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ARTICLE

Reativation of Taxaquara Fault and its morphotectonic influence on the evolution of Jordão River catchment, Paraná, Brasil

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ABSTRACT: *The Paraná basin is one of the major morphotectures of the South American continent. Although its tectono-sedimentary evolution has been widely studied and fairly well understood, this paper aims to fill a gap in knowledge comprising the tectonic evolution after the end of its last sedimentary cycle, in the Upper Cretaceous. In this context, the Jordan River watershed, situated in the surroundings of Guarapuava municipality, south central region of Paraná State, was selected for structural and morphometric analysis where the Cretaceous volcanic rocks of Serra Geral Formation are exposed. The Jordan River watershed was studied for the influence exerted by Taxaquara Fault Zone on its morphologic evolution, since Taxaquara Fault Zone is associated to the Brazilian cycle and extends eastwards to the Ribeira belt in the state of São Paulo. The morphometric analysis consisted in the interpretation of the Jordan River watershed drainage network and relief elements, considering the distribution of existing knickpoints in the water courses. Structural analysis was based on the calculation of the stress fields responsible for the activation of local fault zones, which were determined by their spatial arrangement and the statistical and mechanical treatments of structural data. During the Oligocene and Miocene, erosional processes developed a planing surface which marks the relief in the central region of the Jordan River watershed and serves as a stratigraphic marker for the associated deformational events. Three events that contributed to the morphological framework of the Jordan River watershed were defined: an oldest one, probably active before the development of the Jordan pediplane in the Paleogene, by a NE-SW maximum horizontal stress (SHmax); and two more recent ones, being one of Plio-Pleistocene age, with a N05W SHmax, and a still active event of transtensive nature showing a N75W SHmax. The paleostress analysis points to a similarity between the Cenozoic evolution of Paraná Basin and the tafrogenic basins of southeast Brazil, revealing the amplitude of the deformation events associated to the studied period and ensuring the importance of further studies on the morphotectonic evolutions of intracratonic regions of the South American plate and their correlation to the Andean tectonic cycle.*

KEYWORDS: *Taxaquara Fault zone; Jordão River catchment; Cenozoic tectonics; morphometric analysis; Paraná Large Igneous Province.*

INTRODUCTION

Although located inside the South American plate, Paraná Basin was subjected to deformations caused by tectonic forces from the plate margins (mainly the Andean) in association with its sedimentary history between the Ordovician and the Cretaceous (Milani & Ramos 1998) and the reactivation of large fault zones (Zalán et al. 1990, Artur & Soares 2002). Unlike the areas situated near stress sources (e.g., the Andes region), the deformation occurring inside tectonic plates are often underestimated, since they are commonly related to very tenuous movements of tectonic blocks, most

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of which aseismic. However, it is precisely in these places that the interaction between the several stresses applied on the plate are better conserved (Angelier 1989), turning these regions into targets of great importance for tectonic studies, allowing for a better understanding on how stresses act on an intraplate context.

Previous studies concerning Cenozoic brittle deformation in Paraná Basin (Rostirolla *et al.* 2000, Strugale *et al.* 2004, Roldan 2007, Machado *et al.* 2012) were considered, but none of them had the temporal and tensor analyses of these deformations as their main objectives. It was therefore necessary to proceed with a more detailed investigation of the faults and their related structures, correlating them whenever possible with the studies accomplished in the tafrogenic basins of southern Brazil (Campanha *et al.* 1985, Riccomini, 1989, 1995b, Salamuni *et al.* 2004), where most of the works on both the Cenozoic and Neotectonic periods are concentrated. The age limit for the Neotectonic period was established according to the last tectonic reorganization of the landscape (Mörner 1989) and defined as 23 Ma for the South American intraplate region (Hasui 1990).

The study area was delimited by the Jordão River catchment, situated in the south-central region of Paraná State, whose main course is controlled by the Taxaquara Fault Zone, one of the major NE-SW structures of Paraná Basin (Zalán *et al.* 1986), where volcanic rocks of Serra Geral Formation are exposed. Taxaquara Fault Zone is oriented between N60-80E direction and was initially described in the state of São Paulo, affecting Neoproterozoic rocks of Ribeira Belt (Hennies *et al.* 1967) as a dextral strike-slip fault. In this context, the generation of the Taxaquara Fault Zone at the final stage of the Brazilian Cycle and its multiple reactivations considerably contributed to the evolution of the Paraná Basin along the Paleozoic and Mesozoic eras (Zalán *et al.* 1990).

The main goal was to determine the possible Cenozoic reactivations along Taxaquara Fault Zone, which were poorly studied until this paper. Therefore, this paper seeks to understand the morphostructural behavior of Taxaquara Fault and how its reactivations influence the relief configuration, allowing for a better understanding of the morphotectonic events — taking place in the Jordão River catchment and Taxaquara Fault Zone region — and evolution of the entire Paraná Basin during the Cenozoic.

The best way to analyze tectonic influence on the relief is by measuring landscape features (Gerasimov & Mescherikov 1968, Ross 1990) using morphological parameters that suggest perturbations on surface equilibrium state provoked by geological agents such as fault structures. This approach was based on the Dynamic Equilibrium Theory (Hack 1960), whose premises include the role of exogenous agents on the constant erosion and shaping of the relief, causing tectonic-related asymmetries to be attenuated with time.

The role of rivers as landscape modelers is shown by studies that quantify the incision and the stream of erosive power associated with climatic, lithologic and tectonic characteristics that control and/or enhance erosive properties and dissection. The application of theories and laws of erosion and denudation rates, evolution of the channel concavities and incision powers of tectonic altered and controlled rivers were used for proposed models (e.g., Hack 1973, Howard 1994, Tucker & Bras 1998, Whipple & Tucker 1999, Whipple et al. 2000, Van Der Beek *et al.* 2002, Spagnolo & Pazzaglia 2005) applied in the interpretation analysis of the Jordão River catchment.

Amongst the analysis methods available, those based on the arrangement of drainage networks were preferred and included the definition of their patterns and anomalies, as well as measurements of their catchment areas. Rivers and drainage patterns, among all other relief components, are the most susceptible elements to tectonic deformation (Schumm 1986), which causes dramatic changes in hydraulic gradients and, consequently, disorganization of drains, to the point of generating anomalous patterns and eventual asymmetries along the drainage basin.

Allied to morphometric indicators, Landsat 8 imagery and Shuttle Radar Topography Mission DEMs — processed by Topodata (Valeriano & Albuquerque 2010, Valeriano & Rossetti 2012) — were analyzed for structural lineaments, slope and knickpoints extraction. Alongside these analyses, and in order to characterize deformation events that contributed to the morphotectonic framework of the Jordão River catchment, a fieldwork was carried out with the purpose of constructing geometric characteristics and structural data of kinematic indicators in fault planes.

STUDY AREA'S CONTEXT

Geology and geomorphology of Paraná

Maack (1947) divided Paraná State into five main geomorphologic domains: the coastland, Serra do Mar, and the First, Second and Third plateaus, all of which deriving a strong influence from the geological units in which they developed. The Coastland consists of Cenozoic sediments and is separated from the first plateau — where the state's capital, Curitiba, is located — by the Serra do Mar Neoproterozoic granite bodies. The second and third plateaus are separated by the Esperança scarp, and both were formed over Paraná Basin. The second plateau exposes rocks of the Rio Ivaí, Paraná, Gondwana I and Gondwana II supersequences (as described in Milani 1997, 2007); in the third plateau, there is the occurrence of volcanic rocks of Serra Geral Formation and the Bauru supersequence, the latter positioned on the top of the Paraná Basin stratigraphic column (Milani 2007).

The study area is delimitated by the Jordão River catchment, with outcrop basaltic and acid volcanic rocks of Serra Geral Formation. The Jordão River catchment, in the central-south region of Paraná State, is situated in the eastern boundary of the Third Plateau of Paraná, west of the Esperança scarp. Jordão River is 198 km long and its drainage area is approximately 4,730 km^2, being the largest tributary of Iguaçu River, which extends throughout the southern region of Paraná State (Fig. 1).

Besides Guarapuava, the Jordão River catchment drains the municipalities of Campina do Simão, Candói, Foz do Jordão, Inácio Martin, Pinhão and Reserva do Iguaçu. The main access road to the region is federal highway BR-277, that connects the state's capital, Curitiba, to the municipality of Guarapuava, as well as state highways PR-170,

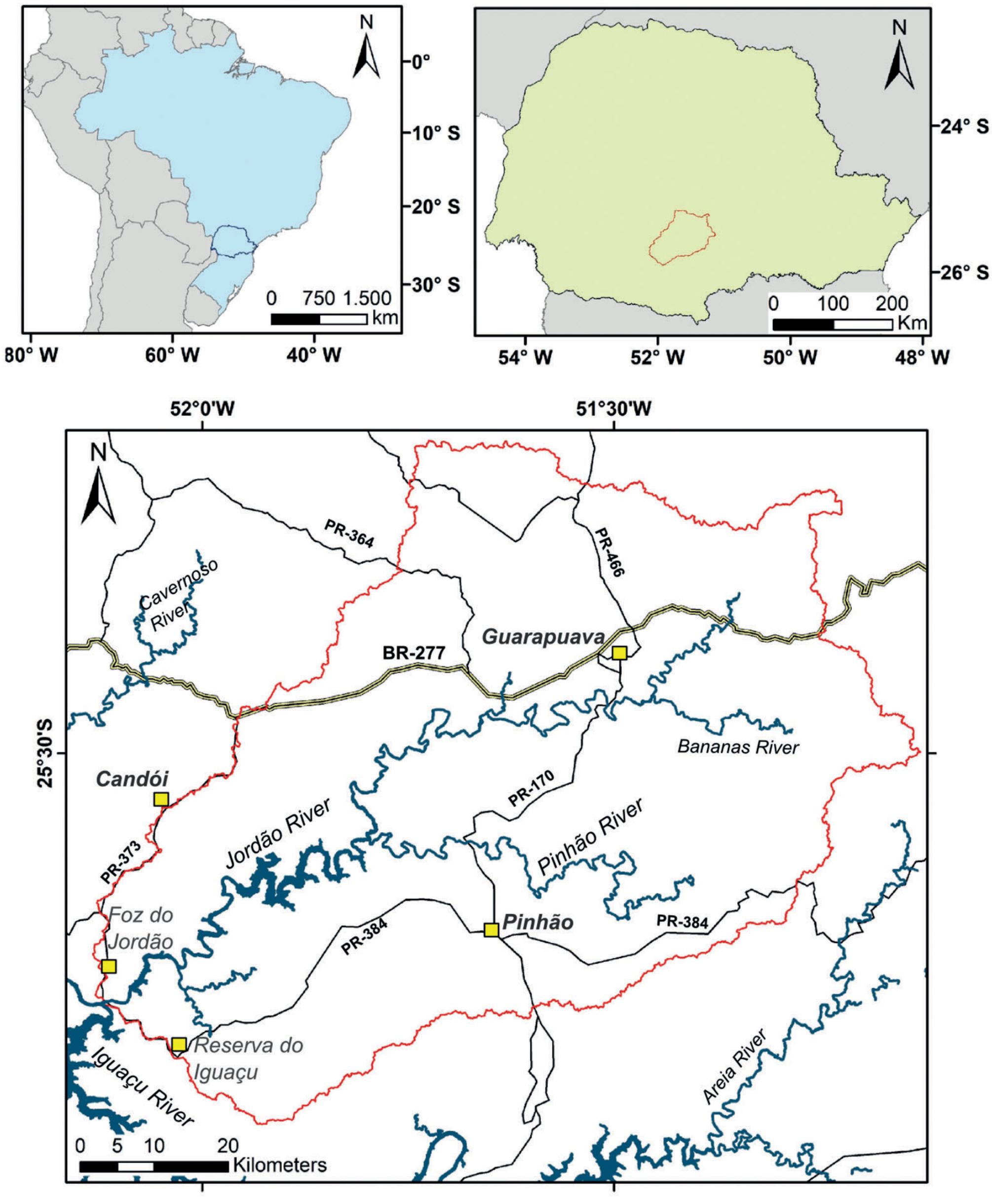


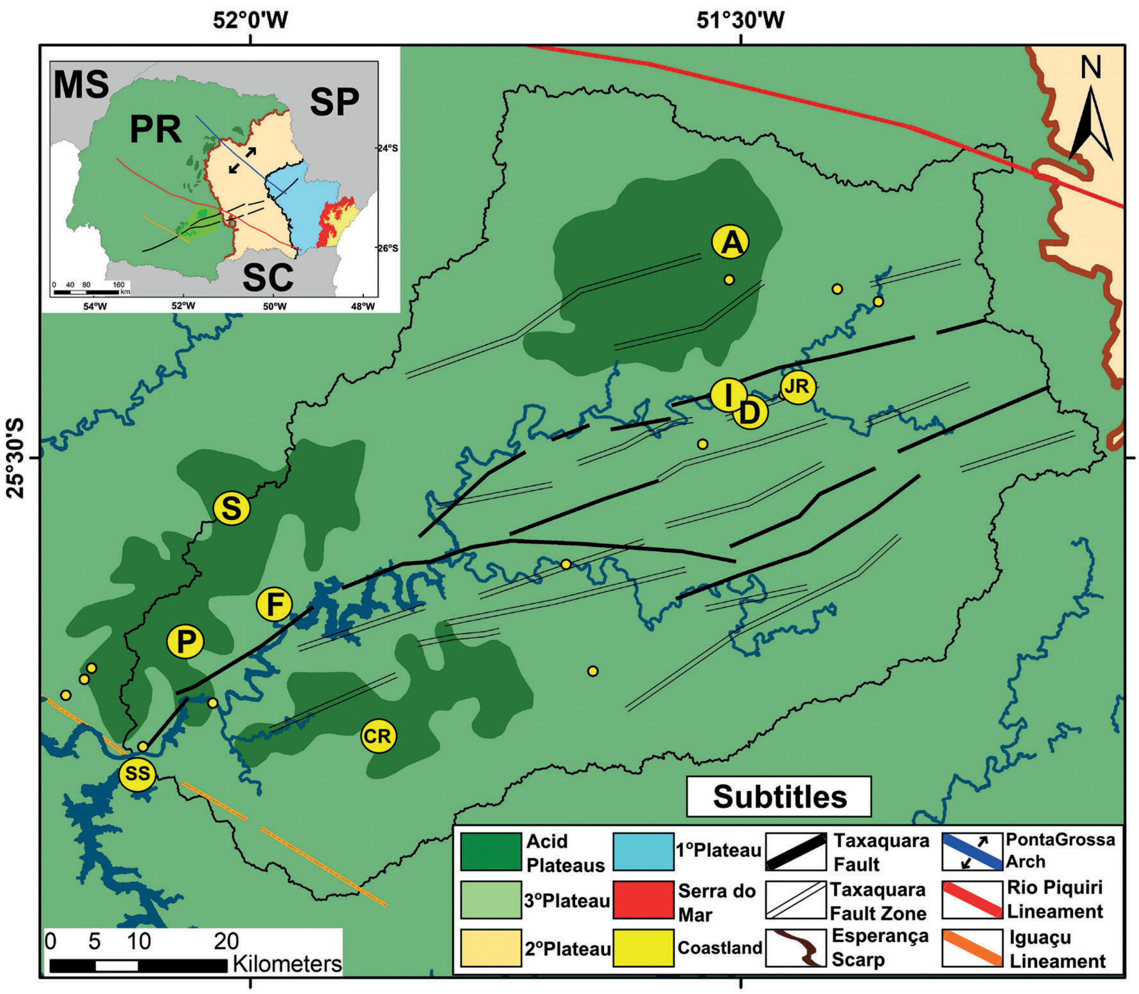
Figure 1. Location map of the studied area showing the location of municipalities and main roads outlined by the Jordão River catchment.

PR-373 to access the municipalities of Pinhão and Candói, respectively, and PR-384 and PR-662, to the municipality of Foz do Jordão.

Geological Setting

Serra Geral Formation is part of the Paraná large igneous province (Peate *et al.* 1988) and comprises volcanic rocks, predominantly basalts, and the restrict occurrence of associated acid flows. At the Jordão River drainage-basin region, the acidic rocks correspond to the Chapecó type trackytes (Bellieni *et al.* 1986, Nardy *et al.* 2008), that occur as three igneous plateaus located in the municipalities of Guarapuava, Candói and Pinhão. The largest of these plateaus, in Guarapuava, is in the northern portion of the catchment area and is circular in shape, while the other two are elongated and closer to the Jordão River's mouth (Fig. 2).

These rocks were formed within a context of the Gondwana rupture (South Atlantian Reactivation, Schobbenhaus *et al.* 1984), during Lower Cretaceous, and $^{40}Ar/^{39}Ar$ dating yielded ages of 134.7 ± 1 Ma (Thiede & Vasconcelos 2008). Flows that originated the basalts took place in a short space of time, of around 1.2 Ma (Thiede & Vasconcelos 2010), even though their effusion rates were relatively slow (Waichel *et al.* 2006), allowing the formation of immense inflated flows, characteristic of Serra Geral Formation. Most of the outcrops within the Jordão River catchment are consisted of massive basalts, belonging to the core of the inflated flows, while the most intensely fractured occurrences are located on the western edge of the catchment area, corresponding to the top of another basaltic flow.



I: Itax; D: Dalba; S: Sul-Britas; JR: Jordão river rapiers; CR: Capão Grande river rapids; F: Fundão hydroelectric power station dam; SS: Salto Segredo hydroelectric power station dam; P: Passo da Cachoeira waterfall; A: Chapecó acid rocks.

Figure 2. Geological/Geomorphological map (MINEROPAR S.A., 2005) of the Jordão River catchment and the outcrops examined (yellow points). The outcrops with a letter inside represent the ones in which quality information were obtained and/or pictures were taken.

Tectonic Setting: The Jordão River catchment is marked by Taxaquara Fault Zone, which controls the main drainages of the watershed, including Jordão and Pinhão rivers, its major affluent located in the left bank, both showing ENE-WSW directions. Flanking the catchment area of Jordão River, two NW-SE lineaments (approximately N60W) occur: the Iguaçu lineament to the southwest and the Rio Piquiri lineament to the northeast (Fig. 2), the two of which are delimited by Zalán *et al.* (1986).

Taxaquara Fault Zone was primarily described in São Paulo State by Hennies *et al.* (1967), in a region near Taxaquara Scarp, affecting the metamorphic rocks of São Roque Group, located in the context of Ribeira Belt. Coutinho (1968) identified a mylonitic formation related to the granites of this unit and associated with Taxaquara Fault Zone. Posteriorly, Morales *et al.* (2014), concluded that the mylonitization is syntectonic to the emplacement of the granites mentioned.

Hennies *et al.* (1967) estimated a clockwise (right-lateral) movement of about 150 km for Taxaquara Fault Zone during the Neoproterozoic, 40 km of which under a strictly ductile regime (Sadowski 1991). Originally, Taxaquara Fault Zone trace was considered between Paraná and São Paulo Basins; however, it was redefined by Hasui *et al.* (1978), which prolonged it until Cubatão Fault Zone (also known as Lancinha-Cubatão Fault Zone) but showed controversial indicators about how its main structure was affected after the union. Zalán *et al.* (1986) identified — through the interpretation of radar and satellite imagery — that Taxaquara Fault Zone spreads to the interior of Paraná Basin, deforming its Paleozoic and Mesozoic sediments and marking the relief. Through the analysis of magnetometric data, Castro and Ferreira (2015) proved this relation and defined depths greater than 2,000 m for the main structure, similarly to what had already been stated by Castro *et al.* (2014) in Lancinha-Cubatão Fault Zone.

MATERIALS AND METHODS

The morphostructural analysis of the Jordão River catchment was based on morphological characteristics and identification of structural lineaments. Within the morphological parameters, we analyzed:

- The local relief, through hypsometric and slope maps and the cartography concepts instituted in Ross (1990);
- The drainage network, by identifying its patterns and anomalies (Howard 1967, Soares & Fiori 1976), as well as the asymmetries of the drainage basins;
- The geometry of structural lineaments sets, extracted through shaded relief imagery derived from DEM data and Landsat 8 scenes.

Knickpoints of the drainage network were extracted from the digital elevation model obtained from radar imagery (Valeriano & Rossetti 2012) through the ArcGIS tool 'Knickpoint Finder' (Salamuni *et al.* 2013). The tool was used to assess differences in river elevations and generate the knickpoints density map (Peyerl 2017), allowing for the visualization of major regional structures. The density map was constructed using kernel density estimation (Parzen 1962) and aided the delineation of flattened surfaces and volcanic plateaus, as well as the confirmation of drainage captures and definition of structural zones, such as Taxaquara Fault Zone. The kernel estimation aims to graphically standardize the distribution of point occurrences (Silverman 1986) and has contributed to the graphical resolution of multiple remote sensing analyses in GIS environment (Quintela-del-Río & Estévez-Pérez 2012, Silva *et al.* 2015).

The drainage-basins symmetry was measured following the methods of Asymmetry Factor (Hare & Gardner 1985) and Transverse Topographic Symmetry Factor (Cox 1994), by Salamuni *et al.* (2004) in the Curitiba Sedimentary Basin as indicators of neotectonic activity. The Asymmetry Factor (AF) was used for the Jordão River catchment and its tributaries, since it constitutes a simple and graphically well representative method. The AF value is determined by the ratio between the area of the right bank of a river and the total area of its watershed, multiplied by 100, given by the formula (Equation 1):

$$AF = 100\ (Ar / At) \quad (1)$$

In which:
Ar = the area of the basin to the right of the trunk stream while facing downstream;
At = the total area of the drainage basin.

In this method, the value 50 means the total symmetry of the watershed, while values either < 50 or > 50 indicate lateral tilting, perpendicular to the direction of the main stream. Also, values between 40 and 60 imply weak asymmetry; and values lower than 30 and higher than 70, strong asymmetry rates (Keller & Pinter 1996). The Transverse Topographic Symmetry Factor (T) was used only for the Jordão River catchment due to its being a punctual method which requires multiples length measurements for the same catchment, which was not an essential analysis for the drainage subbasins related to the Jordão River tributaries in this study. This method is only necessary in watersheds on which asymmetry varies along the course of the river, as in the case of the Jordão River catchment. T value is defined as in Equation 2:

$$T = Da / Dd \quad (2)$$

In which:
Da = the distance between the midline of the left banks of the watershed and the midline of the active meander belt;
Dd = the distance from the basin midline to the basin division;
T = a vector with direction and magnitude ranging from zero to one, zero meaning a perfect symmetric catchment and one a hypothetical maximum asymmetry, which is a highly improbable situation in nature (Cox 1994, Keller & Pinter 1996, Burbank & Anderson 2001). T values lower than 0.2 indicate weak asymmetry of the river basin, while medium values are concentrated between 0.2 and 0.5. Higher values of more than 0.5 show significant asymmetry in the watershed.

The hypsometric and slope maps were derived from SRTM-Topodata imagery (Valeriano & Rossetti 2012), which also served as basis for drainage network extraction and delimitation of their respective catchment areas. The data was processed in GIS environment, by using ArcGIS 10.1 (ESRI), and allowed for the identification of structural lineaments and construction of the general tectonic map. The slope map was generated using the class definition proposed by EMBRAPA (1979), which shows more detailed subdivisions — with pre-determinate values — than the main slope configuration used by ArcGIS tools.

The statistical treatment of structural data collected on fieldwork was done through the Wintensor 5.8.2 and Stereo32 1.0.1 softwares and the separation of the inserted sample groups was supported by Tchalenko and Wilcox tectonic models (Tchalenko 1970, Wilcox *et al.* 1973). Those models are based on the Riedel shear model, sustained by Mohrs-Coulomb failure criteria and the right dihedral model (Angelier & Mechler 1977), this last one used due to the existence of faults and joints previous to the studied Cenozoic deformation events. Therefore, this paper considered that the application of the Riedel Model alone would not be precise enough, since it was developed by studying massive blocks.

The relation between the fractures set was established by two main fieldwork criteria: the occurrence of synthetic faults showing the same kinematic relations (like the R and the Y fractures in the Riedel Model), and those with antithetic relation (R and R', for example) or flower structures. The other criteria observed in fieldwork was the overlay and crosscutting relations between structures, seeking to understand how different sets — defined by the previous criteria — interact with each other, which also allowed to infer possible relative ages for them.

RESULTS

Morphostructures

The relief in the catchment area was divided into three zones, based on both surface texture (slope) and digital elevation model analysis (Fig. 3). Zone I shows moderate roughness and occupies the highest topographic levels. This surface extends beyond the catchment area, toward Esperança Scarp, to the east. Zone II is located around Jordão River, marked out by a flattened relief of low roughness, between 830 and 950 m in elevation (Fig. 4). This surface is alveolar in shape, borders Jordão River and is at a lower elevation compared to Zone I. Zone II comprehends the greatest part of the right bank of the river — being less present in its left margin — and is concentrated in the surroundings of the main watercourse. Zone III is the least extensive one, showing strong-wavy to mountainous relief, formed by valleys developed around lower Jordão River and its main tributary, Pinhão River (see profiles in Fig. 3 and pictures in Fig. 4).

The largest knickpoints are concentrated in the boundaries between these zones, mainly at the interface between zones II and III, at the points where the valleys that characterize Zone III begin (Fig. 5). Most of these valleys are oriented N65-80E or E-W, but the most prominent knickpoint of the Jordão River catchment is associated to the formation of a N15W oriented canyon, connecting the upper and lower reaches of Jordão River, in the central portion of the catchment area (profile B-B' in Fig. 3). The canyon cuts through the interfluve between upper Jordão and Pinhão rivers; this interfluves direction is ENE and it extends over most of the catchment area, although it is considerably eroded after the canyon in the western part of the basin, in a further downstream region of Jordão River. This canyon ends in the confluence of Jordão and Pinhão rivers, marking an ENE-WSW valley, which extends from the headwaters of Pinhão River until Jordão River mouthing Iguaçu River.

In fieldwork, the greatest knickpoints are located in the interface between zones II and III and are configured by waterfalls and rapids (Fig. 6), often with N60-75E or E-W (N80E-N80W) directions, which are consistent with Taxaquara Fault Zone (N70E) and its subsidiaries (E-W). A less prominent concentration of knickpoints was formed around the three acid volcanic plateaus but mainly in the Guarapuava Plateau region, generating zones with low knickpoint concentrations surrounded by areas of low-medium density of knickpoints. These zones were weakly marked in the topographic profiles and were not associated with any occurrence of waterfalls or rapids along the streams. The boundaries of these zones follow

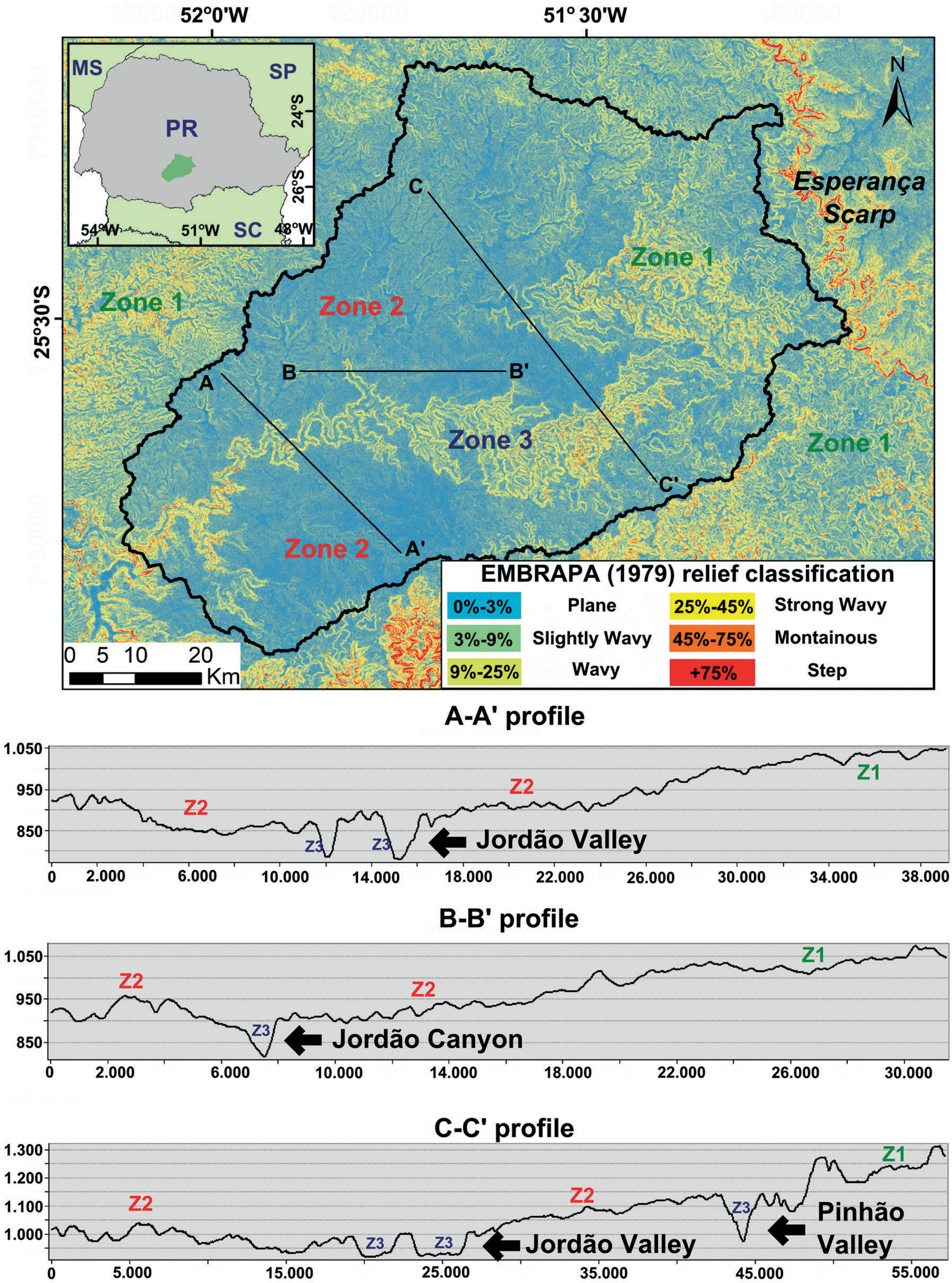


Figure 3. Slope map of the Jordão River catchment area. Zone 1 (Z1), written in green, presents smooth to strongly wavy relief and represents the South American Surface, described by De Martone (1943), King (1965) and Valadão (1998); Zone 2 (Z2), written in red, comprises the pediplane of Jordão River, with relief varying from flattened to smoothly wavy, equivalent to the *Cristas Médias* surface (Ab'Saber 1962) and PD2 surface (Bigarella *et al.*, 1965). The valleys of Lower Jordão and Pinhão rivers, where the relief varies from strongly wavy to mountainous, represent Zone 3 (Z3), written in blue. The relief classes are set according to the EMBRAPA (1979) classification.

the limits of the acid flows, and according to the geological map of Mineropar S.A. (2005), are, therefore, excluded as a structural source for these limits. This relation shows that despite the occurrence of knickpoints related both to structures and lithological variations, they can be differentiated when analyzed in detail.

The drainage patterns are quite distinct on each of the banks of Jordão River. Its right bank is marked by a dendritic to subdentritic pattern, with predominantly NE-SW (N30-75E) segments of streams, while in its left bank, the drainage segments are relatively extensive, oriented mainly to ENE-WSW/E-W (between N70E and N80W) and configuring asymmetric basins. In the left margin — southeast of the E-W drainages — NW-SE streams developed in parallel patterns, forming an anomalous drainage configuration that indicates tilting in this portion of the catchment area (Fig. 7).

These asymmetric drainages occur along the three largest tributaries of the left bank of Jordão River: Bananas, Pinhão and Capão Grande rivers. Their AF values are 25, 26 and 15, respectively (ranging on a scale from 0 to 100), indicating strong asymmetry in the NNW direction and

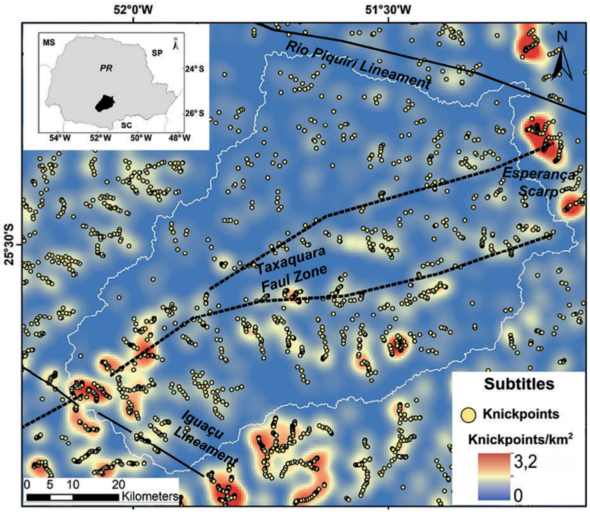


Figure 5. Knickpoints density map (Peyerl 2017) of the Jordão River catchment area. This image shows the high concentration of knickpoints in lower Jordão and Pinhão rivers showing ENE-WSW directions, all along the Taxaquara Fault Zone trend. The high concentration of knickpoints in the northeast portion of the map is related to Esperança Scarp, a natural division between the Second and Third plateaus of Paraná State (Maack 1947).

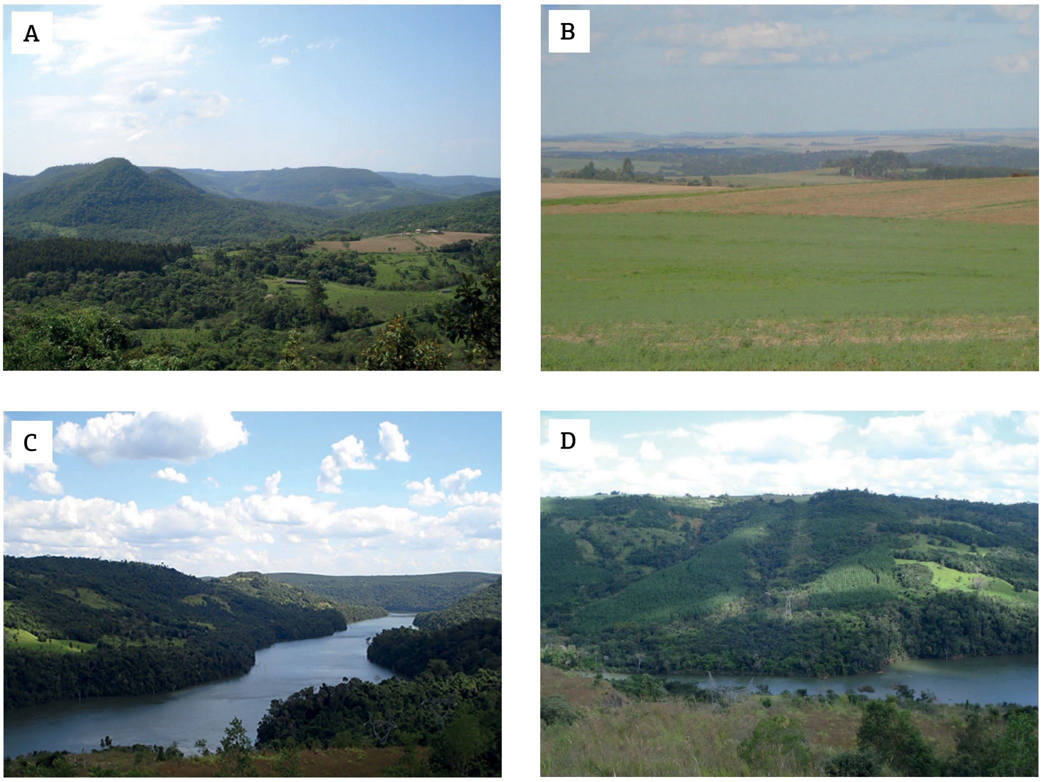


Figure 4. (A) South American surface (zone 1) on the border of Parana's second and third plateaus. The lowlands configure the second plateau and the highlands the third plateau, the scarp between them is Esperança Scarp; (B) Jordão Surface (Zone 2) marked by a plane to wavy relief; (C) Lower Jordão river valley (Zone 3), near the Fundão hydroelectric power station dam; (D) Lower Jordão river valley (Zone 3), near the confluence to Pinhão River at the end of Jordão Canyon.

consequent tilting of the blocks, suggesting surface lowering to the northwest and rising to the southeast.

The occurrence of these streams causes the asymmetry of the entire catchment area, especially in the upstream portion. The AF value for the Jordão River catchment equals to 41, revealing smooth asymmetry to NW direction. However, the T values vary along the course of Jordão River, ranging from 0.048 at its headwaters to 0.68 at its mouth, where it reaches its maximum values (Fig. 7). Values gradually increase from the surroundings of the Jordão canyon and, after that, along lower Jordão River, assuming moderate to high values of asymmetry (greater than 0.5).

Jordão River and the minor basins of its left bank are superimposed on the Jordão River pediplane, measured by AF and indicating smoother asymmetry, with values ranging from 40 to 60 in most basins (Fig. 7). The only three exceptions were the drainage basins of Cascavel (32), Coutinho (84) and Passo da Cachoeira (63) rivers, being the first and last one moderately in asymmetric and the second one — Coutinho River — strongly asymmetric to the east, as a result of the capture of drainages by its neighboring basins to the north and northwest of the river.

Knickpoints are mostly related to drainage captures, including the ones before the Jordão canyon, caused by flowing of stream segments along the direction of NNE-SSW and NNW-SSE alignments, diverting the flow of NE-SW channels. These alignments and their respective NNE and NNW oriented streams are present on both banks and throughout the whole Jordão River catchment area.

Structural lineaments

In addition to the drainage lineaments mentioned, the ENE-WSW ones and a series of other relief lineaments were observed through hillshaded SRTM-topodata imagery and knickpoints density maps (Figs. 5 and 8, respectively). The most evident of these lineaments is Taxaquara Fault Zone, oriented to N70E direction and well marked in the shaded relief imagery and density maps. It is characterized by a 'scar' shaped mark on the relief, over which lower Jordão River and Pinhão River fit together. In the knickpoints density map, the fault zone is revealed by a band where the highest values of knickpoints are concentrated, coinciding with the previous alignment; in this last map, it is possible to observe that Taxaquara Fault Zone divides into Jordão Canyon,

Figure 6. Waterfalls and rapids in the Jordão River basin controlled by NE-SW (F1) and E-W (F2) faults. (A) Rapids of Capão Grande River, controlled by F2 fractures; (B) waterfall in Passo da Cachoeira River, controlled by the F2 set of faults; (C, D) rapids in upper Jordão River, controlled by both F1 and F2 structures.

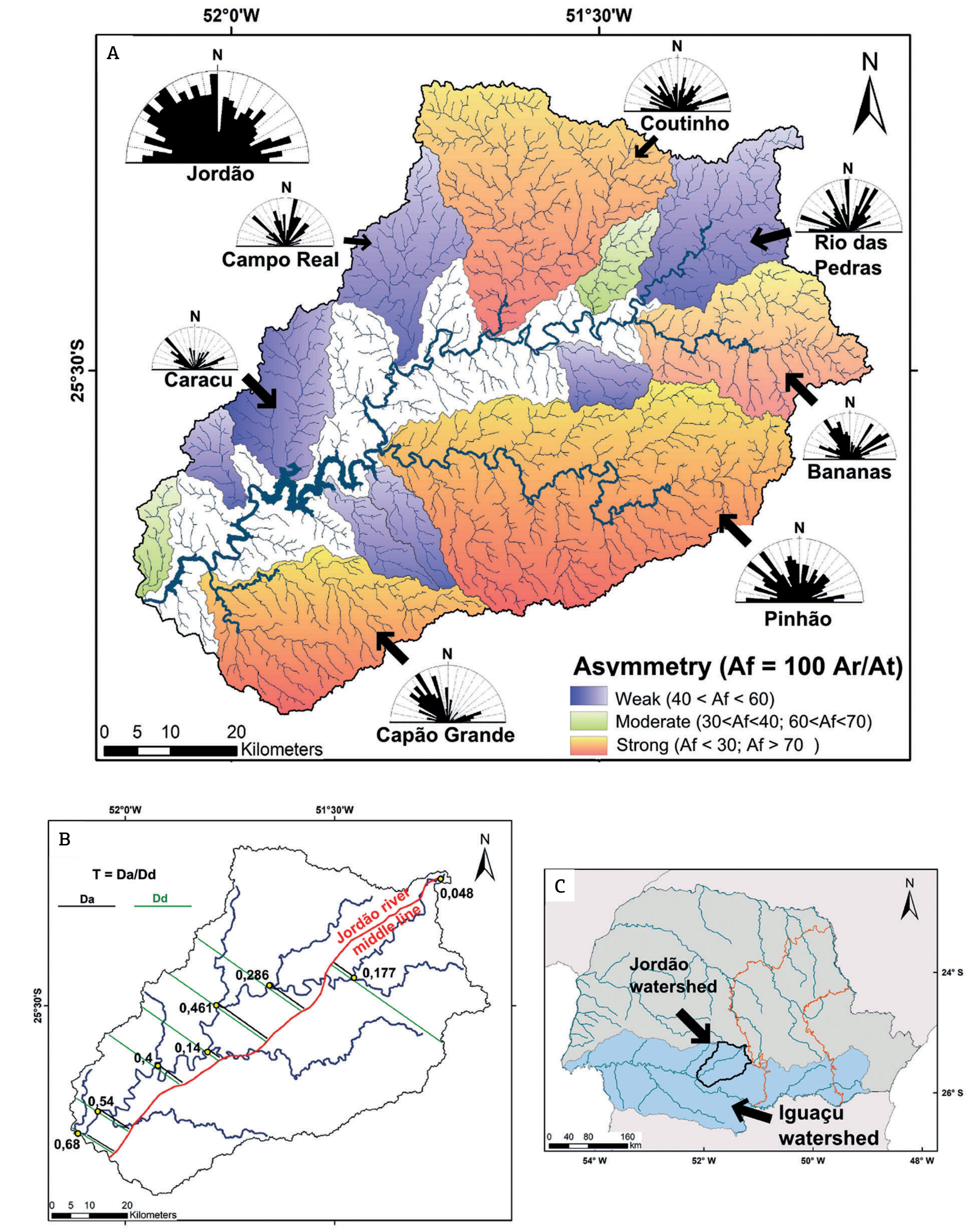


Figure 7. Drainage network of Jordão River. Colored polygons in main figure (A) represent subbasins asymmetry (Using Asymmetry Factor), ranging from symmetric (blue) to strongly asymmetric (red). The figure also includes the rosettes stereograms for Jordão River and Jordão's main tributaries. (B) This map represent the variation of asymmetry in Jordão River according to the Transverse Topographic Symmetry Factor method (T), the red line represent the Jordão River catchment middle line. (C) Paraná Hydrographic map in 1:1,000,000 with Iguaçu (blue) and Jordão rivers (black line).

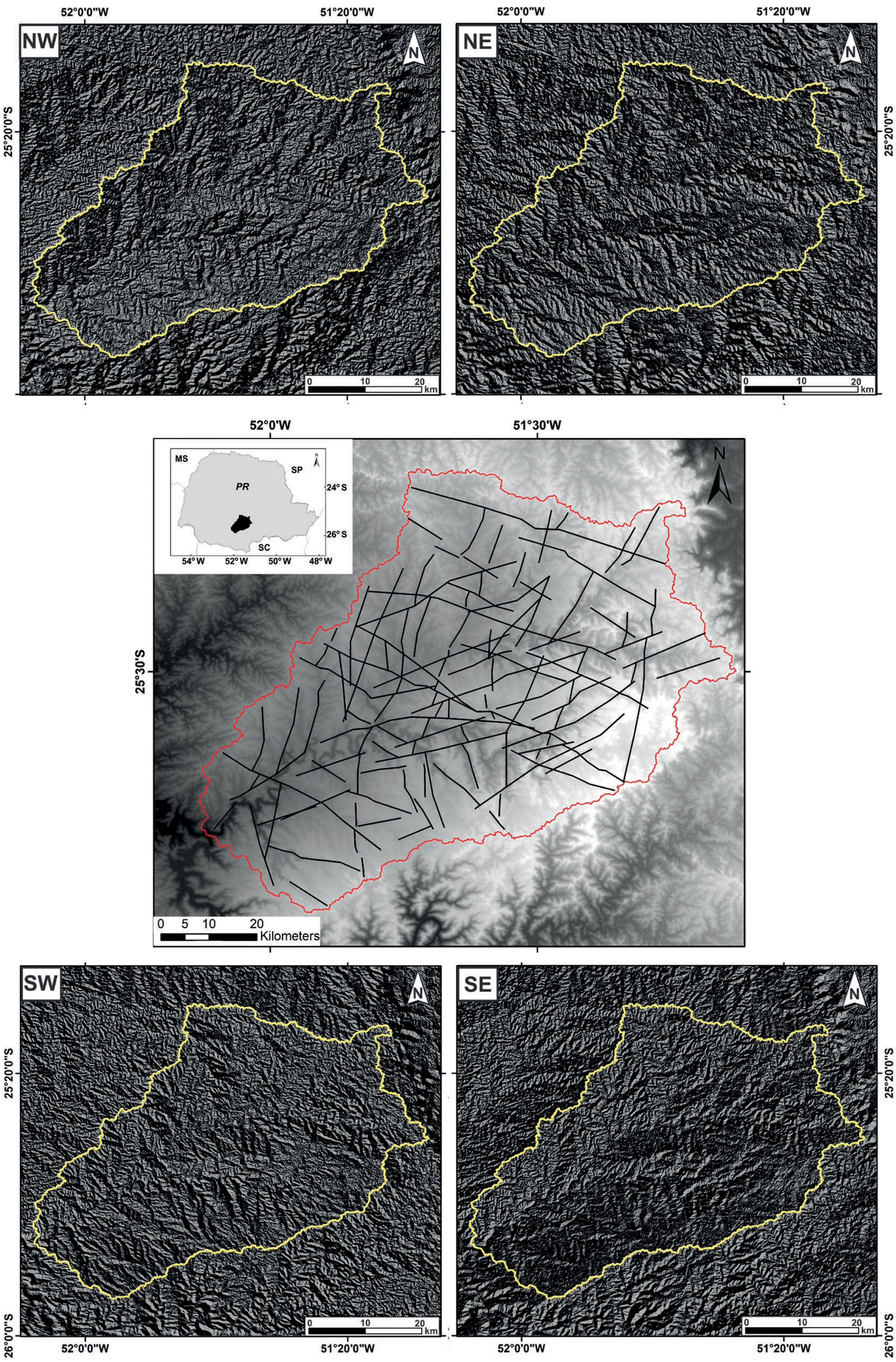


Figure 8. In the corners, four shaded relief images derived from SRTM-Topodata digital elevation models (Valeriano & Rossetti 2012) of the Jordão River catchment, illuminated from different azimuth directions (45°, 135°, 225° and 315°). In the center of the figure, the lineament map of the Jordão River catchment based in shaded relief imagery as shown.

running parallelly to upper Jordão River in the northern portion of the catchment area.

NNE-SSW and NNW-SSE drainage alignments are highlighted in the shaded relief imagery, the most outstanding ones being on the right bank of the catchment area. The asymmetric drainage, typical of the left margin of the drainage basin, can be observed in both density maps and shaded relief imagery, embedded as 'scar' marks on the ground. Among these asymmetric drainages are the segments of lower Jordão and Pinhão rivers. The traces in shaded relief are often oriented to NE-SW direction and are composed mainly by short and shallow aligned segments, which correspond to the main drainage pattern observed in the catchment region.

Landsat 8 imagery allowed for the visualization of large NW-SE lineaments sectioning the catchment area, which were also observable in shaded relief images. These lineaments are parallel to Iguaçu and Piquiri River basins, which border the Jordão River catchment to southwest and northeast, respectively. Although NW-SE lineaments are relatively dense in the region, with an average spacing of 10 km in between them, their contribution to local relief was interpreted as secondary, only important when fitting NW-SE parallel streams associated to ESE-WNW asymmetric drainages.

Structural analysis

Out of 637 measurements of fault and joint planes, 263 of them showed reliable kinematic indicators, of which five main sets of faults were defined after their attitude frequencies (Tab. 1). The most representative of these sets groups vertical faults with directions ranging between N45E and N75E (F1 set), which comprises Taxaquara Fault Zone, and is characterized by decametric plans of rupture, reaching more than 50 m length by tens of meters high (Figs. 9 and 10) as observed in quarries located on the banks of Jordão River, in the municipality of Guarapuava. F1 planes show dextral and sinistral kinematic indicators, suggesting reactivation of the faults and causing the generation of two sets of slickensides in the plane, one of them showing sub-horizontal rakes (up to 10º) and the other one presenting oblique rakes (between 20 and 35º).

Table 1. Fault sets and systems described at the region and their respective orientations and predominant kinematics.

Set		Direction	Kinematic
F1		N45E – N75E	Dextral/Sinistral
F2		N75E – N75W	Dextral/Sinistral
F3		N15E – N45E	Sinistral/Dextral
F4		N15E – N15E	Dextral
F4		N30W – N50W	Sinistral
System	**σ1**	**Dextral Side**	**Sinistral Side**
D1	N75W	F1 – F2	F5
D2	N05W	F4	F3
D3	N45E	F3	F1 – F2

The second most frequent trend (F2 set) is roughly oriented to E-W, with directions varying between N75E and N75W. Its planes also contain F1-like slickensides, with a sub-horizontal and oblique rake (bimodal pattern), as well as kinematics of both right- and left-lateral movements. These fault planes dimension reaches up to 15 m of lateral extension and are observed in quarries at the northeast region of the Jordão River catchment. In the analyzed outcrops, the association between these two main tendencies of fractures — F1 and F2 — is constant (Fig. 11), one of which (usually F1) characterized as the main fault and the other as secondary structures occurring in *en echelon* pattern. This same arrangement of fractures is responsible for the development of waterfalls (knickpoints) in Jordão River and its main tributaries, as well as in the rapids of both Jordão and Capão Grande rivers, situated respectively to the northeast and to the south of Jordão River (Fig. 6).

The planes ranging from N10E to N45E (F3 set) and those oriented between N25W and N10E (F4 set) also stand out in the examined outcrops of the Jordão River catchment. The F3 set structures are metric in dimension, rarely exceeding 5 m and show both dextral and sinistral kinematic indicators — as the F1 and F2 sets — although they always present unidirectional striae; the F4 set, on the other hand, is predominantly composed by right-lateral strike-slip faults, reaching extensions greater than 15 m and up to 10 m of vertical continuity.

Closer to the NW-SE lineaments, a fifth set of structures occur showing considerable density and represented by N30-50W subvertical left-lateral strike-slip faults (F5 set). These faults are frequently reactivated with normal kinematic and their planes are frequently smooth and decametric in dimension. The highest concentration of these faults was observed near Iguaçu Lineament, situated in the south/southeast boundary of the catchment area of Jordão River. Around the NW-SE parallels lineaments along the Pinhão and Capão Grande rivers catchments, they occur showing similar density, but rarely presenting normal kinematics indicators.

The differentiation between tectonic fractures and columnar jointing was relatively simple. Whereas the last one is

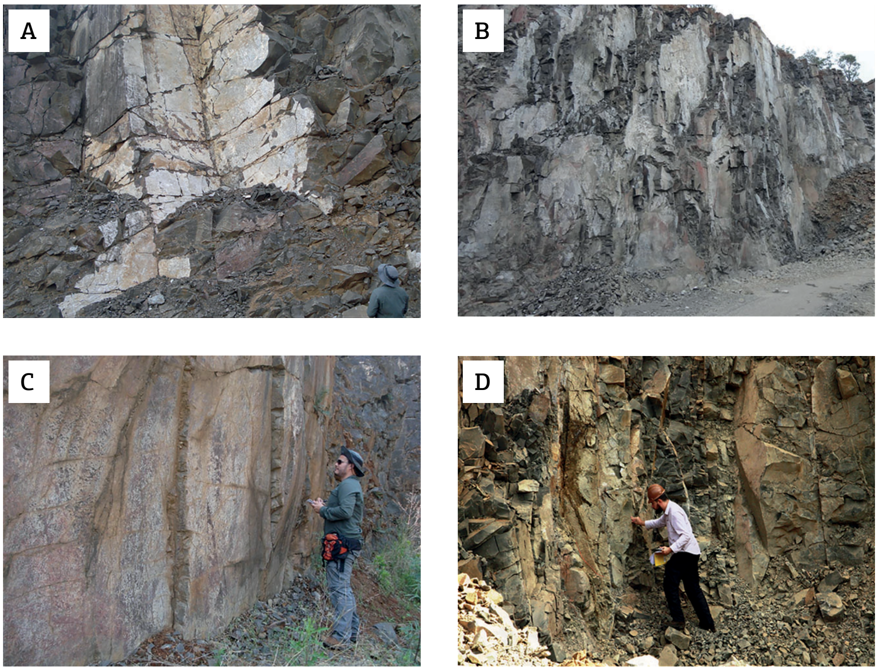


Figure 9. (A) Conjugated faults in Itax quarry, the pair is composed by a dextral F3 fault and sinistral F2 Fault forming a 55º between them. (B) Decametric F1 faults at Taxaquara Fault Zone, observed in Dalba quarry near Jordão River. (C) Example of decametric right-lateral strike slip fault oriented to N10W (Itax quarry). (D) Typical aspect of the F1 fault planes, characterized by fault breccias, typical from the top of the flows (Sul-Britas Quarry).

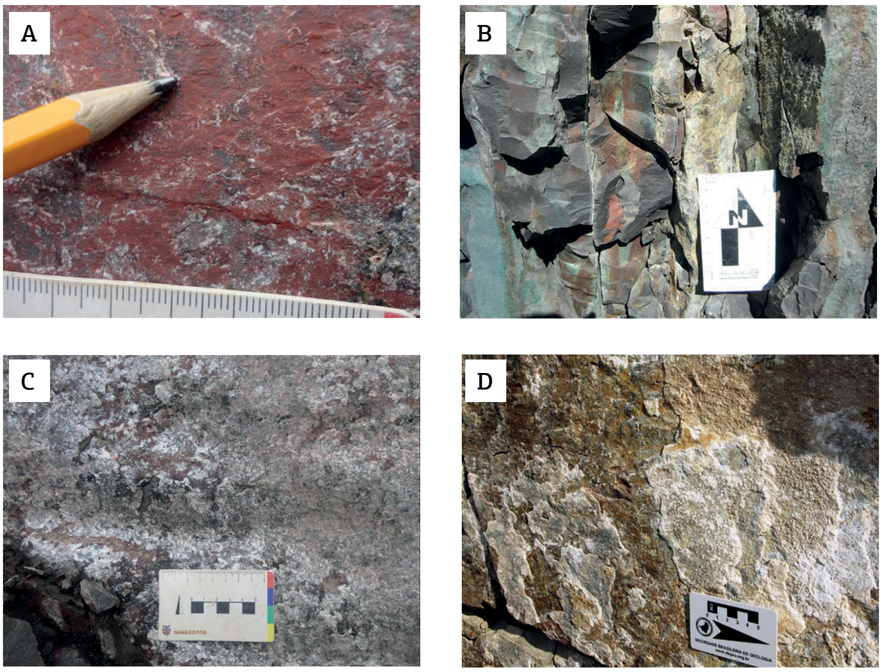


Figure 10. (A) Aspect of F4 (NNW) fault planes, typically showing reddish coloration because of the Fe oxides that fill them (Itax quarry). (B) Deformation bands in detail, characterized by NE fault breccias (Sul-Britas quarry). (C) Mesoscopic picture of a F1 fault plane (N45-75E), usually filled by carbonatic minerals. The plane shows a decimetric subhorizontal slickenline, indicating the strike-slip movement of the fault (Dalba quarry). (D) Typical plane of a F2 fault (E-W), often yellowish because of the carbonate and oxide fillings showing steps that indicate the left-lateral movement of the observed surface (Itax quarry).

characterized by straight and flat planes concentrated at the tops of the flows and, showing dense frequency with geometric arrangements between themselves, tectonic fractures occur in all levels of the basalt flow, showing rough and striated planes with different arrangements between them. When fractures occur in horizons with high concentration of columnar jointing, they tend to be less dense than the rest of the flow, frequently spaced by tens of meters. In this situation, the occurrence of associated fault breccia is frequent (Figs. 9 and 10), which, despite being generally associated with flow tops, are not restricted to them. The fault breccia is frequently oriented N50-70E (F1 set), although it also occurs at lower frequencies ranging between N-S and NW-SE, forming subvertical fractures and deformation bands (damage zone) with lateral extensions of about 10 and up to 50 cm.

Two sets of conjugate faults occur at the Jordão River catchment area, both configured by a left-lateral/right-lateral strike slip pair. The most common of these consists of N60-85E right-lateral strike-slip faults (F1 and F2 sets) and N30-50W left-lateral strike-slip faults. The second set (Fig. 9) consists of N20-40E right-lateral strike-slip faults (F3 set) and N60-75E and N75E-N85W left-lateral strike-slip faults (F1 and F2 sets, respectively; Tab. 1).

In several outcrops, it was possible to observe crosscutting relations between the four main sets of faults, indicating the existence of more than one deformation event responsible for nucleation/reactivation of the existing fractures in the Jordão River catchment area (Fig. 11). Two moments can be distinguished by the crosscutting relationship between different sets of faults, one of them represented by the E-W faults (F2 set), cut by N-S and NNW-SSW right-lateral strike slip faults (F4 set), observed in the rapids of Capão Grande River and in the Dalba quarry; and a last one, recognized in outcrops at the Fundão hydroelectric power station dam — lower course of Jordão River — in rapids of Jordão River and also in the Dalba and Itax quarries. Exposures were marked by the presence of N-S fractures (F4 set) being cut by NE-SW (F1 set) and E-W (F2 set) right-lateral strike-slip faults, as well as by N45-60W left-lateral strike-slip faults (Tab. 1).

DISCUSSION

Statistical treatment of the data revealed the existence of three compressive events responsible for the nucleation and reactivation of the faults present in the Jordão River

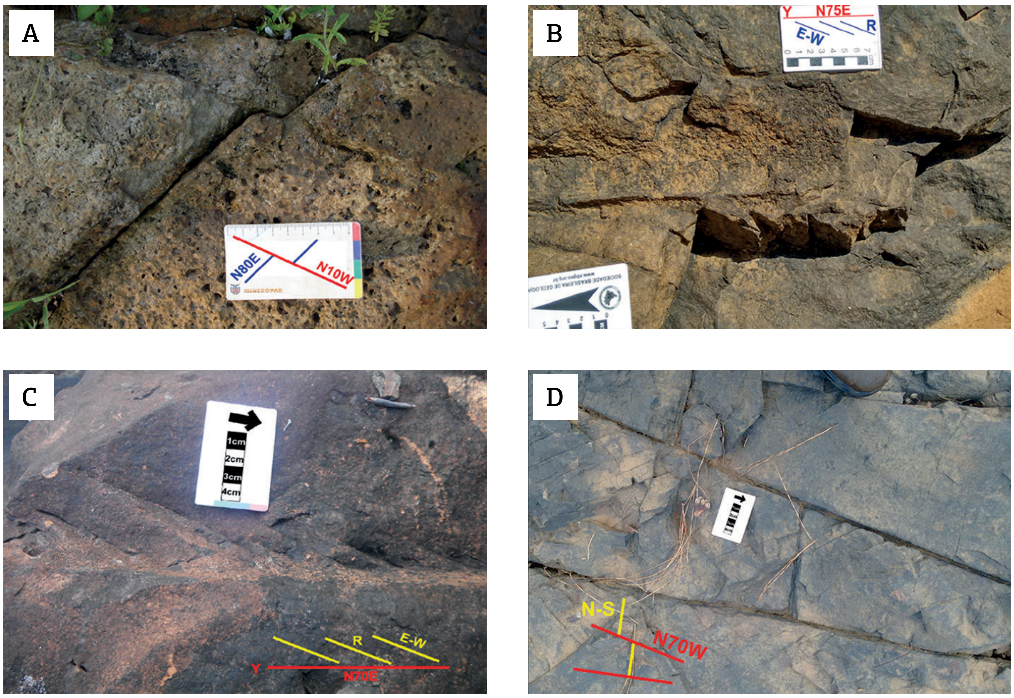


Figure 11. (A) Crosscutting relation between F2 and F4 fractures, the F2 fracture being cut by F4 dextral fault, active by a N-S tensor (D2). (B) The relation between F1 (main fault) and F2 (*en echelon*) fault planes, common in the Jordão River catchment area, where the main fault represents the Y fault of the Riedel model, while the *en echelon* faults correspond to the R fractures. (C) Same relation between F1 and F2 faults in Y and R position (respectively) and both with dextral kinematic. (D) Crosscutting relation regarding a D3 event, when a NW sinistral fault cuts a F3 fracture.

catchment (Fig. 12), which were characterized through the analysis of crosscutting relations between the described faults. N60-75E and E-W left-lateral strike-slip faults (F1 and F2 sets, respectively) were generated by a horizontal maximum paleostress (S_{Hmax}) oriented to N45E, as well as the F3 set right-lateral strike-slip faults. NNW-SSE right-lateral strike slip faults (F4 set) nucleated under a S_{Hmax} oriented to N-S (precisely in N05W), also responsible for the reactivation of NE-SW left-lateral strike slip faults (F3 set). The third direction of paleostress is N75W and was responsible for the dextral and transtensive reactivation of F1 and F2 sets of faults and the sinistral reactivation of NW-SE (F5) strike-slip faults. Although these NW-SE faults are not frequent in the area, they show planes that cut through the faults of the F4 set, being, therefore, important in defining the relative chronology of deformation events.

The F1 and F2 sets of faults are sub-parallel to Taxaquara Fault Zone, so the events responsible for the activation/reactivation of these faults also caused the movement of Taxaquara Fault Zone, showing analog kinematics. As these two sets of faults show both dextral and sinistral kinematics,

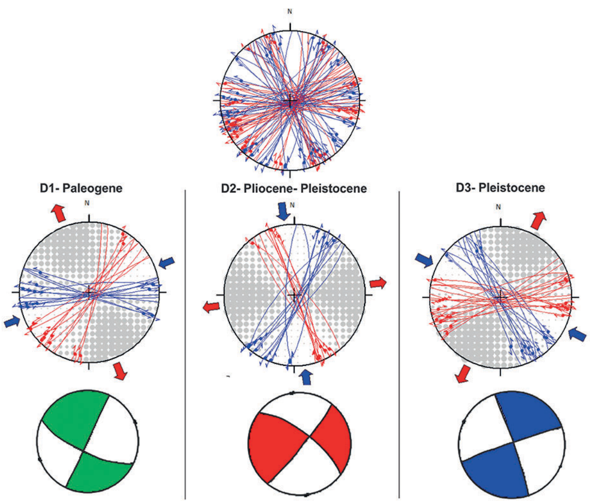


Figure 12. Stereograms (Schmidt, lower hemisphere) showing fault planes related to each of the three pulses events (D1, D2 and D3). Blue planes represent left-lateral strike-slip faults and red planes represent right-lateral strike-slip faults. In the bigger stereogram, all measurements obtained during fieldwork were plotted and individualized by sets of compatible kinematics shown in the smaller diagrams, where the maximum (in blue) and minimum stresses (in red) are also represented. The lower diagrams show the focal solutions of paleostrees (beach balls) calculated through the right dihedral method (Angelier & Mechler 1977), where the distensive field is white and the compressive field is green (D1), red (D2) and black (D3).

it can be deduced that two distinct fields of paleostress acted on Taxaquara Fault Zone causing its reactivation, which corresponds to the maximum horizontal stress oriented to N45E (left-lateral strike-slip reactivation) and the N75W S_{Hmax} (right-lateral strike-slip reactivation), as previously mentioned.

The hierarchy of events was defined by the crosscutting relationship between the described sets of faults; the first event (D1) is represented by the paleostress σ1 directed to N45E, subhorizontal, which would have generated the left-lateral strike-slip faults of F1 and F2 sets, later sectioned by the right-lateral strike slip faults of the F4 set, as observed in the rapids of Capão River (southern catchment area). The D1 event, as already mentioned, caused the sinistral reactivation of Taxaquara Fault Zone, consequently establishing the domain of NE-SW oriented streams in the region, embedded into its subsidiary joints. The large fault planes of the F1 set (N60-75E) observed in quarries near Jordão River are confined within Taxaquara Fault Zone damage zone.

The second event (D2) corresponds to a SHmax oriented to N-S, also subhorizontal, responsible for the right-lateral movement of the NNW-SSE strike-slip faults (F4 set), cutting Taxaquara Fault Zone. This movement probably caused the formation of the Jordão River canyon (parallel to the F4 set), which, in turn, sectioned the ENE-WSW interfluve that individualized the ancient drainage basins of upper Jordão and lower Pinhão rivers before surface level deformation. When NNE-SSW lineaments cut through the ENE-WSW interfluve, the entire drainage network that is now related to the Jordão River catchment began to respond to the base level of the superimposed river on Taxaquara Fault Zone, showing higher hydraulic quotient and causing drainage capture of the adjacent catchments. The magnitude of the knickpoints, as well as the slope of the valleys embedded in these NNE-SSW lineaments, allowed to deduce that this event has a recent age, since landforms are still in the juvenile stage of development instead of smoothened by erosive agents.

Even if the D2 event is relatively young, it is not the most recent event that contributed to the morphology of the Jordão River catchment area, being succeeded by a third event (D3) revealed by the observed crosscutting fault relations in fieldwork. During the D3 event, the maximum horizontal stress S_{Hmax} was oriented to N75W, causing clockwise/oblique reactivation of Taxaquara Fault Zone and nucleation of left-lateral strike-slip faults with NW-SE direction. This event led to the formation of the ENE-WSW lineaments in control of the asymmetric drainages, parallel to F2 set (E-W). As seen in the rapids of Jordão River, this arrangement of structures analogous to the F1 and F2 sets of faults was generated by the movement of Taxaquara Fault Zone, responding as its secondary structures. The arrangement of these lineaments and their asymmetric drainages and the oblique slickensides in F1 and F2 planes suggest a rotational movement of the blocks to the southeast of these lineaments, generating hemi-grabens; while in the northwestern part of the rotated blocks — the one in contact with the oblique faults — it has been tilted relatively southeast, to its other end, and to the adjacent block.

D3 event relief features, similarly to D2 ones, show characteristics of young reliefs, either by the remarkable knickpoints located along the watercourses of Jordão, Pinhão and Capão Grande rivers, or by the configuration of these river valleys along the ENE-WSW direction, still in process of downwearing instead of backwearing, which is only dominant once the denudation process becomes more mature (King 1953).

Chronological relationship between the deformation events

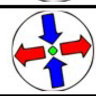
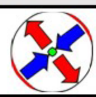
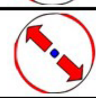
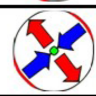
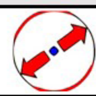
Due to the fact that the lithological units of the Jordão River catchment are similar in age (Lower Cretaceous), it was not possible to establish the absolute age of the events through this type of relation between structures. The maturity of the landforms is sufficient to establish the relative temporal relationship between the events, but not to precisely date them; therefore, the ages obtained for analogous events described in other locations within south and southeast Brazil were used as chronological references, as well as the age of regional planning surfaces (Tab. 2).

The three topographic surfaces dissecting the terrain (homologous zones) were correlated in literature and described by De Martonne (1943), King (1956), Ab'Saber (1962), Bigarella *et al.* (1965), Valadão (1998) and Silva (2009). The surface of the upper level (Zone I), which occupies the borders of the catchment area of Jordão River and its neighborhoods (Fig. 3), corresponds to the South American Surface described by King (1956) and Valadão (1998), also known as Pd3 in Paraná State (Bigarella *et al.* 1965). This surface was developed between the Late Cretaceous and the early Paleogene; therefore, this age was established as a limit for the deformation events that acted over the landscape of the Jordão River catchment, since all relief features deformed this surface, either directly or indirectly.

Zone II, younger than the previous one, corresponds to the *Cristas Médias* surface (Ab'Saber 1962) — also named Pd2 by Bigarella *et al.* (1965) —, developed during the Oligocene and Miocene. According to Mörner (1989) concepts; it can be deduced, therefore, that the events deforming this surface can be considered of neotectonic age, as it is the case of D2 and D3 events. The third surface, called Zone III, has not yet reached the planning phase in the catchment area, but is at the same base level as the Pd1, described as the Iguaçu Surface by Bigarella *et al.* (1965). Therefore, the dissection of the *Cristas Médias* surface in the catchment area (Zone II) occurs under the tectonic stresses of D2 event and posteriorly to the still active D3 event, concomitantly to the development of Iguaçu Surface in other locations of Paraná State. This context also allows for the interpretation that they correspond to neotectonic events as described by the Stewart and Hancock (1994) definition and according to the Living Tectonics concept of Wegmann (1955).

The age of the D1 event is uncertain, since two NE-SW direction deformation events occurred between the development of zones I and II, one taking place between the end of the Upper Cretaceous and the Eocene (Riccomini 1995a, Roldan 2007, Machado *et al.* 2012) and the other during the Oligocene (Riccomini 1989). It is possible that these two events may in fact correspond to a single progressive event acting throughout the Paleogene, intercalated by a NW-SE distensive/transtensive phase (inversion of σ1 and σ2) which would result in the generation of the tafrogenic basins of southeast and south Brazil, although not significantly deforming Paraná Basin. Due to the uncertainty about the continuity of these events and the absence of

Table 2. Relative chronology of planning surfaces and tectonic deformation events obtained for other localities in southern and southeastern Brazil. Literature reference (second column) corresponds to the first time this event was described in previous papers.

		Literature Reference	σ1	σ3	Graphical Representation
Pleistocene	D3	Riccomini, 1989	NW-SE	NE-SW	
		Continental Rift of Southeast Brazil			
Plio-Pleistocene	D2	Chavez-Cuz & Salamuni, 2008	N-S	E-W	
		Curitiba Sedimentary Basin			
Miocene	S2	Ab'Saber, 1962	Cristas Médias Surface		
	D1	Riccomini, 1989	NE-SW	NW-SE	
		Continental Rift of Southeast Brazil			
Oligocene		Riccomini, 1989	VERTICAL	NW-SE	
		Continental Rift of Southeast Brazil			
Paleocene	D1	Riccomini, 1995a	NE-SW	NW-SE	
		Cananéia Alkaline Massif (SP)			
	S1	De Martonne, 1943; King, 1956	South American Surface		
Lower Cretaceous		Soares et al., 1978	VERTICAL	NE-SW	
		Paraná Basin			

NW-SE oriented stress deformations in the Jordão River catchment rocks, the age of D1 was considered Paleogene, which would be more plausible since the ages of the second NE-SW compressive event and the Jordão River pediplane are fairly similar.

The features originated by D2 event are parallel to the paleostress N-S oriented event proposed by Chavez-Kus and Salamuni (2008) within Curitiba Sedimentary Basin, which is one of the Brazilian southeastern tafrogenic basins that would have developed during the Pliocene and Pleistocene. The following event (D3) corresponds to the Holocene neotectonic event described by Riccomini (1989), responsible for the activation of the E-W right-lateral binary, also defined in the tafrogenic basins of the Continental Rift of Southeast Brazil (Tab. 2).

Tectonic pulses and their correlation with the relief: The morphotectonics of the Jordão River catchment is strongly related to the reactivation of Taxaquara Fault Zone, leading the sculpture of local landforms to be controlled by the fault zone itself. On the other hand, it is considered that the planing surfaces existing in the catchment area of Jordão River developed during periods of tectonic quiescence. The tectonic influence on the landscape is not limited to Taxaquara Fault Zone, but also to the subsidiary structures. These structures include the NE-SW oriented faults formed during the D1 event (Paleogene) that predominantly control streams of the Jordão River watershed; and the conjugate faults of the D3 event (Neogene), responsible for the establishment of the Lower Jordão River valley for the asymmetric ENE-WSW drainages controlled

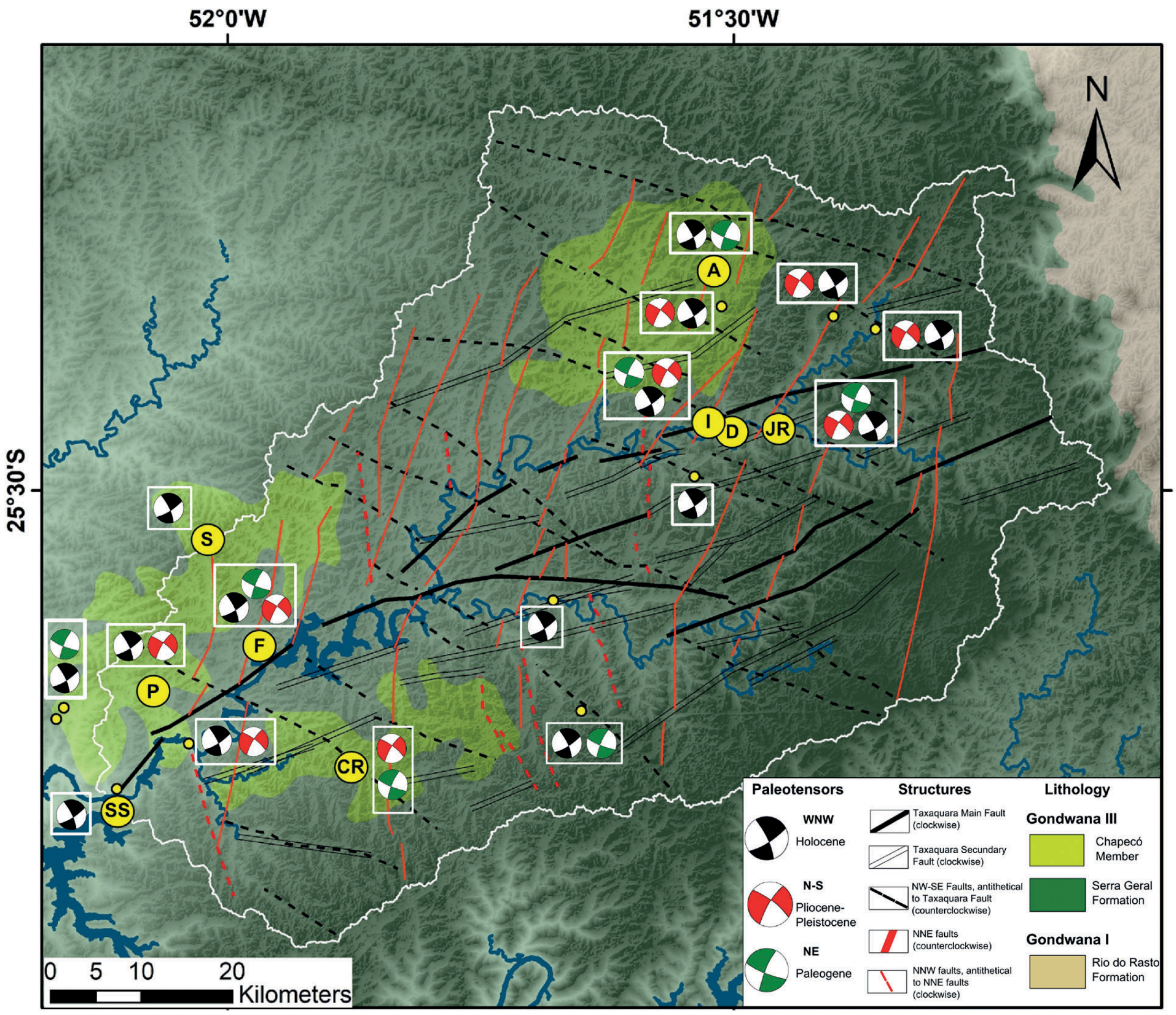


Figure 13. Tectonic map of the Jordão River catchment, constructed after several morphometric analysis. Each described outcrop was plotted with its respective beach ball diagram, representing observed structures. The beach balls showing green right dihedrals represent the D1 event (Paleogene); the red ones represent the D2 event (Plio-Pleistocene); and the black ones, the D3 event (Holocene).

by faults with similar direction, as well as for the development offer of parallel drainage networks embedded on NW-SE left-lateral strike-slip faults. Figure 13 shows the respective faults related to these two neotectonic pulses described in the area, being the D2 event (N-S) represented by red beach balls and fault lines and the D3 event (WNW-ESE) by black beach balls and fault lines.

Similarly to Taxaquara Fault Zone's control over the Jordão River catchment, other NE-SW fault zones — which according to Zalán *et al.* (1990) are inherited from Brazilian structures originated from the Gondwana suture during the Neoproterozoic — acted on the morphosculpture of other lithostratigraphic units of south and southeast Brazil. The Continental Rift of Southeast Brazil is one of the outstanding Cenozoic morphostructures formed due to the activation of NE-SW faults, including those that would be subparallel to Taxaquara Fault Zone during a transcontinental event during the Oligocene (Hasui *et al.* 1978, Campanha *et al.* 1985, Riccomini 1989, 1995b). Structures related to this NE-SW set were determinant to the development of Serra do Mar's morphostructure during the Paleogene (Almeida & Carneiro 1998, Morales 2005, Nascimento *et al.* 2013). Furthermore, these influences on Cenozoic tectonics find support in the conclusions of Soares et al. (1978), Zalán et al. (1990) and Artur & Soares (2002), which state that these same structures — along with the NW-SE set of faults — would have controlled sedimentation and erosion within Paraná Basin throughout its Paleozoic and Mesozoic evolutional history. In this context, it was possible to infer that the regional amplitude of influence related to these fault zones would not be exclusively limited to their associated lithostratigraphic units and morphostructures, but probably throughout southern Brazil.

CONCLUSION

The Jordão River catchment is affected by three tectonic episodes, intercalated by a period of tectonic stability associated with the development of a planning surface during the Oligocene-Miocene. Over this stability period, the maximum horizontal main stress would have varied from NE-SW, dominant throughout the Paleogene, to WNW-ESE, which corresponds to the current stress field on the South American plate, considered as neotectonic. Both paleostress directions caused reactivations along Taxaquara Fault Zone, initially as left-lateral strike-slip faults and posteriorly as transtensive right-lateral strike-slip faults.

Between the formation of the pediplane of the Jordão River drainage basin and the instauration of the WNW-ESE stress direction, a N-S compressive stress event occurred. This stress was probably responsible for the destabilization of the previously isolated drainage network and its consequent reorganization under the influence of the hydraulic gradient model of lower Jordão and Pinhão rivers, which run along the Taxaquara Fault morphostructure.

The slopes of NNW-SSE and NNE-SSW valleys, as well as ENE-WSW valleys, are steep and scarped, showing sharp knickpoints generated by recent tectonic pulses and indicating young erosion processes. The formation of these valleys led to the disorganization of the catchment, caused by drainage capture through the valleys, especially on those which have not yet had their equilibrium state restored by erosive processes. The sum of these aspects allowed the assumption that the D2 and D3 events defined for the Jordão River catchment are both neotectonic, concordant to the events defined within the tafrogenic basins of the Continental Rift of Southeast Brazil and also in Curitiba Basin.

The current movement of Taxaquara Fault Zone, which reflects in the development of the Jordão River catchment, is caused by the maximum horizontal WNW-ESE oriented stress, which is still active and causing the fault to show right-lateral oblique movement. The southeastern and southern blocks are rotated by the N70E and E-W secondary faults, culminating in the development of asymmetric ENE-WSW and WNW-ESE channels, typical of the left bank of Jordão River. Possibly, the NW-SE parallel drainage system associated to the asymmetric drainages developed under the tectonic pulse related to the NW-SE faults, which are conjugated to the E-W faults.

This research confirmed that Taxaquara Fault Zone had an important actuation in the development and evolution of the Jordão River catchment. During the Paleogene, its sinistral activation was responsible for starting the process of denudation of South American Surface, originating NE and ENE drainages, particularly in upper Jordão River. Posteriorly, in the Oligocene and Miocene, Taxaquara Fault Zone underwent a moment of quiescence, during which the expansion of Jordão Surface occurred around the fault zone. In the Holocene, a new phase with dextral kinematics leads to a new process of downwearing, denuding Jordão Surface and creating the asymmetric ENE valleys — mainly Pinhão and lower Jordão rivers — oriented along Taxaquara Fault Zone. As a result, the processes and agents that acted in the configuration of local landscape morphology were elucidated in this paper. The authors suggest that further studies should focus on the search for similar indications and relations in other NE-SW lineaments in the morphostructural context of Paraná Basin.

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REFERENCES

Ab'Saber A.N. 1962. *Compartimentação topográfica e domínios de sedimentação Pós-Cretácios do Brasil*. Thesis, Departamento de Geografia, Universidade Federal do Paraná, Curitiba, 80 p.

Almeida F.F.M., Carneiro C.D.R. 1998. Origem e evolução da Serra do Mar. *Revista Brasileira de Geociências*, **4**(2):23-40.

Angelier J. 1989. From orientation to magnitudes in paleostress determinations using fault slip data. *Journal of Structural Geology*, **11**:37-50.

Angelier J., Mechler P. 1977. Sur une methode graphique de recherche des constraintes principales egalament utilizable en tectonique et en seismologie: La method des diedres droids. *Bulletin of the Geological Society of France*, **7**:1309-1318.

Artur P.C., Soares P.C. 2002. Paleoestruturas e Petróleo na Bacia do Paraná, Brasil. *Revista Brasileira de Geociências*, **32**(4):433-448.

Bellieni G., Comin-Chiaramonti P., Marques L.S., Melfi A.J., Nardyc A.J.R., Papatrechas C., Piccirillo E.M., Roisenberg A., Stolfa D. 1986. Petrogenetic aspects of acid and basaltic lavas from the Paraná plateau (Brazil): geological, mineralogical and petrochemical relationships. *Journal of Petrology*, **27**:915-944. https://doi.org/10.1093/petrology/27.4.915

Bigarella J.J., Mousinho M.R.M., Silva J.X. 1965. Processes and environments of the Brazilian Quaternary. *In*: INQUA Congress, 10., Rio de Janeiro. *Caderno Especial*... Rio de Janeiro, Universidade Federal do Rio de Janeiro, 156p.

Burbank D.W., Anderson R.S. 2001. *Tectonic Geomorphology*. Oxford, Blackwell Science, 274p.

Campanha G.A.C., Riccomini C., Melo M.S., Hasui Y., Almeida F.F.M., Dehira L.K. 1985. Análise do padrão de fraturamento Mesozoico-Cenozoico de bacias tafrogênicas continentais do sudeste do Brasil. *In*: Simpósio Regional de Geologia, 5., São Paulo. *Atlas*..., **1**:332-350. São Paulo, SBG.

Castro L.G., Ferreira F.J.F. 2015. Arcabouço geofísico-estrutural da porção meridional do Cinturão Ribeira. *Brazilian Journal of Geology*, **45**(4):499-516.

Castro L.G., Ferreira F.J.F., Cury L.F., Fiori A.P., Soares P.C., Lopes A.P., Oliveira M.J. 2014. Interpretação qualitativa e semiquantitativa dos dados aeromagnéticos sobre a Zona de Cisalhamento Lancinha, porção meridional do Cinturão Ribeira no Estado do Paraná, Sul do Brasil. *Geologia USP. Série Científica*, **14**(4):3-18.

Chavez-Kus L.G., Salamuni E. 2008. Evidências da tenção N-S intraplaca no Neógeno. Complexo Atuba – região de Curitba (PR). *Revista Brasileira de Geociências*, **38**(4):439-454. https://doi.org/10.25249/0375-7536.2008383439454

Coutinho J.M.V. 1968. *Petrologia do Pré-cambriano em São Paulo e arredores*. Thesis, Universidade de São Paulo, São Paulo.

Cox R.T. 1994. Analysis of drainage and basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-clock tectonics: an example from the Mississippi Embayment. *Geological Society of America Bulletin*, **106**:571-581. https://doi.org/10.1130/0016-7606(1994)106%3C0571:AODBSA%3E2.3.CO;2

De Martonne E. 1943. Problemas morfológicos do Brasil Tropical Atlântico. *Revista Brasileira de Geografia*, **5**(4):532-550.

Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA). 1979. *Serviço Nacional de Levantamento e Conservação de Solos (Rio de Janeiro, RJ)*. Súmula da 10ª Reunião Técnica de Levantamento de Solos. Rio de Janeiro, Empresa Brasileira de Pesquisa Agropecuária, 83p. (Embrapa-SNLCS. Micelânea, 1).

Gerasimov I.P., Mescherikov J.A. 1968. Morphostructure. *In*: Fairbridge, R.W. (ed.), *The encyclopedia of geomorphology*. New York: Reinhold Book Co., p. 731-732.

Hack J.T. 1960. Interpretation of erosional topography in humid temperature regions. *American Journal of Science*, **258**:80-97.

Hack J.T. 1973. Stream-profile analysis and stream-gradient index. *Journal Research of the U.S. Geol. Survey*, **1**(4):421-429.

Hare P.W., Gardner I.W. 1985. Geomorphic indicators of vertical neotectonism along converging plate margins. Nicoya Peninsula, Costa Rica. *In*: Morisawa M., Hack J.T. (eds.), Tectonic Geomorphology, 15. *Proceedings*... Annual Binghamton Geomorphology Simposium.

Hasui Y. 1990. Neotectônica e aspectos fundamentais da tectônica ressurgente no Brasil. *In*: Workshop sobre Neotectônica e Sedimentação Cenozoica Continental no Sudeste Brasileiro, 1. *Boletim*...

Hasui Y., Gimenez A.F., Melo M.S. 1978. Sobre as bacias tafrogênicas continentais do sudeste brasileiro. *In*: Congresso Brasileiro de Geologia, 197 8, Recife. *Anais*..., **1**:328-391. Recife, SBG.

Hennies W.T., Hasui Y., Penalva F. 1967. O falhamento transcorrente de Taxaquara. *In*: Congresso Brasileiro de Geologia, 21., Curitiba. *Anais*..., 159-168.

Howard A.D. 1967. Drainage analysis in geologic interpretation: summation. *Bulletin of the American Association of Petroleum Geologists*, **51**(11):2246-2259.

Howard A.D. 1994. A detachment-limited model of drainage basin evolution. *Water Resources Research*, **30**(7):2261-2285. https://doi.org/10.1029/94WR00757

Keller E.A., Pinter N. 1996. *Active tectonics*: earthquake, uplift and landscape. New Jersey, Prentice Hall, 338p.

King L.C. 1953. Canons of landscape evolution. *Bulletin of the Geological Society of America*, **64**:721-732. https://doi.org/10.1130/0016-7606(1953)64[721:COLE]2.0.CO;2

King L.C. 1956. A Geomorfologia do Brasil Oriental. *Revista Brasileira de Geografia*, **18**(2):147-266.

Maack R. 1947. Breves Notícias Sobre a Geologia dos Estados do Paraná e Santa Catarina. *Arquivos de Biologia e Tecnologia*, **2**:63-154.

Machado R., Roldan L.F., Jacques P.D., Fassbinder E., Nummer A.R. 2012. Tectônica transcorrente Mesozoica-Cenozica no Domo de Lages – Santa Catarina. *Revista Brasileira de Geociências*, **42**(4):799-811. http://dx.doi.org/10.5327/Z0375-75362012000400011

Milani E.J. 1997. *Evolução tectono-estratigráfica da Bacia do Paraná e seu relacionamento com a geodinâmica Fanerozoica do Gondwana sul-ocidental*. PhD Thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre.

Milani E.J., Melo J.H., Souza P.A., Fernandes L.A., França A.B. 2007 Bacia do Paraná. *Boletim de Geociências Petrobras*, **15**(2):265-287.

Milani E.J., Ramos V.A. 1998. Orogenias Paleozoicas no domínio sul-ocidental do Gondwana e os ciclos de subsidência da Bacia do Paraná. *Revista Brasileira de Geociências*, **28**(4):473-484.

Morales N. 2005. *Neotectônica em ambiente intraplaca: exemplos da região sudeste do Brasil*. Thesis, Instituto de Geociências, Universidade de São Paulo, São Paulo, 201 p.

Morales N., Artur A.C., Peres J.P., Morais S.M. 2014. Indicadores cinemáticos deformacionais do granite Itapeti, região de Mogi da Cruzes – SP. *Geociências*, **33**(3):360-377.

Mörner N.A. 1989. Paleoseismicity and neotectonics. *Tectonophysics*, **163**:181-184. https://doi.org/10.1016/0040-1951(89)90255-2

Nardy A.J.R., Machado F.B., Oliveira M.A.F. 2008. As rochas vulcânicas Mesozoicas ácidas da Bacia do Paraná: Litoestratigrafia e considerações geoquímico-estratigráficas. *Revista Brasileira de Geociências*, **38**(1):178-195.

Nascimento E.R., Salamuni E., Queiroz G.L., Silva P.A.H., Fiori A.P. 2013. Evidências de determinação morfotectônica e neotectônica no relevo da Serra do Mar no estado do Paraná. *Revista Brasileira de Geomorfologia*, **14**(3):287-299.

Parzen E. 1962. On Estimation of a probability Density Function Model. *The Annals of Mathematical Statistics*, **33**:1065-1076. http://doi.org/10.1214/aoms/1177704472

Peate D.W., Mantovani M.S., Hawkesworth C.J. 1988. Geochemical stratigraphy of the Paraná continental flood basalts: borehole evidence. *Revista Brasileira de Geociências*, **18**(2):212-221.

Peyerl W.R.L., Silva C.L., Nascimento E.R., Santos J.M., Gimenez V. 2017. Mapa de densidade de Knickpoints, uma nova ferramenta na investigação morfotectônica por meio de sensoriamento remoto. *In*: Simpósio Sul-Brasileiro de Geologia, 10., 2017, Curitiba.

Quintela-del-Río A., Estévez-Pérez G. 2012. Nonparametric Kernel Distribution Function Estimation with kerdiest: An R Packpage for Bandwidth Choice and Applications. *Journal of Statistical Software*, **50**(8). http://dx.doi.org/10.18637/jss.v050.i08

Riccomini C. 1989. *O Rift Continental do Sudeste do Brasil*. Thesis, Instituto de Geociências, Universidade de São Paulo, São Paulo, 256p.

Riccomini C. 1995a. Padrão de fraturamento do maciço alcalino de Cananéia, estado de São Paulo: Relações com a tectônica Mesozoica-Cenozoica do sudeste do Brasil. *Revista Brasileira de Geociências*, **25**(2):79-84.

Riccomini C. 1995b. *Tectonismo gerador e deformador dos depósitos sedimentares Pós-Gondwânicos da porção centro-oriental do estado de São Paulo e área vizinhas*. Thesis, Instituto de Geociências, Universidade de São Paulo, São Paulo, 100 p.

Roldan L.F. 2007. *Tectônica Rúptil Meso-Cenozóica na Região do Domo de Lages, SC*. Dissertation, Instituto de Geociências, Universidade de São Paulo, São Paulo, 121 p.

Ross J.L.S. 1990. *Geomorfologia:* Ambiente e planejamento. São Paulo, Contexto, 80 p.

Rostirolla S.P., Assine M.L., Fernandes L.A., Artur P.C. 2000. Reativação de peleolineamentos durante a evolução da Bacia do Paraná – O exemplo do Domo de Quatiguá. *Revista Brasileira de Geociências*, **30**(4):639-648.

Sadowski G.R. 1991. A Megafalha de Cubatão no sudeste brasileiro. *Boletim IG-USP, Série Científica*, **22**:15-28.

Salamuni E., Ebert H.D., Hasui Y. 2004. Morfotectônica da Bacia Sedimentar de Curitiba. *Revista Brasileira de Geociências*, **34**:469-478.

Salamuni E., Nascimento E.R., Silva P.A.H., Queiroz G.L., Silva G. 2013. Knickpoint Finder: ferramenta para a busca de geossítios de relevante interesse para o geoturismo. *Boletim Paranaense de Geociências*, **70**:200-208. http://dx.doi.org/10.5380/geo.v70i0.32797

Schobbenhaus C., Campos D.A., Derze G.R., Asmus H.E. 1984. *Geologia do Brasil – texto explicativo do mapa geológico do Brasil e da área oceânica adjacente, incluindo depósitos minerais, escala 1:2.500.000*. Brasília, Departamento Nacional da Produção Mineral, 501 p.

Schumm S.A. 1986. Alluvial river response to active tectonics. *In*: National Research Council (ed.), *Active Tectonics*. Washington, D.C.: National Academy Press, p. 80-94.

Serviços Geológicos do Paraná (Mineropar S.A.). 2005. *Mapa Geológico do Estado do Paraná, Escala 1:650.000*. Curitiba, Mineropar S.A.

Silva C.N., Silva J.M.P., Castro C.J.N. 2015. Methodological Guidelines for the Use of Geoprocessing Tools: Spatial Analusis Operations – Kernel, Buffer and the Remote Sensing Image Classification. *Agriculture Sciences*, **6**:707-716. https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.4236%2Fas.2015.67068

Silva T.M. 2009. Superfícies Geomorfológicas do Planalto Sudeste Brasileiro: Revisão teórico-conceitual. *Geo UERJ*, **20**(3):1-22. https://doi.org/10.12957/geouerj.2009.1426

Silverman B.W. 1986. *Density Estimation for Statistics and Data Analysis*. London, Chapman & Hall.

Soares P.C., Barbosalandim P.M., Fúlfaro V.J. 1978. Tectonic cycles and sedimentar sequences in the Brazilian intracratonic basins. *GSA Bulletin*, **89**:181-191. http://dx.doi.org/10.1130/0016-7606(1978)89%3C181:TCASSI%3E2.0.CO;2

Soares P.C., Fiori A.P. 1976. Lógica e sistemática na análise e interpretação de fotografias aérea em geologia. *Notícia Geomorfológica*, **16**:71-104.

Spagnolo M., Pazzaglia F.J. 2005. Testing the geological influences on the evolution of the river profiles: A case from the northern Apennines (Italy). *Geogr. Fis. Dinam. Quat*, **28**:103-113. http://gfdq.glaciologia.it/028_1_07_2005/

Stewart I.S., Hancock P.L. 1994. Neotectonics. *In*: Hancock P.L. (ed.), *Continental Deformation*. Oxford, Pergomon Press, p. 370-409.

Strugale M., Rostirolla S.P., Mancini F., Portela Filho C.V. 2004. Compartimentação estrutural das Formações Pirambóia e Botucatu na região de São Jerônimo da Serra, estado do Paraná. *Revista Brasileira de Geociências*, **34**:303-316.

Tchalenko J.S. 1970. Similarities shear zones of different magnitudes. *Geological Society America Bulletin*, **81**(6):1625-1640. https://doi.org/10.1130/0016-7606(1970)81[1625:SBSZOD]2.0.CO;2

Thiede D.S., Vasconcelos P.M. 2008. Paraná flood basalts: Rapid extrusion hypothesis confirmed by new $^{40}Ar/^{39}Ar$ results. *In*: Congresso Brasileiro de Geologia, 44., Curitiba. *Proceedings*...

Thiede D.S., Vasconcelos P.M. 2010. Paraná flood basalts: Rapid extrusion hypothesis confirmed by new $^{40}Ar/^{39}Ar$ results. *Geology*, **38**(8):747-750. https://doi.org/10.1130/G30919.1

Tucker G.E., Bras R.L. 1998. Hillslope processes, drainage density, and landscape morphology. *Water Resources Research*, **34**(10):2751-2764. https://doi.org/10.1029/98WR01474

Valadão R.C. 1998. *Evolução de longo-termo do relevo do Brasil Oriental (desnudação, superfícies de aplanamento e soerguimentos crustais)*. Thesis, Instituto de Geociências, Universidade Federal da Bahia, Salvador, 243 p.

Valeriano M.M., Albuquerque P.C.G. 2010. *Topodata:* processamento dos dados SRTM. São José dos Campos: INPE / Coordenação de Ensino, Documentação e Programas Especiais (INPE-16702-RPQ/854), 79 p.

Valeriano M.M., Rossetti D.F. 2012. Topodata: Brazilian full coverage refinement of SRTM data. *Applied Geography*, **32**:300-309. https://doi.org/10.1016/j.apgeog.2011.05.004

Van Der Beek P., Summerfield M.A., Braun J., Brown R.W., Fleming A. 2002. Modeling postbreakup landscape development and denudational history across the south-east African (Drakensberg Escarpment) bank. *Journal of Geophysics Research*, **107**(B12), 2351 p. https://doi.org/10.1029/2001JB000744

Waichel B.L., Lima E.F., Lubachesky R., Sommer C.A. 2006. Pahoehoe flows from the central Paraná Continental Flood Basalts. *Bulletin of Volcanology*, **68**:599-610. https://doi.org/10.1007/s00445-005-0034-5

Wegmann E. 1955. Lebendige tektonik eine Übersicht. *Geologische Rundschau*, **43**(1):4-34.

Whipple K.X., Hancock G.S., Anderson R.S. 2000. River incision into bedrock: Mechanics and relative efficacy of plucking abrasion and cavitation. *GSA Bulletin*, **112**(3):490-503. https://doi.org/10.1130/0016-7606(2000)112%3C490:RIIBMA%3E2.0.CO;2

Whipple K.X., Tucker G.E. 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. *Journal of Geophysical Research*, **104**:17661-17674. https://doi.org/10.1029/1999JB900120

Wilcox R.E., Harding T.P., Seely D.R. 1973. Basin wrench tectonics. *Bulletin American Association of Petroleum Geologists*, **57**:74-96.

Zalán P.V., Conceição J.C., Wolff S. Astolfi M.A., Vieira I.S., Appi V.T., Neto E.V.S., Cerqueira J.R., Zanotto O.A., Paumer M.L., Marques A. 1986. Análise da Bacia do Paraná. *Internal Report Gt-Os-009/85*. Rio de Janeiro, PETROBRAS (DEPEX-CENPES), 195 p.

Zalán P.V., Wolff S., Astolfi M.A.M., Vieira I.S., Conceição J.C., Appi V.T., Marques A., Zanotto O.A. 1990. Bacia do Paraná. *In*: Raja-Gabaglia G.P., Milani E.J. (Eds.), *Origem e evolução de bacias sedimentares*, Rio de Janeiro, 34 p.