Fig. 1 Contextualization map of the study area. *Source* Prepared by the authors

Mountains syncline, following the NE-SW axis in a south-south direction, passing through the hanging depression of the Gandarela syncline, where, after about 90 km from the source, it flows into the Una River downstream of the city of São Gonçalo do Rio Abaixo/MG (Saadi et al. 2005; Barros 2010, 2012).

According to the geological characterization of Alkmim and Marshak (1998), the lithological substrate is mostly part of the Rio das Velhas Supergroup, specifically the Nova Lima Group, which consists mainly of green shales of metasedimentary and metavolcanic origin, phyllites with intercalations of quartzites, grauwackes, dolomites, talc schists, and iron formations. However, there are important areas of headwaters in the rocks of the Minas Supergroup, represented by the Caraça and Itabira groups, besides rocks of the crystalline basement in the lower course. In the Caraça Group, the Moeda Formation is composed of conglomerates, quartzites, and phyllites, while the Batatal Formation has sericite phyllites and carbonatic sediments. In the Itabira Group, the Gandarela Formation is composed of carbonate rocks (mainly dolomites), itabirites, and phyllites, while the Cauê Formation, at the base of the group, is composed predominantly of dolomitic and amphibolitic itabirites, with small lenses of phyllites. In the northern portion of the basin, there is a small area in the Espinhaço Supergroup, represented by the Cambotas Formation, which is formed by Mesoproterozoic quartzites, with thin lenses of conglomerates present in the Cambotas and Tamanduá mountain ranges. It is also worth mentioning the occurrence of Quaternary superficial formations such as alluvial deposits and cangas, as well as diabase dikes that fill faults in the upper Ribeirão Caraça basin (Alkmim and Marshak 1998).

As described by Endo and Fonseca (1992) and Ferreira Filho and Fonseca (2001), the Conceição basin comprises two main structural systems. The Fundão-Cambotas Fault System is composed of two major westward pushing faults dated to the Brazilian orogeny and is confined by the anachronistic Caeté Dome. The Água Quente Fault System composes a set of reverse and thrust structures responsible for the uplift of the Santa Bárbara Metamorphic Complex over supracrustal rocks of the Minas and Rio das Velhas supergroups. The area is situated in the Suspended Depression of the Gandarela Syncline, where the headwaters of Preto creek occur, presenting external flanks delimited by escarpments with expressive levels (300–400 m), carved in itabirites of the Cauê Formation (Fig. 2). The carved relief of the interior of the syncline has itabirite ridges lowered and dismantled, in part, by the evolution of the drainage of the tributaries of the Conceição River.

In the SE portion of the area is the Caraça Massif, characterized by a succession of syncline and anticline faults with imbricated blocks and imposing scarps of sub-vertical quartzite, conditioned by SE oriented structures (Medina et al. 2005). In the NW direction, the relief gradually loses altitude, with evidence of a geomorphological evolution based on erosive processes and tectonic movements (Barros 2012). The anticlinal valley of the Conceição River represents an extensive semi-rectilinear valley situated between the Caraça Massif and the Gandarela Syncline Depression. This excavated anticlinal goes back to the post-Pliocene erosive phase that inverted the folded structures of the Iron Quadrangle resulting in levels that vary between 180 and 300 m, with declivities between 30° and 40°. Nevertheless, the Marginal

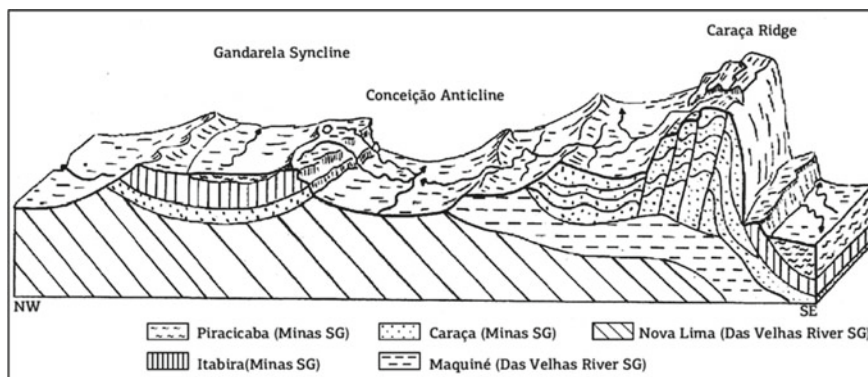


Fig. 2 Schematic geological profile of the study area. *Source* Adapted from Barros (2012)

Depression of Piracicaba River, situated between the middle and the lower course of Conceição River, has a contrasting relief with the one existing upstream the basin. An undulated model predominates, with hills of convex and convex-concave geometry, with little dissection, with levels between 40 and 100 m and slopes between 10° and 20° (Medina et al. 2005).

The regional climate is characterized as semi-humid tropical according to the Brazilian Institute of Geography and Statistics (IBGE), with hot and humid summers, and dry winters with mild temperatures conditioned by altitude (Barros 2010). According to the Köppen classification, the area features a high altitude tropical climate—Cwb—in the higher zones, with rainy summers, while the lower areas have the high altitude tropical climate—Cwa, with higher temperatures (annual average of 20.6 °C).

According to Mourão and Stehmann (2007). The regional vegetation features native remnants of the Semideciduous Seasonal Forest, transition areas between the Atlantic Tropical Forest and the Cerrado biome (savanna), as well as herbaceous mountain vegetation. In this last case, there are rare species associated with and adapted to iron crusts (“cangas”) formed by the hematite concentration.

3 Materials and Methods

The initial stage consisted of a bibliographic survey about the theme, involving the methodological procedures employed in studies on hydrographic rearrangements. Then it was performed the analysis of the geometry of the drainage network through images. Thus, the Geographic Information System (GIS) software ArcGis (ESRI) in version 10.5, the software QuantumGis in version 3.14, and the software Google Earth Pro in version 7.3.3 (Google) were used. Satellite images provided by Google Inc. were used, as well as satellite images provided by the *National Aeronautics*

and Space Administration (NASA) with 30 m² spectral resolution by the *Shuttle Radar Topography Mission* (SRTM) satellite interferometry method, as well as the *Advanced Land Observing Satellite* (ALOS Palsar) of the *Japan Aerospace Exploration Agency* (JAXA), with 12.5 m² resolution, which uses the same image acquisition method. The application stage of the morphometric indices involved the calculation of the Declivity-Extent Ratio Index (RDE), proposed by Hack (1983), the Drainage Basin Asymmetry Factor Index (FABD), proposed by Gardner (1983), and the Transverse Topographic Symmetry Factor Index (FSTT), proposed by Cox (1994).

The application of the RDE aims at an analysis of the longitudinal fluvial profile, relating the slope and the length of the channel and its segments using the tool “*Knickpoint Finder*” of ArcGis. The index is traditionally applied for the identification of “anomalies” in the longitudinal profile using the formula $RSL = (RSLs/RSLt)$, where $RSLs$ is the slope-to-segment length ratio, $RSLt$ the slope-to-total length ratio, and RSL the slope-to-channel length ratio (Etchebehere 2006; Barros et al. 2012; Araújo and Rodrigues 2016; Bueno 2016; Sordi 2018). For this, an SRTM satellite image with spatial resolution of 30 m² limited by the interfluve of the Conceição River basin was used.

The FABD signals the degree of lateral displacement of the main watercourse, perpendicular to its axis, and may indicate tectonic influences and internal fluvial processes expressed by the formula: $FA = 100 * (ar/at)$, where FA is the Asymmetry Factor, ar the basin area on the right margin and at the total basin area (Salamuni 2004). When the result is a value close to or equal to 50, the index indicates little or no tectonic activity; for values higher than 50, the scenario indicates probable right margin tilting, while values lower than 50 denote probable left margin tilting.

The FSTT represents the distance of displacement of the main river course of the basin by the formula $T = Da/Dd$, where Da —the distance from the midline of the drainage basin axis to the midline of the current channel and Dd —the distance of the midline of the basin in relation to the hydrographic divider. If there are no changes in the topographic profile, T is close to zero, whereas if the asymmetry advances, the value approaches one (Firmino 2016; Moreira and Perez Filho 2018).

4 Results

The drainage network of Ribeirao Preto shows two abrupt changes of direction with angulations close to 90°. These drainage elbows are commonly associated with structural conditioning (Barros 2012), and may also reflect the lithological and tectonic context. In this sense, elbows are indicators often used to signal possibilities of drainage rearrangement processes by fluvial captures (Bishop 1995), which in this work would involve drainage segments of the Barão de Cocais river basin.

The FABD was calculated for the Ribeirão Preto basin, and the data were distributed by the contributing basins of the main river (Fig. 3). Near the downstream drainage elbow, there is a tendency for the main channel to shift moderately

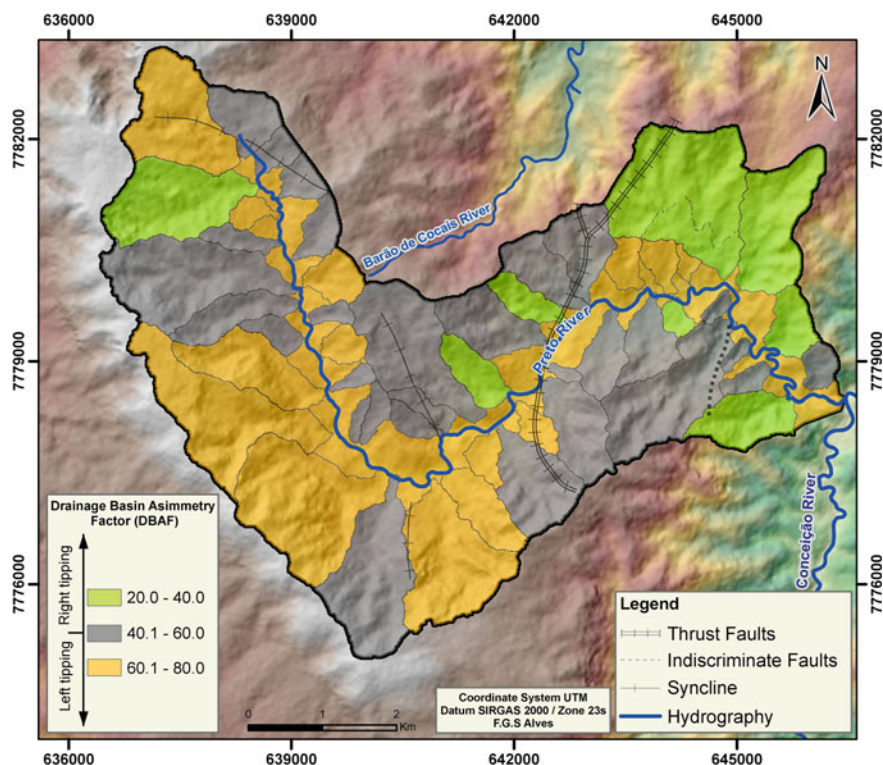


Fig. 3 Drainage Basin asymmetry factor (DBAF). *Source* Prepared by the authors

toward the right bank of the valley in an SW direction. Just downstream of the elbow there occurs an indistinct fault (Codemig 2018) on the right bank of the Ribeirão Preto valley. In turn, upstream of the elbow occurs a thrust fault that cuts the valley in the N–S direction. The induction of stream migration processes by structural control can lead to drainage network rearrangement processes (Searle 1987).

In the most upstream sector of the basin, where another drainage elbow occurs, the migration trend of the channel is opposite, that is, moderately toward the left bank of the valley, in the NE direction. The elbow coincides with synclines that cut through the valley on both banks.

The Transverse Topographic Symmetry Factor was elaborated from transversal profiles along the Conceição River basin and, in more detail, the Ribeirão Preto one (Fig. 4). The calculations for the Conceição basin aimed to provide subsidies for the interpretation of the FSTT data of the Ribeirão Preto basin since the behavior of the base level conditions that of its tributaries. The profiles were based on the basin morphology and geometric symmetry as delimitation criteria; the profiles must be perpendicular, and their tracing must have opposite ends in the basin of contribution. The results show average anomaly degrees (0.41–0.8) in the middle and lower Conceição, with higher values near the mouth (0.63 and 0.76). The valley presents

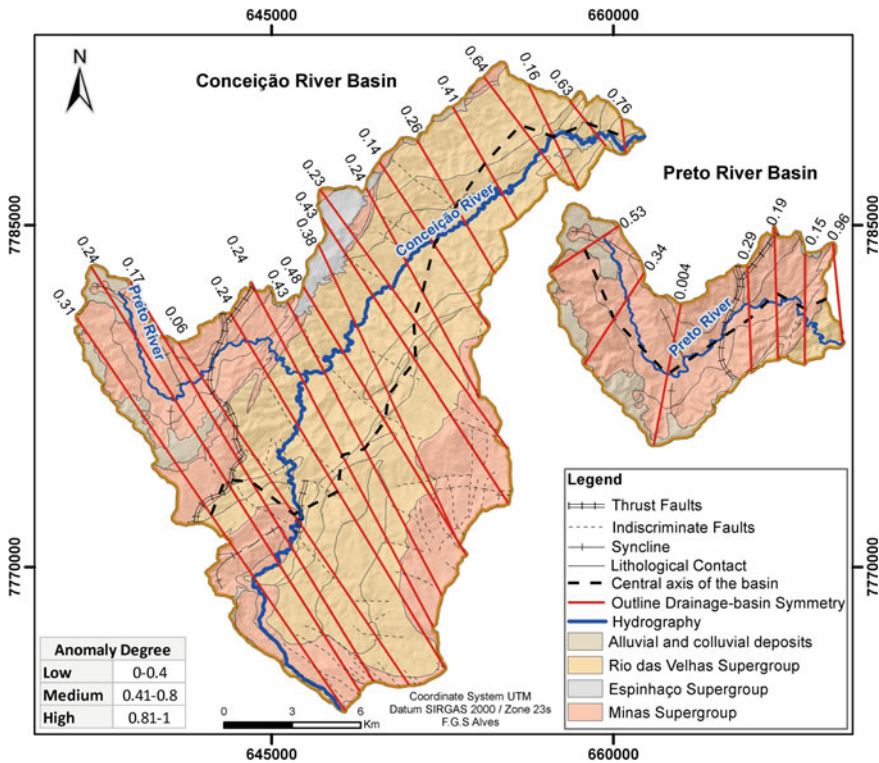


Fig. 4 Transversal topographic symmetry factor (TSTF) for the Conceição River and Preto creek basins. *Source* Adapted from Codemig (2018)

several structural systems and lithological units, with the area of the mouth marked by the occurrence of shales and banded ferritic formations. This fact may be linked to the preferential direction of the watercourse along with banded iron formations.

In the middle part of the basin, near the confluence of the Preto stream, the Conceição River demonstrates a dissonant behavior concerning the central axis of the basin, with a displacement toward the left margin in the SE–NW direction. In this sector, there is the presence of a complex of faults of the same direction, transversal to the axis of the channel, which, together with the lithological framework, maybe direct the watercourse. In the upper basin, the faults present NE–SW and NW–SE directions, and the FSTT values are low.

In the case of the Ribeirão Preto basin, the lithological factor is of paramount importance in the behavior of the watercourse, since the entire valley bottom is carved in dolomites, except near the mouth where itabirites outcrop. However, the presence of a contractional fault that cuts the mid-valley should be highlighted and that may have conditioned its change in direction, since, after contact with the fault, the stream starts to migrate in the contact zone between itabirites and dolomites. In the Ribeirão Preto basin, there is also a predominance of medium anomaly degrees, but with the

highest asymmetry values in the upstream (0.53) and downstream (0.96) extremes. In the first case, moderate asymmetry is perceived from the stream to the left bank, coinciding with a contact zone between shales and itabirites on the right bank and the presence of dolomites on the left bank (CODEMIG 2018). In turn, the area of the mouth (confluence with the Conceição) coincides with an indistinct fault and with lithological contacts between dolomites, itabirites, and phyllites, rocks with different levels of resistance to denudation. However, when one compares these values with those obtained for the whole Conceição basin, one notices that, in this case, the degrees of asymmetry are much lower and do not indicate important anomalies (0.32 and 0.39). This illustrates the important influence of the scale of the analysis and the morphological and geological factors on the calculation of the index.

The RDE pointed out several 2nd order *knickpoints* in the Preto river valley and a 1st order anomaly in the contact between the ferritic and quartzite units that sustain the highland relief of the upper-middle stream, and the shales present in the lower course (including the confluence zone with the Conceição river)—Fig. 5. In fact, this anomaly coincides with a craggy zone that configures an important morphological change in the valley and that is cut by indistinct faults. The anomalies shown by

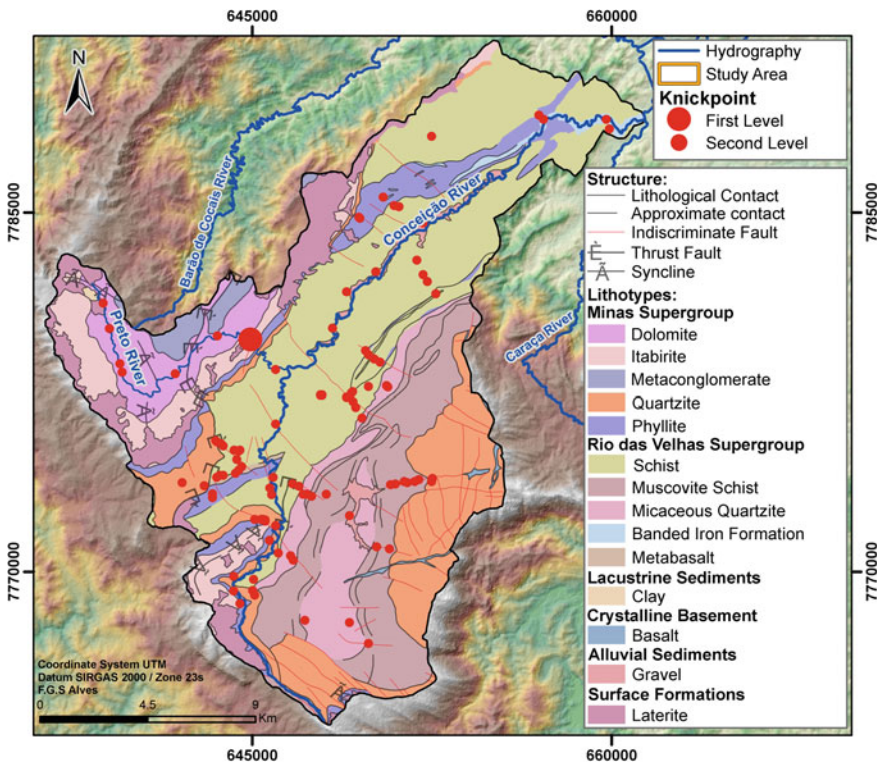


Fig. 5 Anomalies of 1st and 2nd orders evidenced by the application of RDE. *Source* Cartographic base adapted from Codemig (2018)

the RDE are generally associated with lithological contacts, structural lineaments, confluences, or tectonic activities, the latter mainly in the case of 1st order anomalies (Etchebehere 2004; Stevaux et al. 2009; Firmino 2015).

The hypotheses regarding the occurrence of rearrangement processes of the drainage network in the Ribeirão Preto basin, throughout the Quaternary, involve an ancient direct tributary of the Conceição River that would have pirated transversely, from the remnant retreat of the drainage headwaters, an ancient tributary of the Barão de Cocais River that ran in the SW–NE direction (Fig. 6). Barros (2012) pointed out that the geological context of the Conceição basin involves thrust faults and ridgeline *nappes* that condition the formation of ramps with variable dips and high slope angles, caused by the compressive *stress* between the structures. This complex framework would favor an important dynamism to the drainage network throughout the Quaternary.

In this sense, Medina et al. (2005) propose the opening of two epigenetic gorges that truncated the itabirite ridges of the eastern flank of the Gandarela Syncline and provided the fluvial capture by remontaneous erosion processes of the former tributary of Barão de Cocais, by a tributary of Conceição. The authors also state

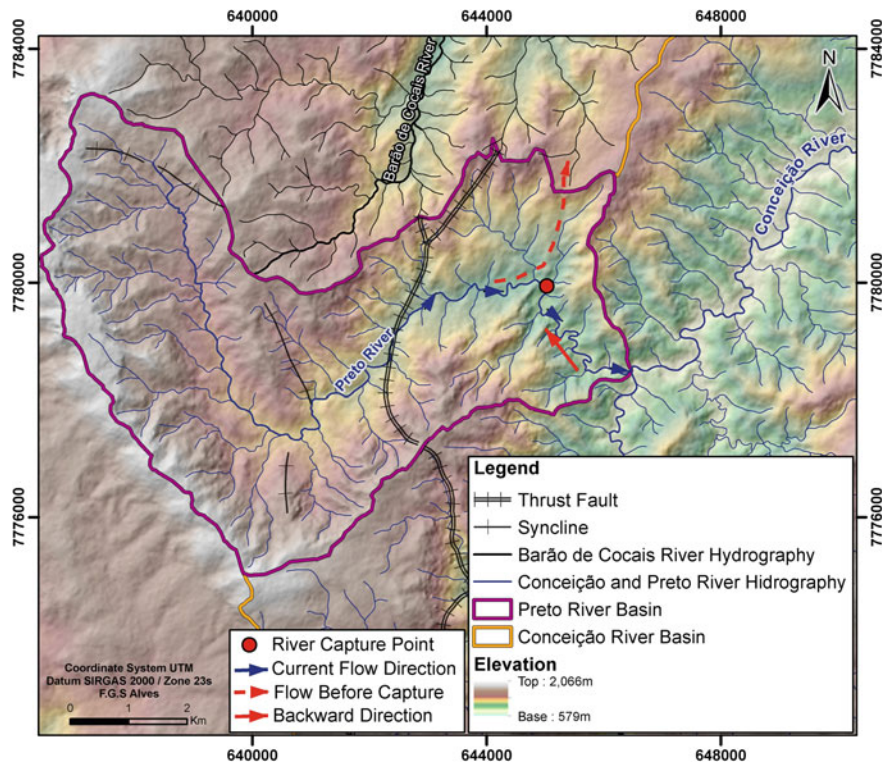


Fig. 6 Illustrative scheme of the fluvial capture hypothesis according to the literature. *Source* Prepared by the authors

that in the southwestern portion of the Gandarela Syncline Suspended Depression (DSSG) there is an aggressive process of adjustment of the drainage network of the Ribeirão Preto stream to the base level (Conceição River), reflected in a typically hilly relief quite eroded by gully processes, with gradients from 40 to 80 m and slopes around 5° to 10°. This context would be responsible for the emptying process of this area and could indicate the evolution of the drainage elbow further upstream. In this sense, Fabri et al. (2008) indicate that the preponderant factor for the opening of the epigenetic gorges was the fitting of the Black Creek along an ancient thrust fault, enhanced by the fragile dolomites of the Gandarela Formation (Minas Supergroup).

The two elbows in the Preto river and the anomalous FSTT values at its mouth reinforce these ideas. The confluence presents lithological contacts (dolomites and itabirites) that may have conditioned the preferential direction of flow toward the Barão de Cocais river basin, anachronistic to the appearance of the drainage elbow. The complex local structural framework must also have contributed to the drainage rearrangement process, given the presence of an important contractional fault in the mid-valley. However, the available mapping bases do not detail the presence of faults near the confluence. The RDE indicated a 1st order *knickpoint* located in the perimeter bordering the contact between the lithologies, which corroborates the capture proposal, besides, through the FSTT, the section presents the greatest anomaly in the channel migration dynamics. In the headwaters of the Ribeirão Preto, the mean FSTT values indicate an anomaly in the migration dynamics of the main channel, and the FABD values show its tendency to migrate to the left bank.

5 Conclusion

Geomorphological theories are often complex and face methodological limitations for their proof. The research on processes of rearrangement of the drainage network faces, in this sense, the challenge of obtaining evidence of hydrographic reorganization over time. To this end, the investigation of case studies is an essential strategy, and the Iron Quadrangle emerges as a prominent stage due to the complex geological and geomorphological evolution throughout the Quaternary period.

The results of the applied morphometry and the analysis of the drainage network geometry contribute to reinforcing the proposal of fluvial capture already indicated in the literature, that is, a former tributary of the Barão de Cocais River would have been pirated by a direct tributary of the Conceição River. In this scenario, the Conceição basin presents greater denudational aggressiveness than the neighboring basin, illustrating how the Quaternary fluvial dynamics contribute to the configuration of the regional relief.

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