



Using morphometric and geomorphic indices to assess Western São Francisco Craton neotectonic traces

Uso de índices morfométricos e geomórficos na análise de traços neotectônicos no setor ocidental do Cráton do São Francisco

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Abstract: Recently, geomorphometric properties of river networks and catchments have been described and applied as an efficient tool in the investigation of the landforms' response to neotectonics. Geometric parameters of the Cotovelo River catchment extracted from an Alos-Palsar digital elevation model were used to compute morphometric and geomorphic indices to investigate whether the bedrock structure and recent active tectonics influence the local drainage network. The Cotovelo catchment is situated in the Middle to Upper Proterozoic western foreland basin of the São Francisco craton, in northwestern Minas Gerais, Southeastern Brazil; it is presumed to be a stable piece of earth's crust. The automatically generated streams were processed at the sub-catchment scale to calculate the hypsometric integral, relief ratio, stream frequency, and drainage density morphometric indices as well as supported a geomorphic study based on the basin shape, asymmetry factor, valley floor width-to-height ratio, mountain front sinuosity, transverse topographic symmetry factor, and stream-length gradient index. Achieved results revealed recent and low-rate tectonic activity and structural control on the fluvial morphology. Prominent knickpoints, aligned with mapped fault scarps, disclose straight erosive fronts away from stratigraphic borders, indicating these features are unrelated to lithological changes. Despite the catchment location, the area exhibits impressive fluvial anomalies, and dissection occurs preferentially along ancient faults and fractures densely occurring in the rocky strata. Channel parallelism in context of medium to high relief and steep slopes, remarkably structurally drive fluvial dissection, asymmetric and elongated drainage catchments, and aligned landforms suggest neotectonic influence on the drainage network.

Keywords: Morphotectonics; drainage network; channel morphology; knickpoints.

Resumo: Recentemente, parâmetros geomorfométricos dos canais fluviais e de bacias hidrográficas têm sido utilizados como uma ferramenta eficiente na investigação da resposta do relevo à neotectônica. Parâmetros geométricos da bacia hidrográfica do Ribeirão Cotovelo extraídos de um modelo digital de elevação Alos-Palsar foram usados para calcular índices geomorfométricos, com o propósito de verificar se a tectônica recente influencia a organização da drenagem local. A bacia do Ribeirão Cotovelo está situada na bacia antepaís Mesoneoproterozoica ocidental do Cráton do São Francisco, no Noroeste do Estado de Minas Gerais, Sudeste do Brasil, portanto, um ambiente crustal presumivelmente estável. Canais gerados automaticamente foram processados e forneceram índices morfométricos como densidade de drenagem, integral hipsométrica, razão de relevo e frequência de rios, bem como subsidiaram um estudo geomórfico baseado no fator de forma da bacia, fator de assimetria, relação largura-altura do fundo do vale, sinuosidade da frente da montanha, fator de simetria topográfica transversal e relação declividade-extensão. Os resultados apontam um controle tectônico e estrutural da morfologia fluvial. Knickpoints proeminentes, alinhados com escarpas de falhas mapeadas revelam frentes erosivas retilíneas, distantes de contatos estratigráficos, portanto, não relacionadas às variações litológicas. Apesar da localização da bacia, os canais fluviais exibem anomalias impressionantes e a dissecação ocorre preferencialmente ao longo de paleoestruturas e estratos rochosos densamente fraturados; o paralelismo dos canais em um contexto de

relevo ondulado e vertentes íngremes, o forte condicionamento estrutural da dissecação fluvial, bacias assimétricas e alongadas e relevos alinhados sugerem controle neotectônico ativo da rede de drenagem.

Palavras-chave: Morfotectônica; rede de drenagem; morfologia fluvial; knickpoints.

1. Introduction

Morphometric analysis of catchments and drainage networks is a useful method to identify the relationship of various regional physiographic aspects (SUKRISTIYANTI *et al.*, 2018), notably the relationship among lithology, structures, and landforms. Thus, numerous studies have been conducted on direct or indirect morphometric analyses, particularly to investigate the evidence of recent tectonic activities (BULL; MCFADDEN, 1977; ROCKWELL *et al.*, 1985; WELLS *et al.*, 1988; KELLER; PINTER, 2002; AZOR *et al.*, 2002; SILVA *et al.*, 2003; EL HAMDOUNI *et al.*, 2008).

These studies have become easily taught and proved to be operative by using a variety of spatial resolution digital elevation model (DEM) data, owing to advances in geographic information system (GIS) technology and tools and noticeable Open Source GIS (QGIS Development Team, 2021). Notably, new freely available and accessible digital spatial data are becoming attractive for more public users (GROHMANN, 2004), and digital terrain data processing supports morphometric analysis accurately, quickly, and inexpensively (GROHMANN *et al.*, 2007). Therefore, DEM processing is an advantageous tool for exploratory analysis or in areas that do not have detailed topographic maps.

Worldwide, these procedures have been widely applied to tectonically active regions, such as the Himalayan Arc (SEEBER; GORNITZ, 1983), Nicoya Peninsula in Costa Rica (HARE; GARDNER, 1984), Mexican Volcanic Belt (RAMÍREZ-HERRERA, 1998), South and Southern Spain (SILVA *et al.*, 2003; EL HAMDOUNI *et al.*, 2008; PEDRERA *et al.*, 2009; PÉREZ-PEÑA *et al.*, 2010). In Brazil, the morphometry of fluvial systems is one of the most common themes in fluvial geomorphology (BARROS; REIS, 2019) and the previously referenced techniques have largely been applied to investigate the correlation between geological features and the physiography of river valleys (ETCHEBEHERE *et al.*, 2006; ROSSETTI *et al.*, 2008; SOUZA; ROSSETTI, 2011; FUJITA *et al.*, 2011; BARBOSA; FURRIER, 2017). Moreover, morphometric and geomorphic indices were trained in Brazil in assessments of development of drainage systems and discrimination of ductile and brittle tectonics (ALVES *et al.*, 2014), progress and growth of river catchments (BARBOSA; FURRIER, 2011), changes in river profiles (BARBOSA *et al.*, 2013), identification and demarcation of morphotectonic features (CAMOLEZI *et al.*, 2012), litho-structural and tectonic zoning (CHERÉM *et al.*, 2011), and effective detection of neotectonics (LIMA; FURRIER, 2014; ALVES; ROSSETTI, 2017).

This research aims to assess whether the western São Francisco deformed cratonic foreland basin (CAMPOS; DARDENNE, 1997a; Reis *et al.*, 2016) provided sufficient evidence to demonstrate recent tectonic activity in a rigid crustal environment. Therefore, the Cotovelo River catchment was used as the study area. It lies over the western Neoproterozoic foreland basin of the São Francisco Craton (ALKMIM; MARSHAK, 1998; CHANG *et al.*, 1987) in the Brazilian Atlantic Shield and is considered a stable piece of crust (CETEC, 1983; VALADÃO, 1998; REIS *et al.*, 2017), despite the large amount of fluvial and landscape anomalies observed in this area by satellite images and topographic data.

2. Study area

The Cotovelo River and its catchment is spread entirely in the municipality of Brasilândia de Minas, Minas Gerais State, southeastern Brazil (**Figures 1A** and **1B**). The river springs in the Canastra Plateau (the local place name of the Paracatu-Urucuia drainage divide) and flows to the southeast, until it meets the low-valley floodplain, where it changes its direction to the southwest in a 90° turn (**Figure 1C**), a feature that justifies its name (“elbow” in English). The hydrological catchment has an area of 788.1 km² and the river is 81,891 m in length; the altitude varies between 743 meters above sea level (masl) at the source and 497 masl at the outlet.

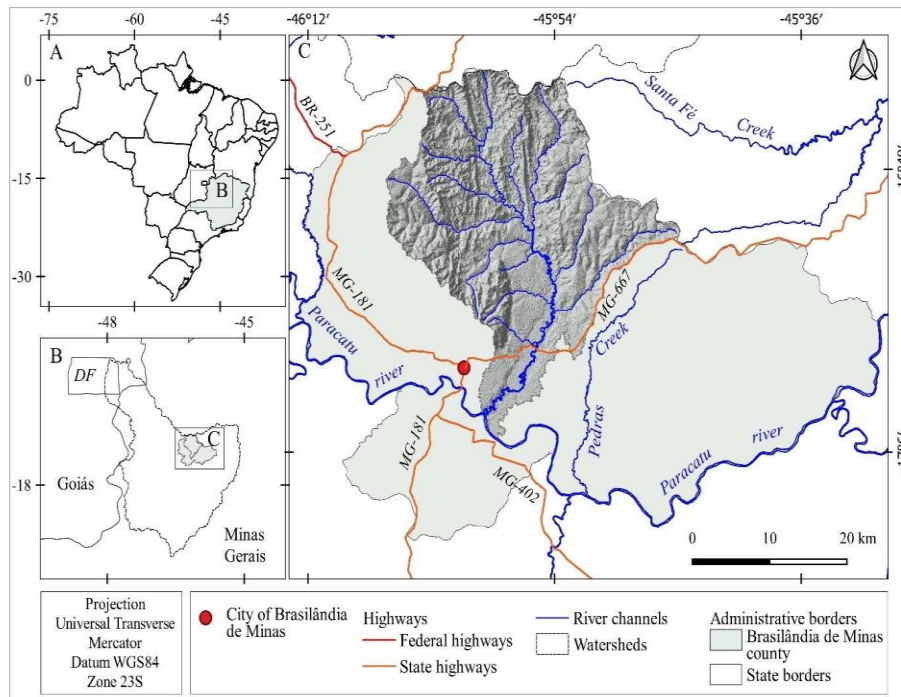


Figure 1: A) Emplacement of Paracatu river catchment in the national context; B) Position of the Municipality of Brasilândia de Minas in the northwestern Minas Gerais State and inner Paracatu catchment; C) Hillshade of the Cotovelo catchment and their tributaries inserted in the Municipality of Brasilândia de Minas. Modified from Prodemge. Minas Gerais State digital cartographic sheets.

The regional geological setting comprises two main sedimentary and metasedimentary sequences (**Figure 2**): the Neoproterozoic-Ediacaran Bambuí Group and the Phanerozoic strata (CAMPOS; DARDENNE, 1997; CPRM, 2003a; 2003b; REIS *et al.*, 2017). The Bambuí Group is essentially composed of siliciclastic lithologies, such as sandstones, siltstones, argillites, limestones, marls, and conglomerates (CAMPOS; DARDENNE, 1997a; PEDROSA-SOARES *et al.*, 1994; REIS *et al.*, 2017), setting up locally in the Três Marias, Serra da Saudade, and Lagoa do Jacaré formations (DARDENNE, 1978; SCHOBENHAUS *et al.*, 1985). The Phanerozoic coverages in the study area consists of sandy and clastic successions from the Middle to Upper Cretaceous, integrated in the Areado and Urucuia Group, along with the Neocenoic unconsolidated sandy, silty, and clayey detrital-regolith, colluvium and alluvium coverages encompassed by the Chapadão Formation (CETEC, 1983; CPRM, 2003a, 2003b; SGARBI *et al.*, 2001). A remarkable feature to be highlighted is the presence of the Precambrian NNW–SSE shear zone (CPRM, 2003a; 2003b) and a thrust and folded zone correlated to the Paraopeba sub-group, which comprises the Sete Lagoas, Serra de Santa Helena, Lagoa do Jacaré, and Serra da Saudade formations of the Bambuí Group (SCHOBENHAUS *et al.*, 1984).

Two regional-scale geomorphological units were described in the area as broad erosive features: the São Francisco Plateau and the São Francisco Depression (CETEC, 1983, 1981). The São Francisco Plateau describes a tableland morphology with elevations ranging from 700 masl to 860 masl. Regionally known as “chapadas”, these landforms correspond to wide and extensive drainage divides, covered by sandy, locally lateritic sediments, delimited for erosive vertical scarps (CETEC 1983). The São Francisco Depression comprises a broad, lowered, undulated, pediplanated, sedimentary area delimited by low escarpments along the main streams; altitudes vary from 480 masl to 560 masl (CETEC, 1983, 1981).

The Cotovelo River is a left bank barbed tributary (HAREL *et al.*, 2019) of the Paracatu River and its catchment lies over the São Francisco Plateaus (CETEC, 1981; 1983) comprising three main geomorphological landscapes. First is a tableland-like elevated plateau sculpted over predominant Carboniferous-Permian (Santa Fé Group) and Cretaceous (Areado and Urucuia Groups) sandy and sandy-silty strata, delimited by highly dissected scarps. Second is a terrace level, conglomeratic, flat-floored landscape, covered by sandy and silty-sand materials, positioned at both margins of the low-valley floodplain and in the southern divides. Third is a wide floodplain, associated with Upper Pleistocene and Holocene alluvial and colluvial sandy, silty, and clayey sediments (CETEC, 1981; CPRM, 2003b).

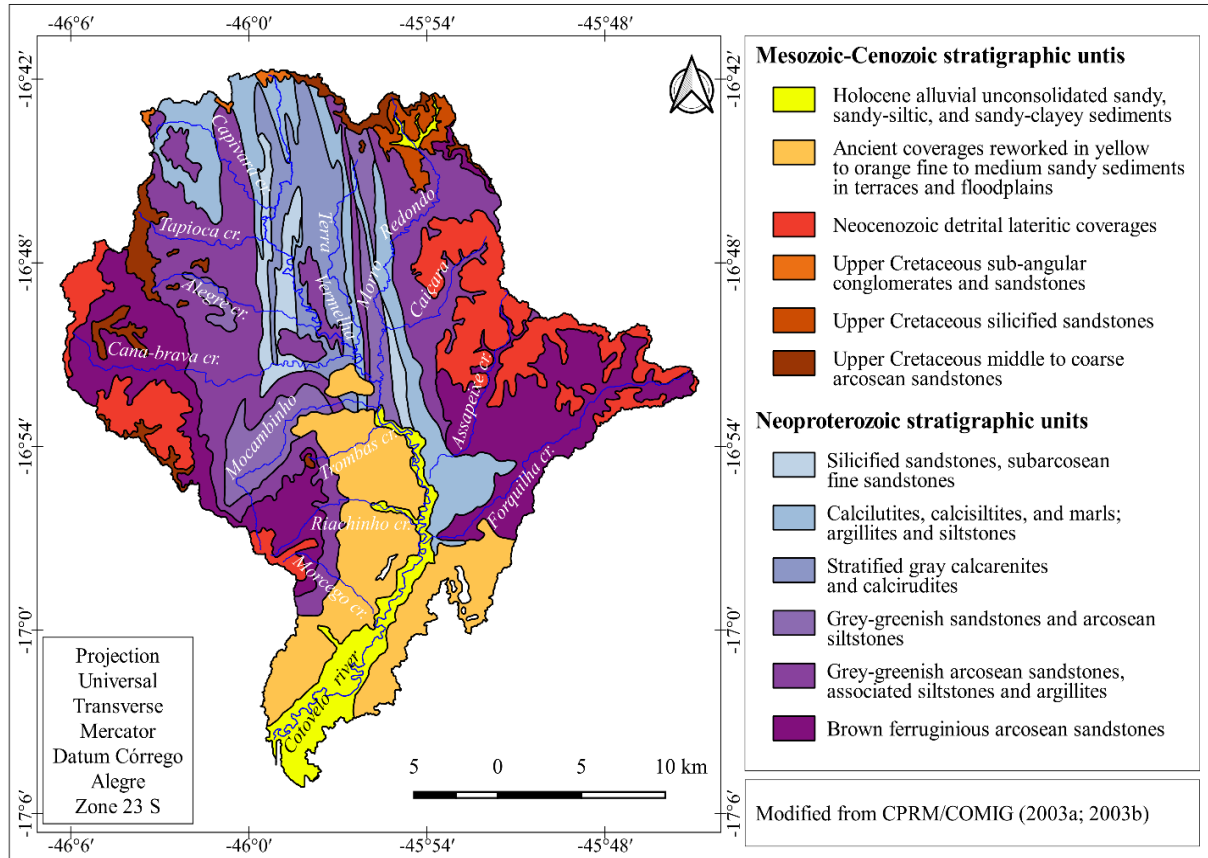


Figure 2: Simplified geological map of the Cotovelo catchment (Modified from CPRM, 2003a; 2003b)

Presently, convective systems explain the regional concentration of rain during the summer season (December-January-February) in the São Francisco catchment (NIMER, 1957; MARENGO *et al.*, 2012), with an average monthly temperature of 18 °C and annual rainfall of 1,500–2,000 mm (BRASIL, 1992).

3. Methods

To accomplish the objective, a Phased Array type L-band Synthetic Aperture Radar digital elevation model, Alos-Palsar DEM (ASF-DAAC, 2015) with 12.5 m per pixel of spatial resolution was processed to obtain the geometric parameters of the rivers and their catchments, using resources of GRASS GIS (Geographic Resources Analysis Support System Geographic Information System; GRASS GIS community, 2021) and SAGA GIS (System for Automated Geoscientific Analyses Geographic Information System; Conrad *et al.*, 2015), embodied into QGIS 3.14 (QGIS Development Team, 2019), such as *r.basin*, *r.watershed*, *r.water.outlet*, etc. (Grohmann, 2004; Grohmann *et al.*, 2007; 2011). Some parameters and basic unprocessed data were obtained using the database functionalities of MapInfo Professional 10.0. Finally, Microsoft Excel electronic spreadsheet was used for the simplest arithmetic operations for practical reasons. These data were used in the computation of morphometric and selected geomorphic indices, and the approach to data generation and processing at the catchment scale was appropriate and very efficient, providing a large automatically generated database that can avoid inhomogeneities.

Conventional morphometric indices processed and analyzed were stream order (STRAHLER, 1952; 1957), stream number (HORTON, 1932; 1945), stream length (HORTON, 1932; 1945), stream frequency (SMITH, 1950; FREITAS, 1952), hypsometric integral (STRAHLER, 1952), relief ratio (SCHUMM, 1956), and drainage density (HORTON, 1932; SMITH, 1950).

Six geomorphic indices were chosen to assess the area: the asymmetric factor, the drainage basin shape, the valley floor width-to-height ratio, the transverse topographic symmetry factor, the mountain front sinuosity, and the stream-length gradient index.

The asymmetric factor (HARE; GARDNER, 1985) quantifies the displacement of the channel from the middle of the catchment due to tilting or tectonic reason, defined by the equation

$$Af = 100 \left(\frac{Ar}{At} \right) \quad \text{Eq. 1}$$

where Ar is the area of the catchment to the right (facing downstream) of the trunk stream and At is the total area of the drainage basin.

The drainage basin shape ratio (SCHUMM, 1956; CANNON, 1976) quantifies the shape of a catchment, while relating their longest and widest points, calculated as follow

$$Bs = Bl/Bw \quad \text{Eq. 2}$$

where Bl is measured from the springs to the outlet, and Bw is the measure of the widest point of the catchment.

The valley floor width-to-height ratio (BULL; MCFADDEN, 1977) is used to discriminate V-shaped dissected and U-shaped flat-floored valleys, by means of the equation

$$Vf = 2Vfw / [(Eld - Esc) + (Erd - Esc)] \quad \text{Eq. 3}$$

where Vfw is the valley floor width, Eld and Erd are elevations to the left and right drainage divide, and Esc is the valley floor elevation.

The transverse topographic symmetry factor (COX, 1994) evaluates the amount of asymmetry of a river within a catchment, as a consequence of lateral tilting that may be correlated to tectonics (COX, 1994; SALVANY, 2004), computed as

$$T = Da/Dd \quad \text{Eq. 4}$$

where Da was computed as the distance from the current channel to the catchment middle line; Dd is the distance from the water divide to the catchment middle line. T Values vary between 0 in symmetric catchments and 1 in asymmetric catchments.

The mountain front sinuosity (BULL; MCFADDEN, 1977) evaluates the tectonic activity along mountain fronts, that is, the scarp created by a vertical displacement of a fault and the sedimentary basin at its piedmont; it is computed as

$$Smf = Lmf/Ls \quad \text{Eq. 5}$$

where Lmf is the length of front or scarp considered, along a selected contour, and Ls is the straight-line length of the same front or scarp.

With respect to the Smf , it must be highlighted that eight different mountain fronts were selected in a visual-based inspection of high-resolution satellite images, from a hypsometric map, and field reconnaissance, for a particular assessment. They are bounded by sharp impressive scarps and with geomorphological significance, being seven located in the right margin and one in the left margin of the Corovelo River. Seven of these cliffs are oriented N-S, roughly parallel to the Cotovelo riverbed; only one scarp is oriented toward the northwest, by the N-NE face of the Boqueirão Plateau.

The stream-length gradient index (HACK, 1973) assesses the deviation of part of a fluvial profile from the theoretical concave longitudinal profile, corrected for the distance to the drainage divide (VIVEEN *et al.*, 2012), calculated as

$$SL = \Delta H / \Delta L * L \quad \text{Eq. 6}$$

where ΔH is the difference in height of the selected channel reach, ΔL is the length of this reach, and L is the length of the entire channel upstream the halfway point of this reach.

The SL-index was obtained for the Cotovelo River, eleven tributaries and one sub-tributary, using DEM data and QGIS functionalities for successive individual reach values from the automatically generated

drainage network, for river lengths ranging from 6,100 m to 82,000 m. For each river, the SL-index values were averaged using a moving window of seven neighbors, which corrected narrow spikes and smoothed out the final curve.

4. Results and discussion

Sensitive to sudden variations in topography (PERUCCA *et al.*, 2014; MANJORO, 2015), rivers have been the most used indicators in exploratory studies of recent tectonic activity (DEMOULIN, 2011; MARPLE; TALWANI, 1993; PÉREZ-PENÁ *et al.*, 2009; RHEA, 1989; SOUGNEZ; VANACKER, 2011). In stable platforms, where tectonic activity is noticeably less expressive than in active zones, rivers tend to respond more quickly to barely noticeable deformations in the topography. Thus, small variations in the fluvial morphology or behavior of the fluvial channel may suggest signs of crustal movement (OUCHI, 1985).

A full drainage network and a row geometric database (**Table 1**) automatically derived from the DEM processing routines provided support for creating a basic map of the Cotovelo catchment, encompassing their main tributaries, and is the starting point for posterior geometric, morphometric, and geomorphic calculations and analyses. Subsequently, these data were used to calculate morphometric parameters (**Tables 2**), morphometric indices (**Table 3**), and geomorphic indices (**Table 4**), which supported the spatial and hydrological analysis of the entire Cotovelo catchment and their sub-catchments. Moreover, linear morphometric parameters were computed for rivers and sub-catchments, relating to channel patterns, drainage density, river incision, and landscape dissection.

Table 1: Basic geometric data of the Cotovelo River, Cotovelo catchment, and their tributaries and sub-catchments.

Catchments	$S_{ord}^{(1)}$	$h^{(2)}$	$H^{(3)}$	$\Delta h^{(4)}$	$L^{(5)}$	$P^{(6)}$	$n^{(7)}$	$A^{(8)}$	$Lt^{(9)}$	$Lcd^{(10)}$	$Ld^{(11)}$
Cotovelo	7	481	830	349	60,690	208,800	7,194	788.10	2,253,565	43,300	43,460
Forquilha	5	504	739	235	23,460	66,780	930	92.37	262,713	18,600	19,200
Assapeixe	5	509	742	233	15,760	41,730	394	39.37	118,825	12,200	12,400
Caiçara	5	533	791	258	10,910	32,610	291	32.17	88,746	8,500	8,900
Morro Redondo	6	522	849	327	25,060	67,210	752	82.66	232,291	17,400	19,000
Terra Vermelha	4	527	809	282	15,590	33,620	246	26.50	72,957	11,700	12,100
Capivara	5	557	845	288	12,650	35,230	363	42.42	115,705	8,300	10,000
Tapioca	4	518	819	301	10,210	26,310	139	16.12	41,018	7,800	8,000
Alegre	4	525	816	291	12,510	31,940	230	25.82	66,283	10,000	10,900
Cana-brava	6	504	781	277	23,600	71,750	1,040	113.40	300,937	18,100	17,900
Mocambinho	5	523	772	249	1,770	45,870	503	52.71	144,136	11,000	12,130
Trombas	4	533	791	258	6,108	18,050	73	9.15	29,689	5,000	5,220
Riachinho	4	518	790	272	12,510	32,170	239	24.69	65,138	9,200	9,520

Note: Data source: Digital processing of the ALOS-PALSAR DEM. ⁽¹⁾ Sord: Stream order (Strahler, 1952); ⁽²⁾ h: outlet altitude; ⁽³⁾ H: Springs altitude; ⁽⁴⁾ Δh : topographic gradient; ⁽⁵⁾ L: channel length (m); ⁽⁶⁾ P: catchment perimeter (m); ⁽⁷⁾ n: total number of channels; ⁽⁸⁾ A: catchment area (km²); ⁽⁹⁾ Lt: total length of the drainage channels (m); ⁽¹⁰⁾ Lcd: vector distance between the channel springs and the outlets (m); ⁽¹¹⁾ Ld is the vector distance between the catchment extreme points (m).

Because Cotovelo has 12 tributaries with remarkable characteristics suitable for the proposed geomorphological investigation, analytical descriptions of the results are presented from a comparative point of view.

Based on the stream order, the Cotovelo catchment was classified as a seventh-order catchment, and the order of their 12 main longest tributaries varied from 4th to 6th (**Table 2**). It is noticeable that a higher number of streams is concentrated in the 2nd order streams.

The total stream length is higher in the 1st order and very low in the 2nd order. Then, it increases again in the 3rd order and progressively decreases until the 7th order (**Table 2**). Deviations in these parameters can be a consequence of changes in lithology, — a characteristic feature of the NNW–SSE shear zone (CPRM; 2003a; 2003b) —, high relief or steep slopes that control the channel shape and channel network of rivers (GIAMBONI *et al.*, 2005), recurrent factors inside the Cotovelo catchment.

Table 2: Morphometric parameters of the entire Cotovelo River drainage network: stream order, number, and length: absolute and relative values

Channel order	Channels		Stream length	
	Number	Percentage (%)	Length (km)	Percentage (%)
1 st	3,613	35.5	1,176	67.8
2 nd	4,694	46.0	55	3.2
3 rd	901	8.8	254	14.6
4 th	484	4.7	136	7.8
5 th	295	2.9	75	4.3
6 th	116	1.1	3	0.2
7 th	97	1.0	36	2.1

The hypsometric integral values (HI) for the studied catchments ranged from 0.19 to 0.53 (**Table 3**). Lower HI values indicate old and more eroded areas, and high HI values suggest young and less eroded areas (EL HAMDOUNI *et al.*, 2008). Three specific trends were observed in this study: first, six catchments yielded HI values under 0.40 (Cotovelo, Morro Redondo, Terra Vermelha, Mocambinho, Trombas, and Riachinho creeks); second, five catchments yielded intermediate HI values ($0.40 \leq HI < 0.50$) (Capivara, Tapioca, Forquilha, Alegre, and Cana-brava); finally, two catchments produce higher HI values ($HI \geq 0.50$) (Assapeixe and Caiçara). Except for the Cana-brava creek, the other courses drain smaller catchments, and the HI values indicate that streams flow over a resistant lithology. Notably, the HI values for Assapeixe and Caiçara creeks indicated active dissection, maybe rejuvenated areas; these results are consistent with analogous of the Araripe and Paraíba sedimentary basins, where $HI > 0.50$ were used to select erosion-prone sub-catchments and support the hypothesis of neotectonic activity in a composite index (ANDRADES FILHO; ROSSETTI, 2015; OLIVEIRA *et al.*, 2018).

The relief ratio (Rr) indicates a variable scenario among the Cotovelo catchment tributaries ($Rr < 0.042$); in general, low values suggested an intensively dissected landscape and low possibility of intense and fast floods. However, the Mocambinho stream presents a very discordant result (0.141), showing steeper slopes shaped by active erosional processes.

The stream frequency (Sf) value of Cotovelo catchment and their sub-catchments range from 8.0 km/km² to 10.1 km/km², which can indicate the predominance of an impervious or less permeable and resistant sedimentary and metasedimentary dominant siltstone and argillite (Serra da Saudade and Lagoa do Jacaré formations) and fine to medium sandstones (Três Barras Formation) rock strata, associated to an undulated or hilly dissected landscape, with a higher and coarse (Smith, 1950) drainage density (2.5 km/km² to 3.2 km/km²). These features fit the sedimentary and metasedimentary rock strata and confirm the characteristic geological heterogeneity of the area. In addition, high values of Dd ($Dd > 2.50$ km/km²) correlated well to reactivated structures and rejuvenated erosive processes along weaker lines and tilted blocks, probably due to neotectonic activity (HIRUMA; PONÇANO, 1994).

Table 3: Hypsometric integral, relief ratio, stream frequency, and drainage density of the Cotovelo catchment and channel, along with their sub-catchments and respective channels

Catchments	HI ⁽¹⁾	Rr ⁽²⁾	Sf ⁽³⁾	Dd ⁽⁴⁾
Cotovelo	0.19	0.006	9.1	2.9
Forquilha	0.44	0.010	10.1	2.8
Assapeixe	0.53	0.015	10.0	3.0
Caiçara	0.50	0.024	9.0	2.8
Morro Redondo	0.31	0.013	9.1	2.8
Terra Vermelha	0.25	0.018	9.3	2.8
Capivara	0.47	0.023	8.6	2.7
Tapioca	0.47	0.029	8.6	2.5
Alegre	0.42	0.023	8.9	2.6
Cana-brava	0.37	0.012	9.2	2.7
Mocambinho	0.26	0.141	9.5	2.7
Trombas	0.21	0.042	8.0	3.2
Riachinho	0.34	0.022	9.7	2.6

Note: ⁽¹⁾ HI, hypsometric integral; ⁽²⁾ Rr, relief ratio ($\Delta h/L$); ⁽³⁾ Sf, stream frequency (n/A); ⁽⁴⁾ Dd, drainage density (Lt/A).

Figure 3 presents the mapped results of the geomorphic parameters calculated for the sub-catchments and channels subjected to analyses. **Figure 3A** identifies the channels; **Figure 3B** shows the ordered channels by the Strahler (1952) method and show a very uniform spatial distribution of the drainage channels in the catchment, suggesting a homogeneous lithology, except for the shear zone, where tectonics deformed highly complex primary structures. However, in a visual inspection, no significantly higher or lower drained area can be differentiated.

Three classes of drainage basin shape (**Figure 3C**) were observed (**Table 4**). High Bs ratio values indicate elongated basins, typical of high relief and steep slope areas; low Bs ratio values indicate more circular basins, common in areas of low relief and gentle slopes (SCHUMM, 1956; CANNON, 1976). The possibility of structural control is considered comparatively low in the Capivara catchment ($B_s < 2$), which indicates a more circular drainage basin. Moderate values ($2.0 \leq B_s \leq 3.5$) were recorded in the cases of Cotovelo, Caiçara, Cana-brava, Mocambinho, and Trombas catchments. High values ($B_s > 3.5$) indicate elongated drainage basins, likely influenced by structural controls, were reported for Forquilha, Morro Redondo, Terra Vermelha, Alegre, Riachinho, and Tapioca creeks; perhaps these catchments may have been influenced by reactivated structures. It is important and representative that 6 out of 13 catchments seem to exhibit structurally controlled drainage incision and downcutting. Notably, only Terra Vermelha and Morro Redondo sub-catchments are entirely situated inside the Precambrian shear zone.

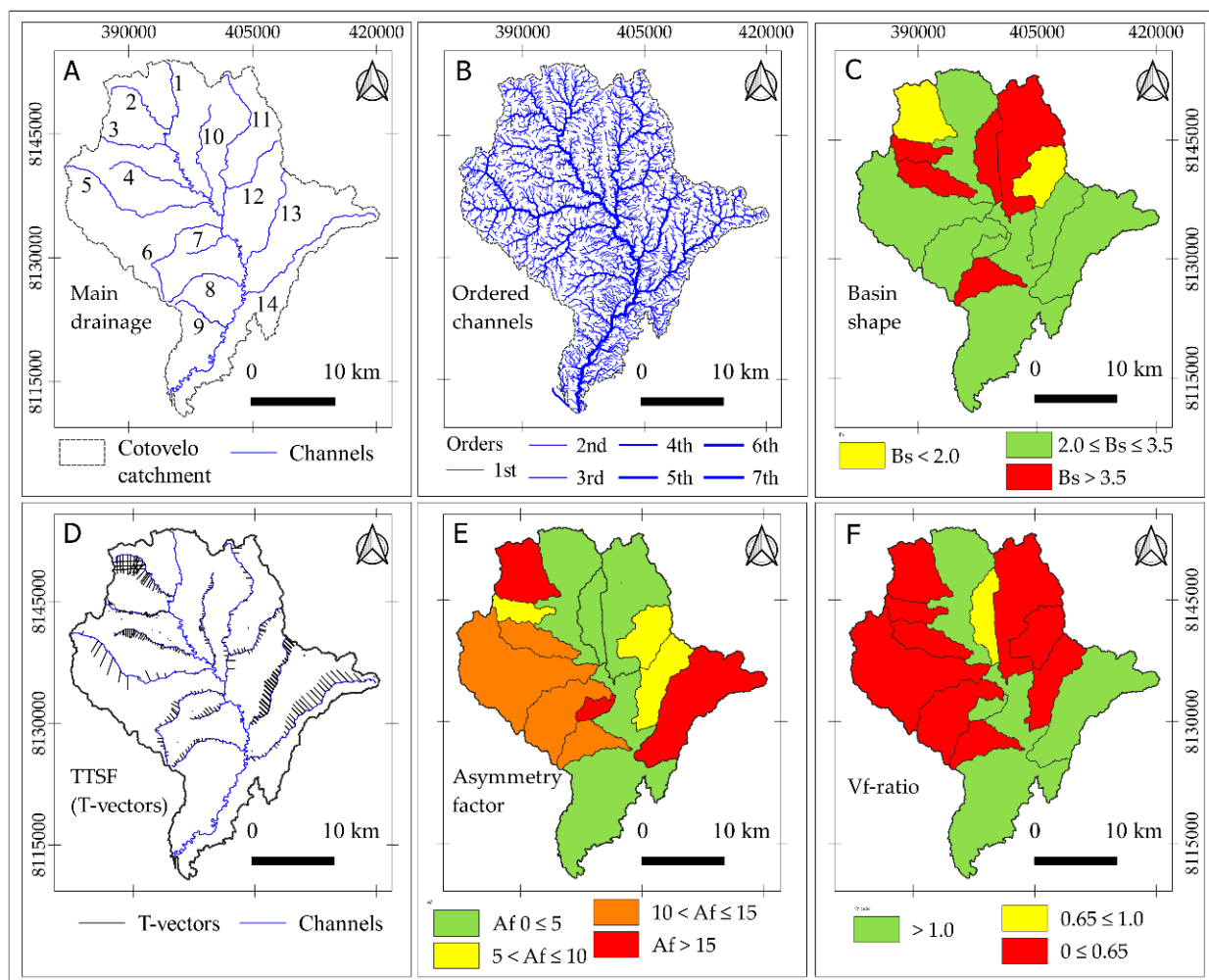


Figure 3: Geographic expressions of the Cotovelo River and their branches: A) Identified channels: 1) Cotovelo River, 2) Capivara Creek; 3) Tapioca Creek; 4) Alegre Creek; 5) Cana-brava Creek; 6) Mocambinho Creek; 7) Trombas Creek; 8) Riachinho Creek; 9) Morcego Creek; 10) Terra Vermelha Creek; 11) Morro Redondo Creek; 12) Caiçara Creek; 13) Assapeixe Creek; 14) Forquilha Creek. B) Automatically generated, ordered channels by the Strahler's (1952) method; C) Asymmetry factor index. D) Drainage basin shape index. E) Transverse topographic symmetry factor index; and F) valley floor width-to-height ratio. Red color highlights the sub-catchments with stronger evidence of structural control (passive and/or active).

Table 4: Computed geomorphic indices for sub-catchments and their respective channels

Catchments	Bs ⁽¹⁾	Af ⁽²⁾	Vf-ratio ⁽³⁾	T-vector ⁽⁴⁾	SL-index ⁽⁵⁾	River bank
Cotovelo	2.16	51.47	11.67	0.29	21,74	-
Assapeixe	3.98	59.94	0.52	0.54	20,58	Left
Caiçara	2.38	42.12	0.12	0.13	19,85	Left
Forquilha	3.99	70.57	1.25	0.39	19,06	Left
Morro Redondo	4.23	45.40	0.24	0.19	25,10	Left
Terra Vermelha	5.56	52.72	0.75	0.16	23,83	Left
Alegre	4.54	62.51	0.10	0.58	33,68	Right
Cana-brava	2.83	64.66	0.29	0.18	29,21	Right
Capivara	1.95	68.20	0.34	0.44	20,58	Right
Mocambinho	3.31	37.03	0.11	0.21	28,94	Right
Riachinho	4.52	39.79	0.07	0.18	30,97	Right
Tapioca	4.27	59.58	0.11	0.17	25,95	Right
Trombas	3.41	25.30	1.14	0.24	26,07	Right

Note: ⁽¹⁾ Drainage basin shape (Bs), ⁽²⁾ Asymmetry factor (Af), ⁽³⁾ Valley floor width-to-height ratio (Vf-ratio), ⁽⁴⁾ Transverse topographic symmetry factor (T-value), and ⁽⁵⁾ Stream-length index (SL-index).

The results of the TTSF (T-vector) calculation showed internal differences among the sub-catchments and tributaries of the Cotovelo River, and at least three internal distinctive patterns were observed (Figure 3D). Values can be grouped into three classes, according to Sajadian *et al.* (2015): Class 1: $T < 0.2$ (low level of tilting); Class 2: $0.2 \leq T < 0.4$ (moderate level of tilting); and Class 3: $T \geq 0.4$ (high level of tilting). The T-vector values indicate low relative tectonic-based tilting (T-vector < 0.2) in sub-catchments of Caiçara, Morro Redondo, Terra Vermelha, Cana-brava, Riachinho, and Tapioca creeks. Moderate values of tectonic-based slant ($0.2 \leq T\text{-vector} < 0.4$) were found in the Forquilha, Mocambinho, and Trombas sub-catchments. Finally, higher relative tectonic-based tilting (T-vector ≥ 0.4) was characteristic of the Assapeixe, Alegre, and Capivara catchments. Apparently, this dip seems to be a randomic response to structural weakness lines. However, they are interpreted as resulting from an uplifted block observed along a line crossing the left divides of Mocambinho and Morro Redondo sub-catchments. Furthermore, the northern tributaries Capivara, Alegre, and Cana-brava creeks migrate toward N-NE, which seems to be caused by the adjustment of Precambrian weakness lines. The southern branches Mocambinho, Trombas, Riachinho, Assapeixe, and Forquilha drifted their channels toward the southeast, indicating control in the SW-NE direction. Finally, the Tapioca, Terra Vermelha, Morro Redondo, and Caiçara creeks have channels fitted to the shear zone structural directions. Assessed Southeastern and Southern Brazilian rivers provided analogous index outputs, showing lateral migration of river channels due to block tilting (CAMOLEZI *et al.*, 2012; PAES; SILVA, 2017).

The asymmetry factor (Af) absolute values ranged from 25.3 to 70.5 (**Figure 3E**) in this study (**Table 4**). Reference values for Af are (SALVANY, 2004; PÉREZ-PEÑA *et al.*, 2010): $Af < 5$ (symmetric catchments); $5 \leq Af < 10$ (gently asymmetric catchments); $10 \leq Af \leq 15$ (moderately asymmetric catchments); $Af > 15$ (strongly asymmetric catchment). Cotovelo, Terra Vermelha, and Morro Redondo were categorized as symmetric catchments, indicated by lower Af values (< 5.0). These three streams flow predominantly in the north–south direction, fitted to the Precambrian NNW–SSE shear zone structures; the Terra Vermelha and Morro Redondo creeks are tributaries of the left bank of the Cotovelo River.

Caiçara, Tapioca, and Assapeixe were classified as gently asymmetric catchments ($5 \leq Af < 10$). However, a distinction must be made: Caiçara and Assapeixe creeks are tributaries of the left bank of the Cotovelo River and have springs in the Morro Redondo Plateau, flowing toward the southwest. Tapioca creek springs at the Boqueirão Plateau, on the right bank, and flows toward the east–southeast.

Alegre, Cana-brava, Mocambinho, and Riachinho creeks were labeled as moderately asymmetric catchments, suggestive of tilting blocks ($10 < Af \leq 15$). All sub-basins are tributaries from the right bank of Cotovelo. The Cana-brava and Alegre streams have displaced their course to the left margin toward the N-NE. Mocambinho and Riachinho moved toward the S-SE to their right margins. In the former cases, a Precambrian structural setting can be responsible for the lateral migration of the channels.

Finally, Capivara, Forquilha, and Trombas belong to the strongly asymmetric catchment typology ($Af > 15$), a powerful indication that their channels flow over tilted blocks. On one hand, the more impressive shift of the Capivara channel toward N-NE indicates an adjustment to the NNW shear zone structures. Being higher energy channels, Capivara and Forquilha creeks do not developed alluvial plains. Differently, outside the shear zone, Forquilha and Trombas channels shifting to the southeast direction may be interpreted as strong evidences of differential and singular adjustment, as well as reinforce the possible existence of a

tilting block toward the southeast; the slant induces preferential erosion in the right margin of the Capivara, Assapeixe, and Forquilha catchments. Trombas, Riachinho, and Assapeixe creeks (and Morcego, a very small, not assessed creek), lower Af values catchments, spread their loads over the Cotovelo river floodplain, in a way of parallel, overlapped alluvial fans. Presently, these fans are subjected to accelerated incision due to a recent fall in the local base-level; this lowering arrived at the Cana-brava and Alegre outlets.

Values of valley floor width-to-height ratio (Vf-ratio) were used to assess the existence of some possible recent tectonic reactivation of Precambrian and/or probable more recent structures and its manifestation in the Cotovelo River catchment and their sub-catchments (**Figure 3F**); the ratios ranged between 0.07 and 1.25 (**Table 4**). High values of Vf (Vf-ratio > 1.0) indicate broad-floored canyons U-shaped valleys; low values of Vf (Vf-ratio ≤ 1.0) indicate dissected V-shaped valleys (BULL; MCFADDEN, 1977; EL HAMDOUNI *et al.*, 2008). Riachinho, Alegre, Mocambinho, Tapioca, Caiçara, Morro Redondo, Cana-brava, Capivara, and Assapeixe creeks displayed the lowest values of this index (between 0.07 and 0.52); these channels fall into Class 1 (tectonically active fronts) of Pérez-Peña *et al.* (2010), that is, streams in high-energy condition, positioned at eastern front of the Boqueirão scarp and western border of the Morro Redondo Plateau. Progressively higher Vf-ratio values provide indicative evidence that local streams actively downcut their beds (SILVA *et al.*, 2003; PEDRERA *et al.*, 2009), influenced by a base-level fall (NTOKOS *et al.*, 2016), which can be correlated with the Boqueirão scarp retreat. The Terra Vermelha creek displays a comparatively high Vf-ratio value (0.75), which explains a slight downcutting, perhaps resulting from the subsidence of the Cotovelo low-valley sedimentary plain. The Trombas and Forquilha creeks present the largest Vf-ratio values (1.14 and 1.25, respectively) among the different sub-basins and are set in inactive fronts (SILVA *et al.*, 2003).

There is a clear correlation between the Vf-ratio values and linear structures in the study area; lower values arose near eastern scarps of the Boqueirão Plateau and Western scarps of the Morro Redondo Plateau, and these values increased away from the structures. Therefore, elevated Vf-ratio values are located on the hanging wall of the Boqueirão and Morro Redondo fault lines (CPRM, 2003a; 2003b), and lower values occurred within the sedimentary basin, noticeable in the pediments and debris flow fanglomerate surfaces. Applied to the Brazilian Northeast onshore region, the index yielded similar results, identifying present tectonic control on landforms (BARBOSA *et al.*, 2013; BARBOSA; FURRIER, 2017), and these values are closer to the ones achieved nearby the Hellenic Arc (NTOKOS *et al.*, 2016).

Additionally, eight specific fronts/scarps (**Figure 4**) were assessed using the mountain front sinuosity index (BULL; MCFADDEN, 1977), and isolated channels crossing the fronts were checked by the valley floor width-to-height ratio (Vf-ratio) index. **Table 5** lists the outcomes. Reference values (RAMÍREZ-HERRERA, 1998; PÉREZ-PEÑA *et al.*, 2003; SILVA *et al.*, 2003) for the index are: $Smf < 1.4$ (probable tectonic activity); $1.4 \leq Smf \leq 3.0$ (probably low or undefined tectonic activity); and $Smf > 3.0$ (totally inactive fronts).

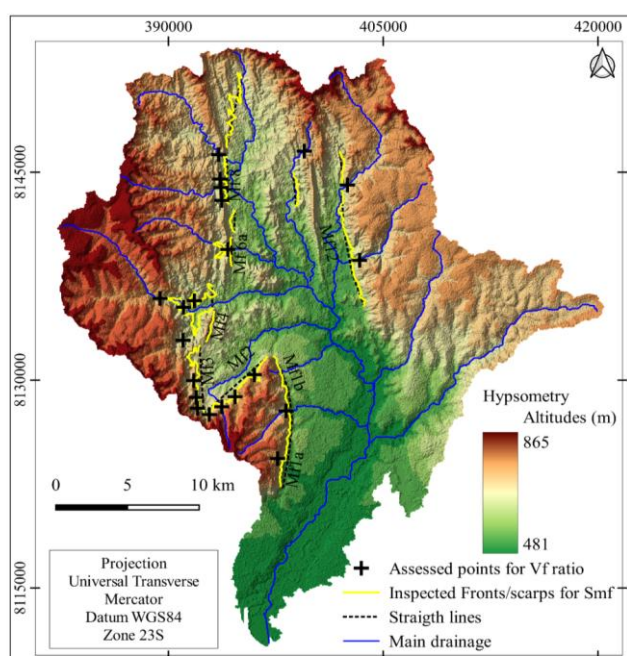


Figure 4: Hypsometry map of the Cotovelo catchment with scarps/fronts assessed using *Smf* index and isolated channels assessed by the *Vf-ratio*

Table 5: Mountain front sinuosity and valley floor width-to-height ratio for eight selected fronts/scarps

Fronts/scarps	Assessed channels	Smf	Vf-ratio		
			$n^{(1)}$	$\sigma^{(2)}$	Vf
Lmf-1a	Morcego creek	1.88	14	1.87	1.56
Lmf-1b	Trombas creek	1.33	23	0.47	0.60
Lmf-2	Mocambinho creek - tributary	1.51	27	0.89	0.76
Lmf-3	Mocambinho creek	2.03	10	0.30	0.46
Lmf-4	Cana-brava creek	10.96	17	0.06	0.15
Lmf-6a	Alegre creek	2.55	9	0.12	0.20
Lmf-8	Tapioca creek	1.91	19	0.03	0.10
Lmf-12	Caiçara creek	1.33	9	0.01	0.06

Note: ⁽¹⁾ n is the number of stream valleys assessed for Vf-ratio calculation. ⁽²⁾ σ is the standard deviation of the Vf-ratio calculation.

On assessing the Vf-ratio for selected mountain fronts, the results showed that seven fronts yielded clustered average values of Vf-ratio < 1.0 , which indicates an aggressive linear incision of the riverbed and suggests the probability of a recent front uplift (PEDRERA *et al.*, 2009). Only one front produces a higher mean value (Vf-ratio > 1.56), which points to dominant lateral erosion and low riverbed dissection and conveys no recent uplift (KELLER; PINTER, 2002).

Seven fronts/scarps (**Table 5**) yielded a broad Smf range from 0.99 to 2.55, and one abnormal result (10.96). Because the lithology is very uniform in the area, variability is probably due to structural passive and active control of the faulted and folded terrain of the NNW–SSE Precambrian shear zone and the existence of a Precambrian inverse fault in the piedmont of the Morro Redondo and Três Irmãos Plateaus (CPRM, 2003a; 2003b).

In agreement with the reference values proposed by Ramírez-Herrera (1998), Pérez-Peña *et al.* (2010), and Silva *et al.* (2003), two fronts (Lmf1b in the right margin and the Lmf-12 in the left margin) present Smf values below 1.4 threshold, and are interpreted as “more likely to record a recent uplifting”. The other five fronts (Lmf-1a, Lmf-2, Lmf-3, Lmf-6a, and Lmf-8, all at the right margin) yielded intermediate Smf values, between 1.4 and 3.0, indicating “a medium or undefined probability of a recent uplifting.” Lastly, the front Lmf-4 (Cana-brava Creek) yielded a Smf value of 10.96, an abnormal result, is explained by the sub-basin topographic settings of the Cana-brava Creek catchment; although it crosses the front in a relatively deep and narrow canyon, the Cana-brava headward aggressive erosion creates a broad drainage area.

Regarding the SL-index, generally, low values correlate to less steeper channels and have been used to describe low-rate or tectonically inactive areas, as well as rivers flowing over less erosion-resistant bedrocks (HACK, 1973; VIVEEN *et al.*, 2012). High SL-index values are usually suggestive of tectonically active areas (KELLER; PINTER, 1999), erosion-resistant bedrock, or headward migrating knickpoints (BURBANK; ANDERSON, 2001; VIVEEN *et al.*, 2012). In doing so, the resulting values were rated in three classes $SL/K < 2.0$ (no anomalous stream), $2.0 \leq SL/K < 10.0$ (2nd order anomaly), and $SL/K \geq 10$ (1st order anomaly), as proposed by Seeber and Gornitz (1983), dividing the SL-value of a reach (SL) for the SL-value of the entire channel (K), and the values were plotted against the longitudinal and the geologic river profiles. From the first outcome resulted the significance of predominant intermediate values ($2 \leq SL/K < 10$), which fall into the 2nd order anomaly. These plots were visually inspected in the DEM, slope map, satellite image, and using field-based experience (**Figure 5**), looking for coexisting knickpoints and filled-up areas, different rock type transitions, mapped and inferred faults, and lineaments.

The SL-index value computed for the whole Cotovelo River channel was 22.25, pointing to an ungraded river, because it supposes the necessity of adjusting the longitudinal profile to the bed (**Figure 6**). The 2nd order anomalies present in the middle valley suggest a rock-resistant bed as well as lithological transitions and diversity inside the NNW–SSE shear zone (CPRM, 2003a; 2003b), acting to the increasing or decreasing stream velocity. These values increase progressively toward the outlet, probably as a consequence of the tributaries' bedload and discharge supply. Entering its low-valley sedimentary floodplain, the river changes the dynamics substantially because of the amount of sediment, while yielding 1st order anomalies; another possible reason for these anomalies is the interference for the highway (MG-667 connecting the cities of Brasilândia de Minas and Santa Fé de Minas) filling of the profile, and increasing the road grade; this obstruction may have caused deep impacts in the fluvial dynamics.

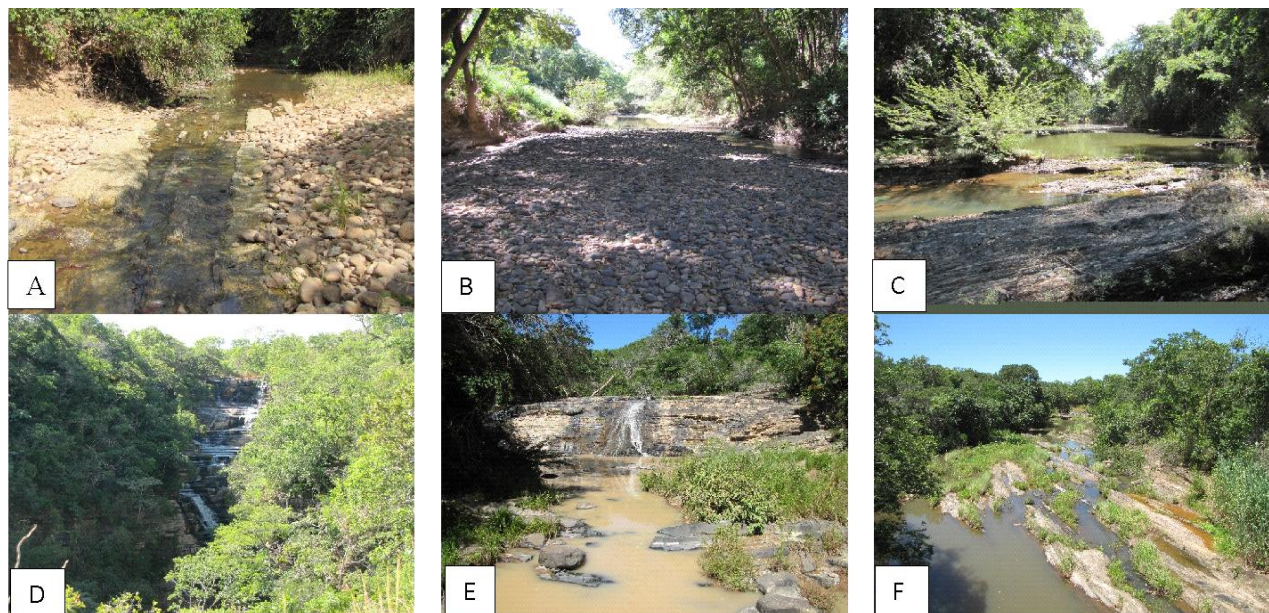


Figure 5: Knickpoints and knickzones along the river channels, in the Cotovelo catchment: A) Knickpoint in the Assapeixe channel, near the outlet (the river crosses the bedrock along the structure); B) Cotovelo riverbed during the dry season (the riverbed is paved with cobbles and pebbles); C) Knickpoints along the Cotovelo riverbed (the river crosses the rock structure diagonally); D) Fall in the Alegre creek (the knickpoint has around a height of 30 m); E) Knickpoint in the Capivara creek channel; F) Knickzone along the Morro Redondo creek channel.

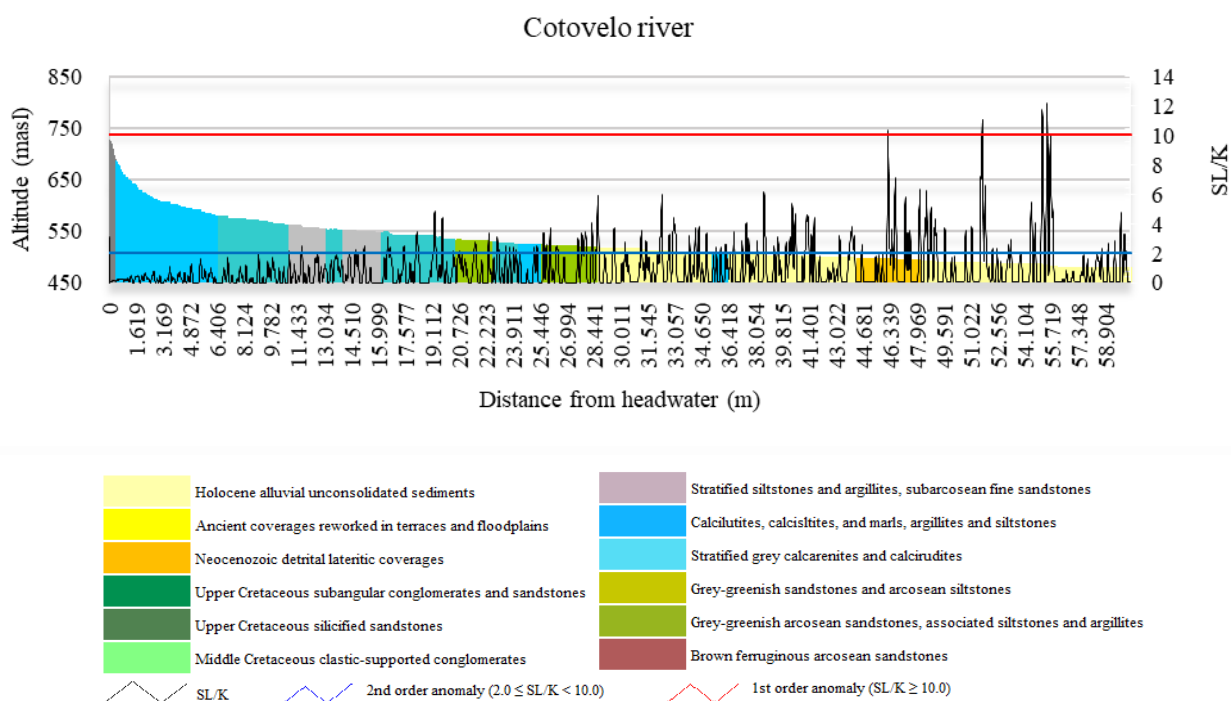
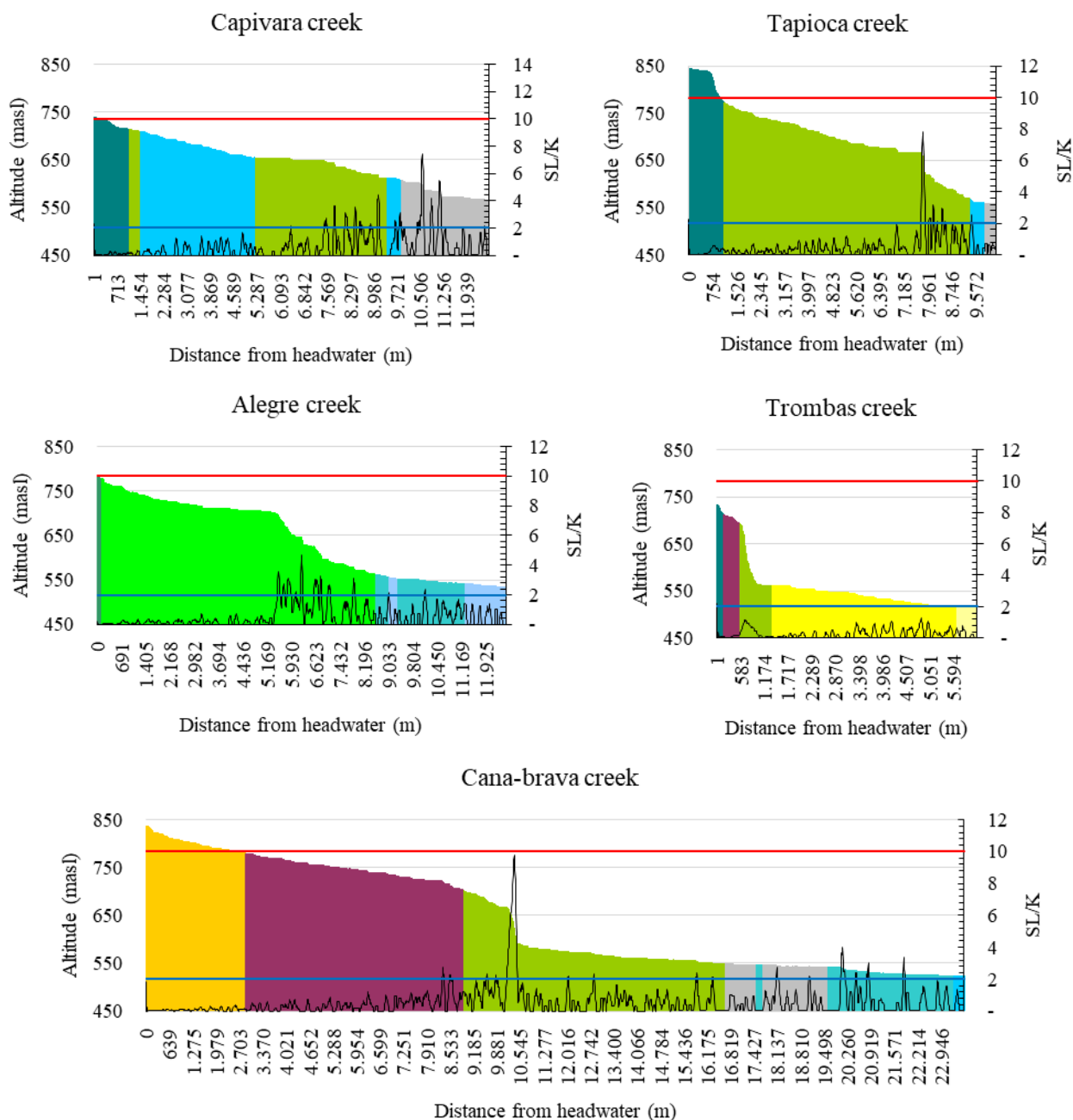


Figure 6: Longitudinal profile of the Cotovelo River, and reaches of steep ($2.0 \leq SL/K < 10.0$) and very steep ($SL/K \geq 10.0$) gradients. Legend refers to all subsequent longitudinal profiles.

In the right bank (**Figure 7**), Capivara Creek presents a regular straight-to-convex upward profile, with no impressive knickpoint perceived in the curve. Anomalies of 2nd order were computed in different pelitic and carbonated bedrock of the Santa Helena and Lagoa do Jacaré formations in the low valley. Therefore, Capivara Creek can be considered to have a non-disturbed graded profile. The other river profiles in the right margin (Tapioca, Alegre, Cana-brava, Mocambinho, Trombas, and Riachinho creeks) have at least one remarkable knickpoint, with more than 150 m, coexisting with 2nd order (Alegre, Mocambinho, Trombas, and Riachinho) or 1st order (Tapioca and Cana-brava creeks) anomalies. These 1st order anomalies occur predominantly at the borders of the arkosean sandstones at higher topographic breaks. The 2nd order

anomalies coincide with siltstones and argillites of the Serra da Saudade Formation, and this break places an upstream straight-to-convex upward segment profile and a downstream concave-segment profile. Another striking feature is the hanging valleys in all these channels upstream of the knickpoints, except for the Capivara creek. These hanging positions at the eastern border of the Boqueirão Plateau can be associated with a normal fault mapped in the scarp (CPRM, 2003a; 2003b).

The Tapioca and Cana-brava creeks show remarkable 1st order anomalies bordering impressive scarps, suggesting the existence of a fault line. A similar feature corresponds to a 2nd order anomaly that exists in the Alegre, Mocambinho, and Riachinho creek profiles. All these anomalies fit the direction of a mapped fault line (CPRM, 2003a; 2003b). The Trombas creek profile yielded no SL-index anomalies, although the course springs at the plateau with an impressive scarp.



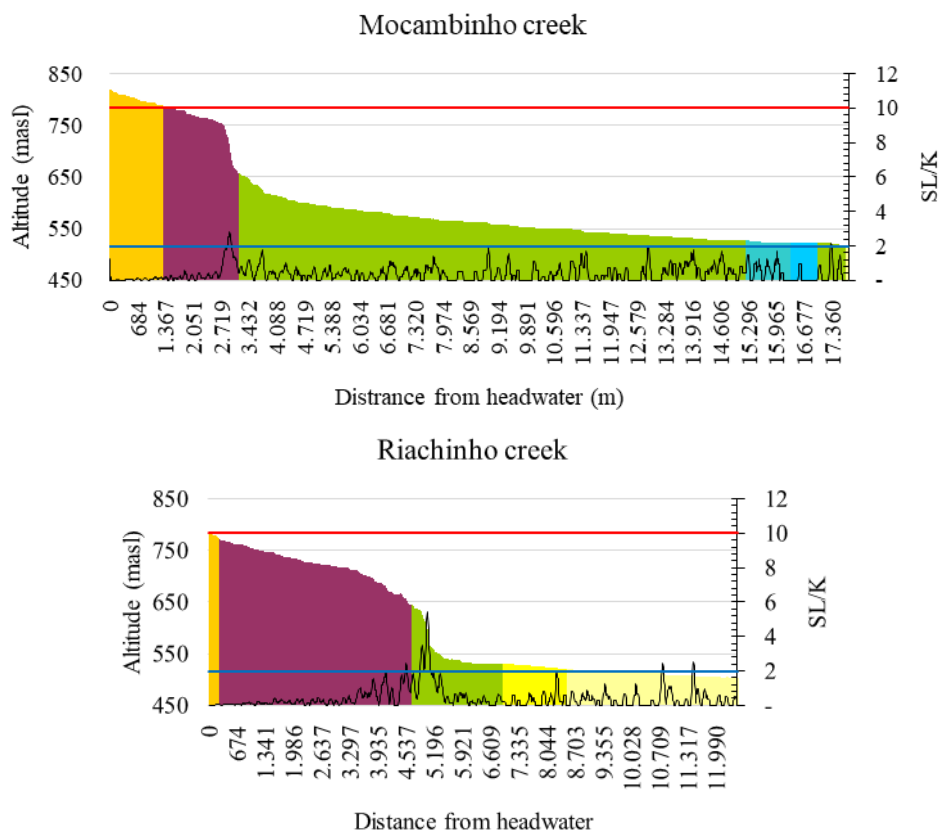
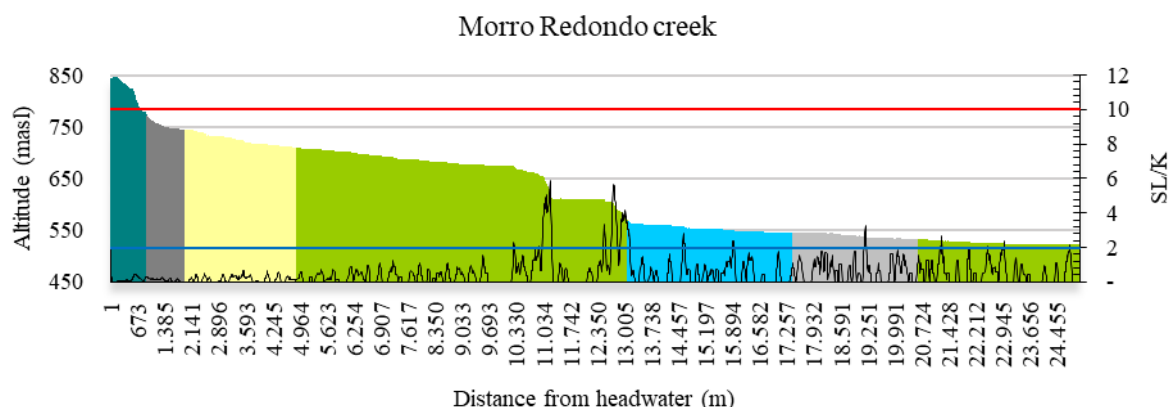


Figure 7: Longitudinal profile of the Capivara, Tapioca, Alegre, Cana-brava, Mocambinho, Riachinho, and Trombas creeks, and reaches of steep ($2.0 \leq SL/K < 10.0$) and very steep ($SL/K \geq 10.0$) gradients.

In the left bank (**Figure 8**), the Terra Vermelha creek has a concave-upward profile, with small knickpoints associated with the predominant pelitic and carbonated bedrock of the Serra da Saudade and Lagoa do Jacaré formations. The Morro Redondo creek has three impressive knickpoints. The first, situated near the headwater, at 100 m, dissects Upper Cretaceous sandstones of the Três Barras Formation; the others, situated in the middle valley, have two main steps, 60 m each one, resulting from the incision over the arkosean sandstones, siltstones, and argillites from the Serra da Saudade Formation. The Assapeixe and Forquilha creeks have convex upward profiles with extensive knickzones because their channels fit to fresh arkosean sandstones of the Três Marias Formation. Numerous 2nd order anomalies result from the steepest segments of the continuous knickzones. The Caiçara Creek has an almost straight longitudinal profile, fitted to arkosean sandstones, siltstones, and argillites of the Serra da Saudade Formation. The 2nd order anomalies correspond to folded and fractured siltstones and argillites of the Lagoa do Jacaré Formation. The Terra Vermelha and Caiçara creeks can be considered non-disturbed because their profiles resemble graded rivers. In the profiles of the left bank tributaries, hanging valleys are observed only in the Morro Redondo creek, emplaced by a knickpoint associated with the fold-and-thrust terrain of the NNW–SSE shear zone.



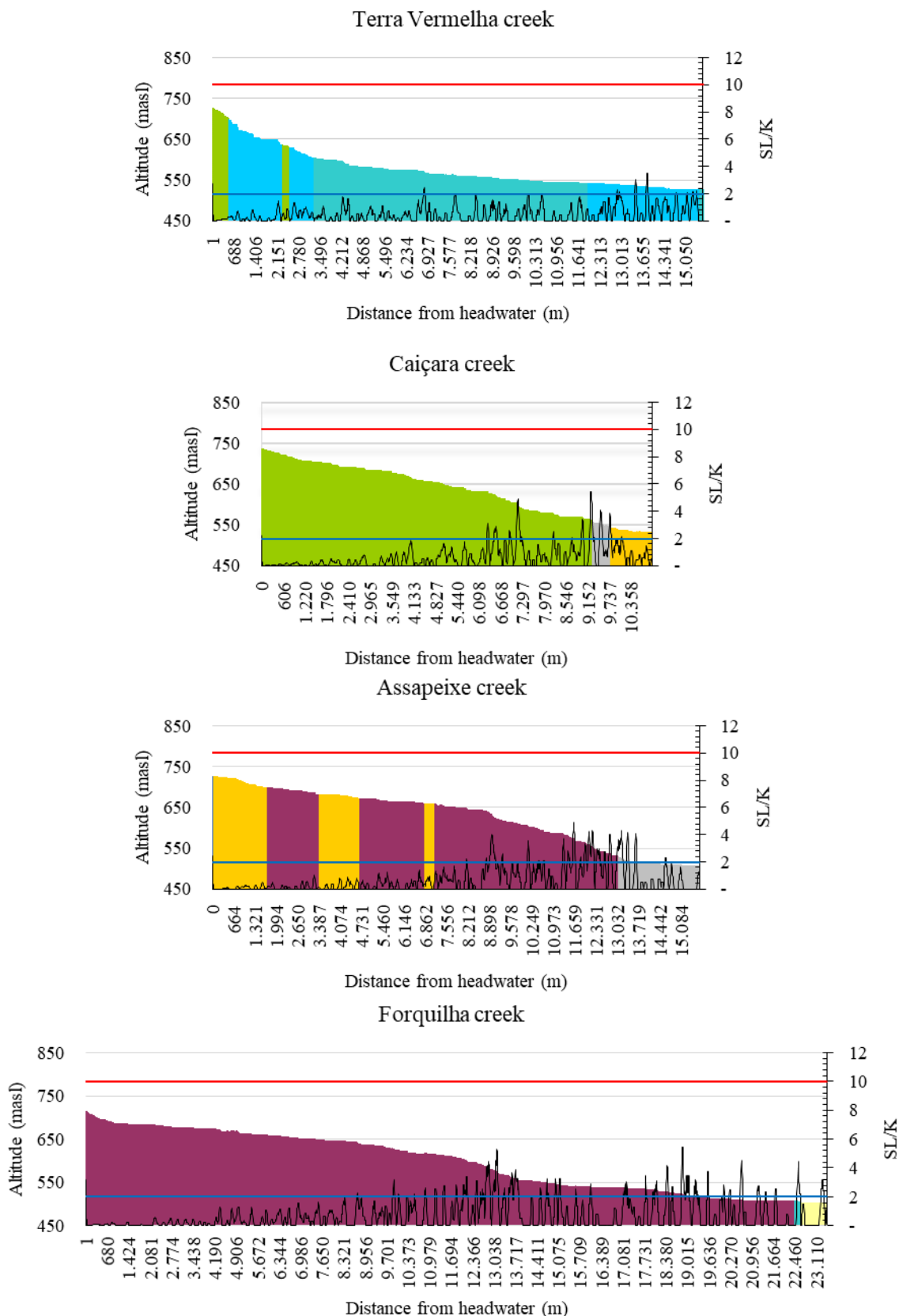


Figure 8: Longitudinal profile of the Terra Vermelha, Morro Redondo, Caiçara, Assapeixe, and Forquilha creeks, and reaches of steep ($2.0 \leq SL/K < 10.0$) and very steep ($SL/K \geq 10.0$) gradients.

Suggestive of relative tectonic activity (EL HAMDOUNI *et al.*, 2008), at the southern boundary of Southern Amazonian Craton, and inside the Paraíba and Araripe sedimentary basins, $SL/K > 6$ support low-rate neotectonic reactivation report (ANDRADES FILHO; ROSSETTI, 2015; OLIVEIRA *et al.*, 2018; ALMEIDA *et al.*, 2020).

In summary, the tributaries of the Cotovelo River share analogous underlying rock strata and geomorphic and geometric characteristics. In the right bank, all the channels have one prominent knickpoint aligned with a mapped fault scarp. Other smaller knickpoints are close to different fractures and inferred lineaments and disclose preferential erosive fronts. Although no one active fault was mapped in the area, the presence of straight segments in the profiles — even the bordering lineaments — can be interpreted as indicative of differential uplift or subsidence taking place in the Cotovelo catchment. Notwithstanding the regional scale of the geologic map, a knickpoint was considered to be derived from a fault or a fracture when it coincided with a lineament on the DEM and did not correspond to a stratigraphic border in the geologic map. Therefore, the knickpoints mapped in the Cotovelo catchment were not related to lithological changes. Channels in the Cotovelo catchment share similar geomorphodynamic conditions, expressed in the headward incision, through the base-level controlled tectonic subsidence of the low river valley.

Essentially, the Brazilian intraplate geomorphic landscape is strongly shaped by the reactivation of weakness zones and Precambrian faults and fractures, a process controlled by the Gondwana break-up and the opening of the Atlantic Ocean, since the Mesozoic that led the South America Plate rotation and drifts toward the West (HASUI, 1990; SAADI, 1991; 1995). Through this process, fluvial and landform dynamics are broadly driven by Proterozoic or older rocks and structures (PINTO *et al.*, 2018). Moreover, straight, parallel, and oriented drainage, asymmetrical catchments, tilted blocks, drifted channels, among others, provide strong evidences of persistent low-rate tectonic processes conditioning the development of small landforms and continuous adjustment of river patterns (MAGALHÃES Jr; SAADI, 1994; FULFARO *et al.*, 2005; ETCHEBEHERE *et al.*, 2006; MENDES *et al.*, 2007; BARROS *et al.*, 2010a; 2010b; GONTIJO-PASCUTTI *et al.*, 2010; MARQUES NETO; PEREZ FILHO, 2013; 2014; CHEREM *et al.*, 2018).

In the case of the Cotovelo catchment, relatively elongated and asymmetric catchments seem to be consequence of block tilting, due to shear zone structural configuration and maybe the recent tectonic reactivation of Brasiliano structures (SAADI, 1991; HIRUMA; PONÇANO, 1994). Because catchments of both margins were assessed, asymmetry of drainage was examined in terms of absolute values. Indeed, T-vector and Af data evoke the existence of two morphotectonic units inside the Cotovelo catchment, delimited by a SW-NE line, crossing the left-bank divides of Mocambinho and Morro Redondo creeks. Actually, from this line, channels shift toward its both flanks, which points out to the possible existence of an uplifted block; analogous features were described in Brazilian intracratonic (SANTOS; CASTRO, 2016; SANTOS; MORAIS, 2017) and passive margin terranes (ALVES; ROSSETTI, 2017; PEYERL *et al.*, 2018), and morphotectonic settings were explained by neotectonics.

Furthermore, significant results of Vf-ratio, Smf, and SI-index in the Boquerão Plateau high-energy drainage systems, associated to migration of river channels induced by tectonic tilting also reinforce the hypothesis of neotectonic activity, as previously shown elsewhere in the Brazilian Shield (SALAMUNI *et al.*, 2004; BARROS *et al.*, 2010a; 2010b; SANTOS *et al.*, 2015; LAVARINI *et al.*, 2016; ALMEIDA *et al.*, 2020).

5. Conclusion

There is solid evidence of structural influence on the Cotovelo River drainage arrangement in the northwestern Minas Gerais State, as impressive shifting of fluvial channels and relevant quantitative values of geomorphic indices that are indicative of asymmetries and block tilting. Though any isolated analysis is still not sufficient to confirm that tectonic control is active, the integrated assessment of geomorphometric indices reveal that this river catchment is a prominent and conspicuous part of the geomorphological landscape that, even inserted in a cratonic environment, have some of their short tributaries (Assapeixe and Caiçara) viewed as younger, vigorous, and lesser-eroded catchments. In contrast, the larger and longer alluvial tributary rivers (Morro Redondo, Terra Vermelha, and Riachinho) are sedimentary-prone catchments. Local bedrock rivers (Capivara, Tapioca, Alegre, Cana-brava, and Forquilha) exhibit more dissected catchments because their courses flow over resistant lithology. The predominance of impervious subsurface, undulated or hilly landscapes, and highly dissected and denser drainage networks correlate to characteristics of sedimentary and metasedimentary regional basement. Adjacent to the Boqueirão scarps, geomorphometric indices reveal elongated drainage basins, characterized by medium to high relief and steep slope, along with geological heterogeneity and higher permeability resulting from fractures, which remarkably indicate structurally drive fluvial dissection.

Despite the lack of detailed topographic, geologic and geomorphologic information, given the scales of available maps, geomorphic description as well as the geomorphic indices computed largely suggest tectonic and structural control on the drainage network, longitudinal river profiles, drainage basin shapes, and

landforms. From one hand, Forquilha and Assapeixe creeks exhibit the clearer structural control, derived from the Cenozoic tectonic event; on the other hand, Tapioca, Alegre, Mocambinho, Trombas, and Riachinho creeks incised their valleys into weaker zones crossing the Boqueirão Plateau. The upper segment of the Cotovelo, the Morro Redondo, and Terra Vermelha catchments are perfectly adjusted to the Precambrian shear zone; in these cases, they are very elongated drainage basins. In the right bank, high energy tributaries drain the Boqueirão plateau dissecting deep and narrow gorges, resulting in impressive knickpoints. In both margins, the parallelism of the channels reinforces the hypothesis of structural control, which is supported by the low average values of the T-vectors, indicating that channel displacement was relatively short.

However, in the absence of any mapped and described active faults, there is still not sufficient evidence to definitively attest the neotectonic activity in the area. Thus, the processes responsible for morphogenetic evolution of the catchment may be ascribed primarily to lithologic and structural patterns, possibly, under blind fault control.

Acknowledgements

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