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Characterization of longitudinal profiles of rivers applied to the study of morphostructural and morphotectonic influence in the relief of the central sector of the Araucaria Plateau - Southern Brazil

Caracterização de perfis longitudinais de rios aplicada ao estudo da influência morfoestrutural e morfotectônica no relevo do setor central do Planalto das Araucárias – Sul do Brasil

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Abstract

Longitudinal profiles were analyzed in the rivers of the central sector of the Araucaria Plateau, aiming to contribute to the understanding of the morphostructural and morphotectonic influence on the relief. Radar images were used to extract the drainage network and contour lines. Channels above the 4th order were considered, in which geological formations and structures were plotted. The results showed that rivers on a single lithology are more at equilibrium, or graded, with less pronounced slope breaks (knickpoints). Those with greater lithological differentiation, on the other hand, have less channel balance and more marked knickpoints. Structural factors are also important, as the main breaks in rivers are associated with lineaments (70%). The sections in ascension and subsidence along the rivers have a strong correlation with geological structures (52%), being more expressive in the Chapecó River basin (72%). This suggests that the study area was subject to morphostructural and morphotectonic influence, with the Chapecó basin being the most affected.
Keywords: Morphometric analysis, drainage channels, topographic rupture; lithological differentiation, tectonic influence.

Resumo

Realizou-se análise de perfis longitudinais nos rios do setor central do Planalto das Araucárias, visando contribuir para o entendimento da influência morfoestrutural e morfotectônica no relevo. Imagens de radar foram utilizadas para extração da rede drenagem e curvas de nível. Foram

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considerados canais acima de 4ª ordem, nos quais plotou-se formações e estruturas geológicas. Os resultados mostraram que rios sobre única litologia são mais equilibrados, tendo rupturas de declive (knickpoints) menos acentuadas. Já aqueles com maior diferenciação litológica apresentam menor equilíbrio do canal e knickpoints mais acentuadas. Fatores estruturais também são importantes, pois as principais quebras nos rios associam-se a lineamentos (70%). Os trechos em ascensão e subsidência ao longo dos rios tem forte correlação com estruturas geológicas (52%), sendo mais expressiva na bacia do rio Chapecó (72%). Isso sugere que a área de estudo esteve sujeita a influência morfoestrutural e morfotectônica, sendo a bacia do Chapecó a mais afetada.
Palavras-chave: Análise morfométrica, canais de drenagem, ruptura topográfica; diferenciação litológica, influência tectônica.

I. INTRODUCTION

The drainage network has been an important tool used for decades to understand the geological and geomorphological context and the structural processes acting in certain areas (COUTO et al., 2011). This is because drainage channels are sensitive and respond quickly to any change at the local or regional level (HOWARD, 1967; SOARES; FIORI, 1976).

Based on this prerogative, several researchers have contributed, through analysis of the drainage network, to a better understanding of the genesis and evolution of the relief (GARBOSSA, 2003; ETCHBEHERE et al., 2004; SALAMUNI et al., 2004; PALHA; CARVALHO, 2005; MUTZENBERG et al., 2006; FORTES et al., 2007; FUJITA, 2009; COUTO, 2011; VARGAS, 2012; LIMA; PONTELLI, 2013; FUJITA, 2014; SORDI et al., 2015; LOPES et al. ., 2016; FUJITA et al., 2017; BORGES et al., 2019). These analyzes can be performed using various morphometric techniques, including: analysis of drainage patterns; drainage anomalies; slope-length ratio index (total RDE/section) and analysis of longitudinal profiles of rivers.

The present study utilizes longitudinal profiles of rivers. Such information brings important contributions to the understanding of the lithological and tectonic influence in the central sector of the Araucaria Plateau. The analysis of these profiles follows the principle that a river seeks a balance between erosion and sedimentation. Rivers in a state of equilibrium have a concave profile, whereas profiles with less concavity are indicative of unbalanced conditions. Ruptures or breaks in the longitudinal profile of the rivers represent processes that are altering the balance of the watercourse in that sector. Based on this premise, stretches of out-of-equilibrium drainage may indicate recent tectonic activities or lithological differentiations (ETCHBEHERE, 2004; LOPES et al., 2016).

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Thus, this work presents results of the analysis of pre-selected longitudinal profiles of rivers in the central sector of the Araucaria Plateau, with the objective of contributing to the understanding of the morphostructural and morphotectonic influence on the relief of the study area.

Location and characterization of the study area

The study area is located in the southern region of Brazil encompassing southwest Paraná, west Santa Catarina and northwest Rio Grande do Sul; making up about 7,000 km^2 (Figure 1). Geologically, the study area is situated in the Paraná basin where volcanic rocks from the Serra Geral group appear. In the portion of the study area belonging to the state of Paraná, the Serra Geral group consists of basic rocks from the Cordilheira Alta, Paranapanema, Esmeralda and Chapecó formations (Fm.). In Santa Catarina, there are rocks from the Campo Êre, Campos Novos, Paranapanema, Chapecó and Palmas formations. In Rio Grande do Sul, there are rocks from the Paranapanema and Chapecó formations (ARIOLLI; LICHT, 2013). The Chapecó and Palmas rocks are acidic, while the other formations are basic (WILDNER et al., 2006).

On an outcrop scale, the volcanic rocks of the Serra Geral group occur as lobed flows interspersed with hydrovolcanoclastic breccias, flow breccias and hydrotuffs, with horizontal and vertical fracturing (ARIOLLI; LICHT, 2013; WILDNER et al., 2006). Basic rock flows, in general, present diaclases and vertical fractures, while acid flows have horizontal/tabular disjunction (ARIOLLI; LICHT, 2013; NARDY et al., 2002).

The structural framework of the Paraná Basin is characterized by three main groups of structural trends, oriented towards NW-SE, NE-SW and E-W. In the study area, the Taquara Verde lineament, the Lancinha/Cubatão fault zone and the Torres syncline can be highlighted. Such lineaments are oriented respectively to E-W, N50-70E, and N50-60W (ZALÁN et al., 1987).

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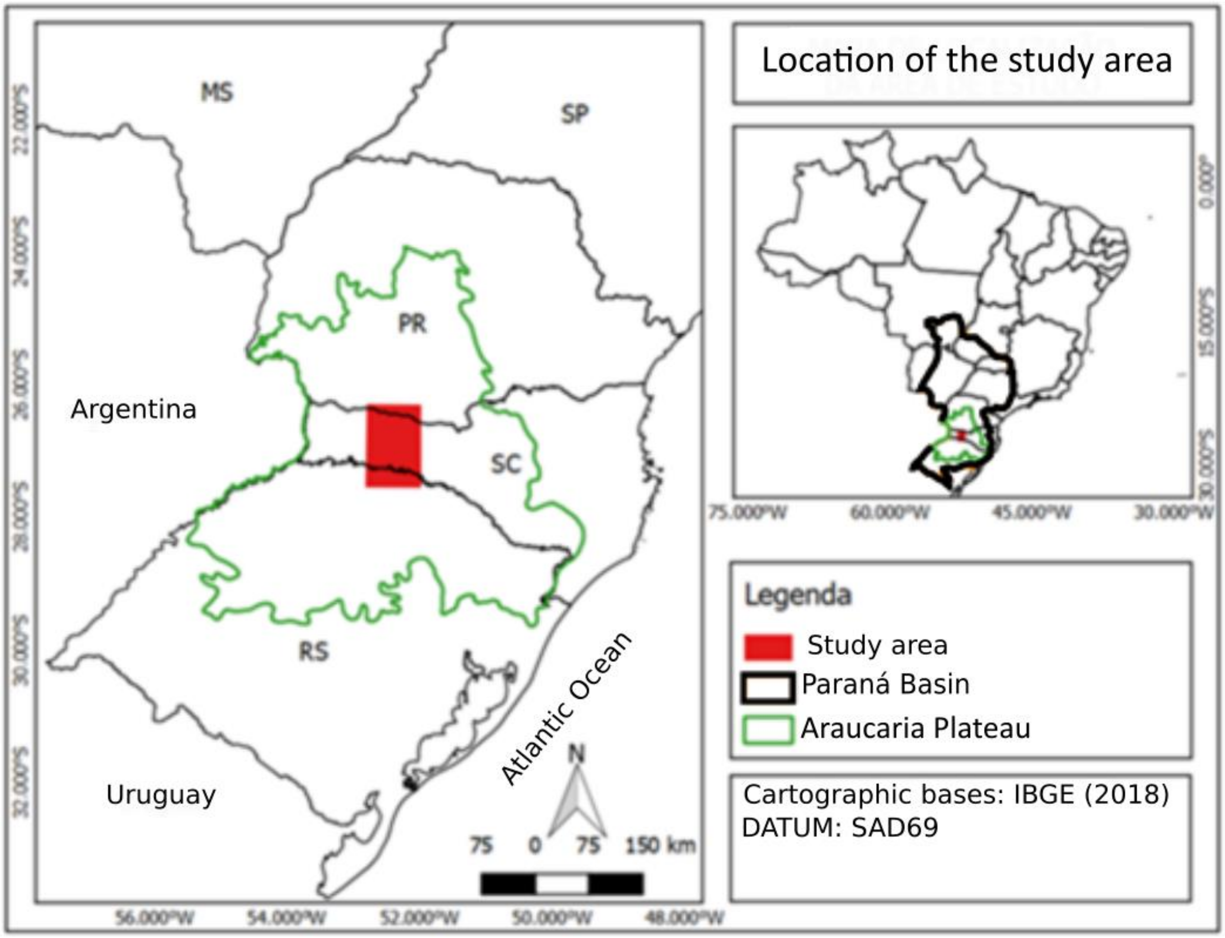

Figure 1. Location of the study area in the Araucaria Plateau. (Elaborated by the authors)

Geomorphologically, the study area is nested in the central sector of the Araucaria Plateau. This plateau presents a general slope to the west, towards the channel of the Paraná River, as well as to the north towards the Ivaí River, and to the south where it abruptly ends with the Serra Geral (ALMEIDA, 1956; PAISANI et al., 2019). General analysis of the geomorphology shows that the landforms vary from gently undulating tabular tops to extensive and short terraces (structural steps), as well as residual reliefs (mesas). The valleys are either closed or open, with mostly convex slopes. In the region, there are rivers with structural meanders, as well as channels connected and disconnected from the hydrographic network (PAISANI et al., 2019).

The study area belongs to two important hydrographic systems, separated by the Serra da Fartura (watershed) between the states of Paraná and Santa Catarina. The rivers that drain north of the Serra da Fartura belong to the Iguaçu River hydrographic system, while those flowing south belong to the Uruguay River hydrographic system. North of the watershed, the main river that drains the area is the Chopim. A tributary of the left bank of the Iguaçu River, it begins in the Palmas municipality and runs in a southeast > northwest

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direction. To the south of the Serra da Fartura, the main river that drains the area is the Uruguay, which runs E-W and has the Chapecó river as its main tributary.

II. MATERIALS AND METHODS

Considering the size of the study area and the high drainage density, longitudinal profiles were analyzed only for rivers above the 4th hierarchical order (Figure 2). Of the total number of rivers analyzed, 2 are affluents of the Chopim River, one of the main tributaries of the Iguaçu River, which in turn flows into the Paraná River. The other rivers analyzed belong to the Uruguay River basin, distributed as follows: 46 on the right bank, 25 belonging to the Chapecó river basin and 9 on the left bank. Due to their importance, sections of the main rivers that drain the study area were also analyzed, such as: Chapecó, Chapecozinho, Irani, Engano, Jacutinga, Passo Fundo and Uruguay (Figure 2). It was decided not to analyze the Chopim River segment because it occupies a small portion of the study area, in the NE quadrant, considered in the context of this work to be unrepresentative of the river as a whole.

The applied methodology consisted of the examination of longitudinal profiles of the rivers analyzed, using altitude data from the *Shuttle Radar Topography Mission* - SRTM (30 m), obtained from the United States Geological Survey - USGS website (htttps://earthexplorer.usgs.gov/). Using the Global Mapper® v.20 Software, a drainage network was extracted on a scale of 1: 50,000 and contour lines with an equidistance of 20 m. Next, the length of the channel between one level curve and another was measured. Then, in the *Excel* program, a table with two columns was set up: in the first column the values correspond to the sum of the length of the channel; and in the second, the altimetric quotas with an equidistance of 20 m. From this table, dispersion graphs corresponding to the longitudinal profile of the river were generated (Figure 3). In the generated graphs, logarithmic trend lines were inserted, making visible the equation in the graph and the R-squared value (adjustment factor between the graded profile and the longitudinal profile of the river). For the analysis of the longitudinal profile, the methodology described by McKeown *et al.* (1988), which addresses that every river course seeks equilibrium, either by erosion or aggradation of the bed itself. Thus, displacements greater than 10 meters from the logarithmic trend line are considered ascension areas, and displacements below the line are subsidence areas.

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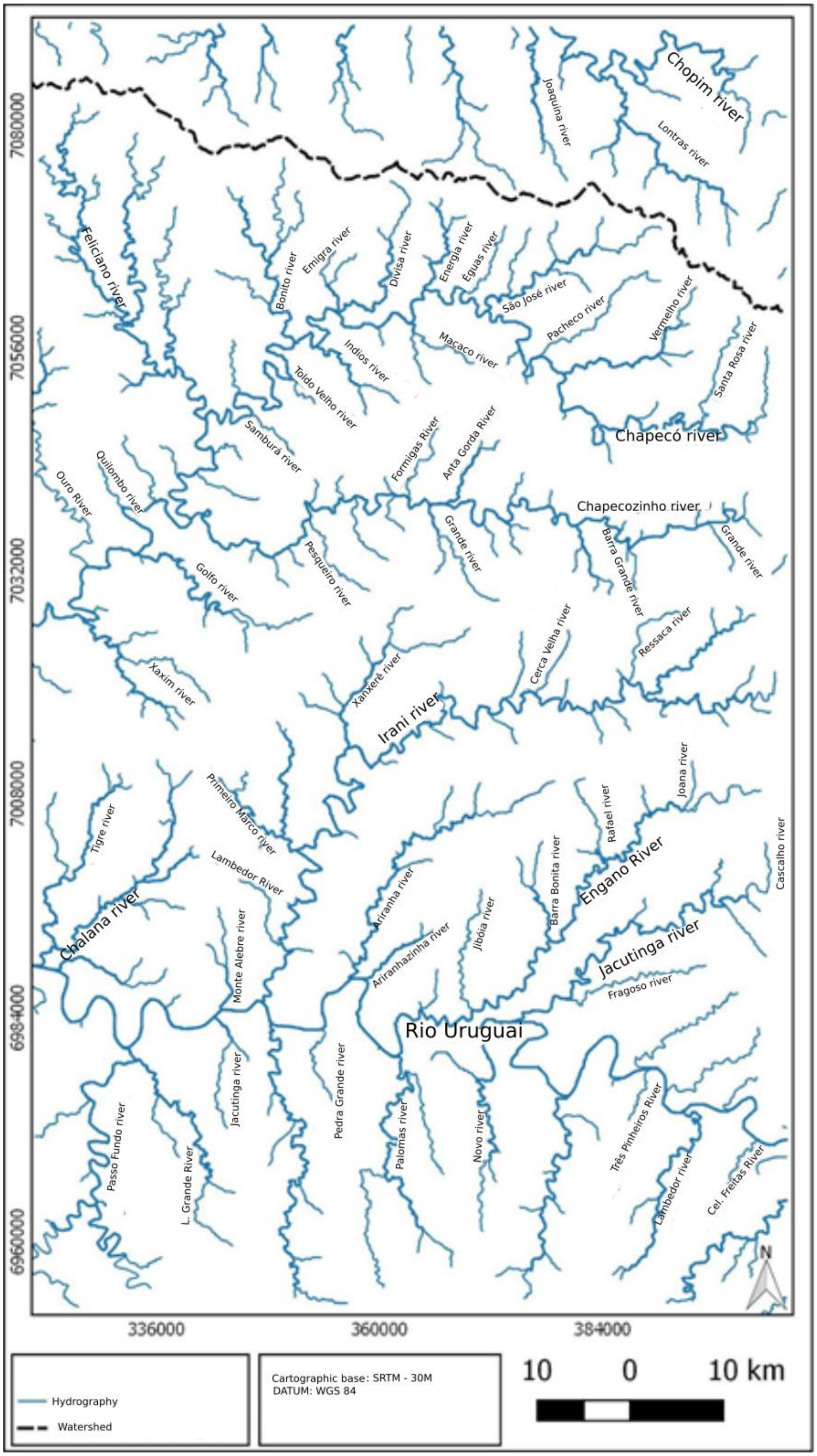

Figure 2. Map of river locations analyzed in the Araucaria Plateau. (Elaborated by the authors)

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The different geological formations that occur along the water course were plotted on the profiles, as well as faults/fractures (CPRM database, 2019) and magnetic lineaments (LIMA et al., 2019; 2022) (Figure 4). This procedure made it possible to verify whether the ascending and subsidence sections and slope breaks are related to lithological change and/or structural influence.

Length	Altimetric quotas
98	1160
522	1140
1362	1120
2439	1100
3936	1080
9427	1060
11895	1040
17148	1020
18616	1000
21858	980
27434	960
31160	940
32680	920
38634	900
46170	880
52614	860

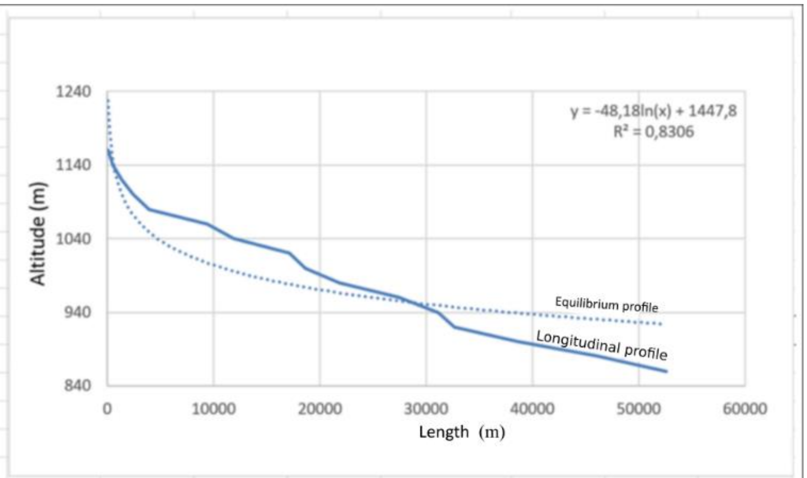

Figure 3. Example of "data" utilized to construct the longitudinal profiles analyzed in this study. (Elaborated by the authors)

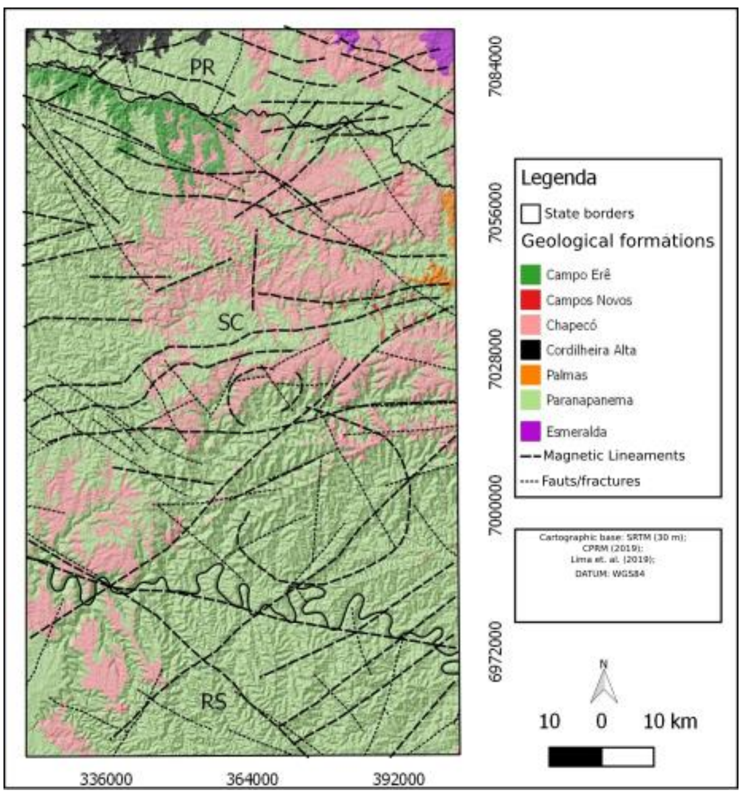

Figura 4. Geological structural map of the study área. (Elaborated by the authors)

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III. Results and Discussion

In the northern portion of the regional watershed, only 2 rivers were analyzed: the Joaquina and the Lontras, both tributaries of the Chopim River. The analysis of the profiles of these tributaries revealed a mismatch in relation to the concave curve of a river at equilibrium (graded river); the segments above the line of best fit (graded profile – Figure 5) are considered in ascension and the segments below in subsidence. In these two tributaries, the subsidence segment corresponds to the lower third of the channel, which runs over acid rock. The ascension stretch constitutes most of the river. Points in equilibrium are observed only near the source and in the transition between the uplifted and lowered sectors. Furthermore, in the middle and lower thirds of the two tributaries, structural lineaments occur.

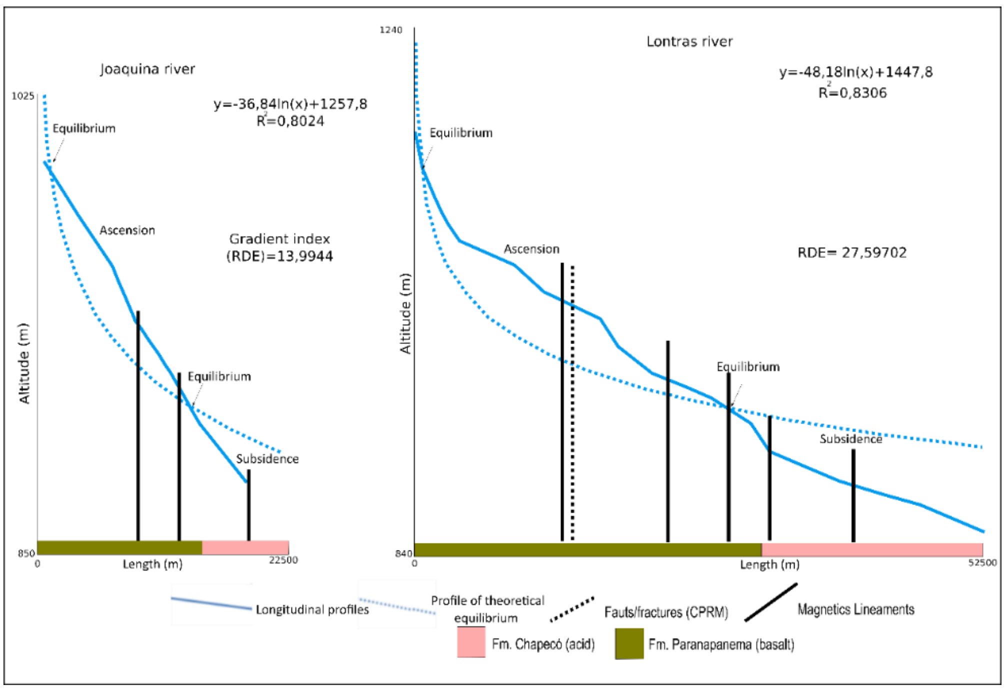

Figure 5. Longitudinal profiles of the Lontras and Joaquina tributaries. (Elaborated by the authors)

Due to the large number of rivers located south of the regional watershed, the longitudinal profiles will be presented in smaller groups: first the tributaries of the Chapecó River, then the tributaries of the Chapecozinho River, then the tributaries of the Irani River and finally the other tributaries of the Uruguay River. In all, 18 tributaries of the Chapecó river basin were analyzed. Of this total, 12 tributaries on the right bank and 6 on the left bank. The Chapecozinho River was analyzed separately, as it is the largest tributary of the Chapecó River, and of it 6 sub-tributaries were analyzed.

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All the tributaries on the right bank of the Chapecó River have sectors in ascension and in subsidence, which denotes dynamic imbalance. The rivers that present the greatest slope breaks and the greatest distances between the theoretical stable profile and the longitudinal profile are the tributaries Santa Rosa, Vermelho, Pacheco, Energia, River das Éguas (Figure 6), Emigra and Arroio da Divisa (Figure 7). In addition, it was emphasized the fact that the large slope breaks observed in the longitudinal profiles of most of these rivers are associated with structural lineaments, which indicates their tectonic character, already indicated in this study area by Fujita et al. (2017) and Lima et al. (2022).

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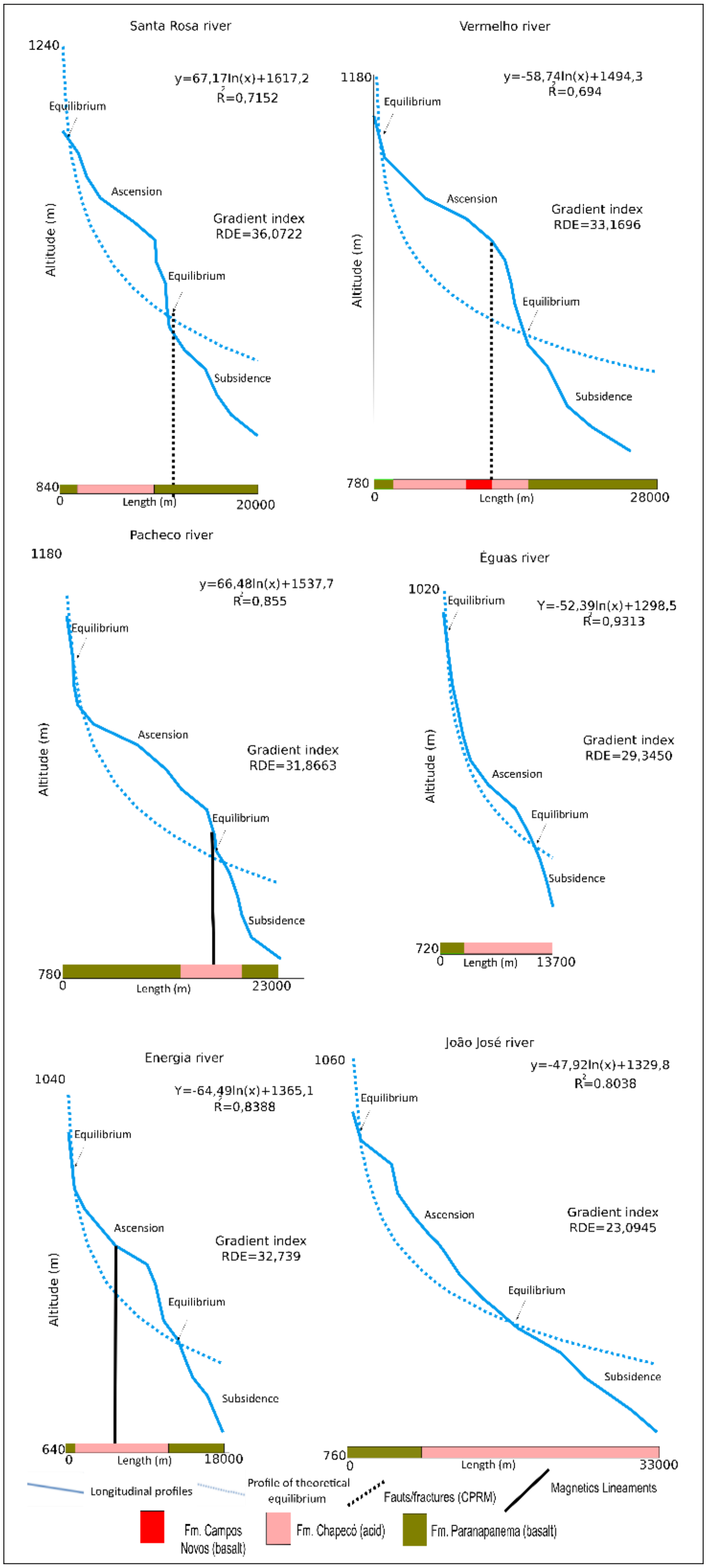

Figure 6. Longitudinal profiles of the right bank tributaries of the Chapecó River. (Elaborated by the authors)

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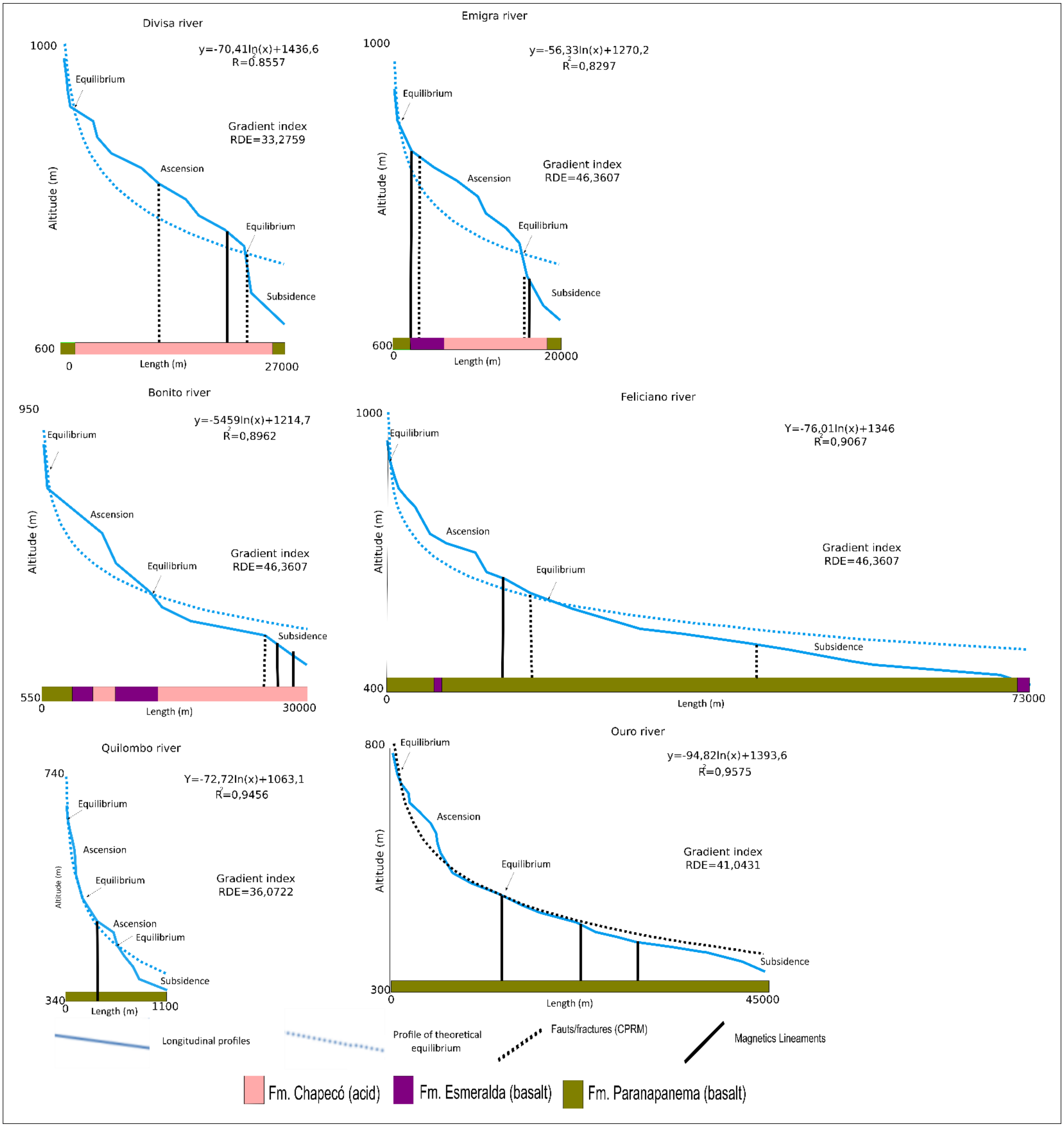

Figure 7. Longitudinal profiles of the right bank tributaries of the Chapecó River. (Elaborated by the authors)

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The tributaries on the left bank of the Chapecó River also present unbalanced sectors in ascension and subsidence; however, their distance between the profile of theoretical equilibrium and the longitudinal profile is smaller compared to those on the right bank (Figure 8). In these rivers, slope breaks occur in fewer numbers and are much less pronounced compared to rivers on the right bank. The number of structural lineaments in these rivers is also smaller, as well as the relationship of these structures with slope breaks is not so clear.

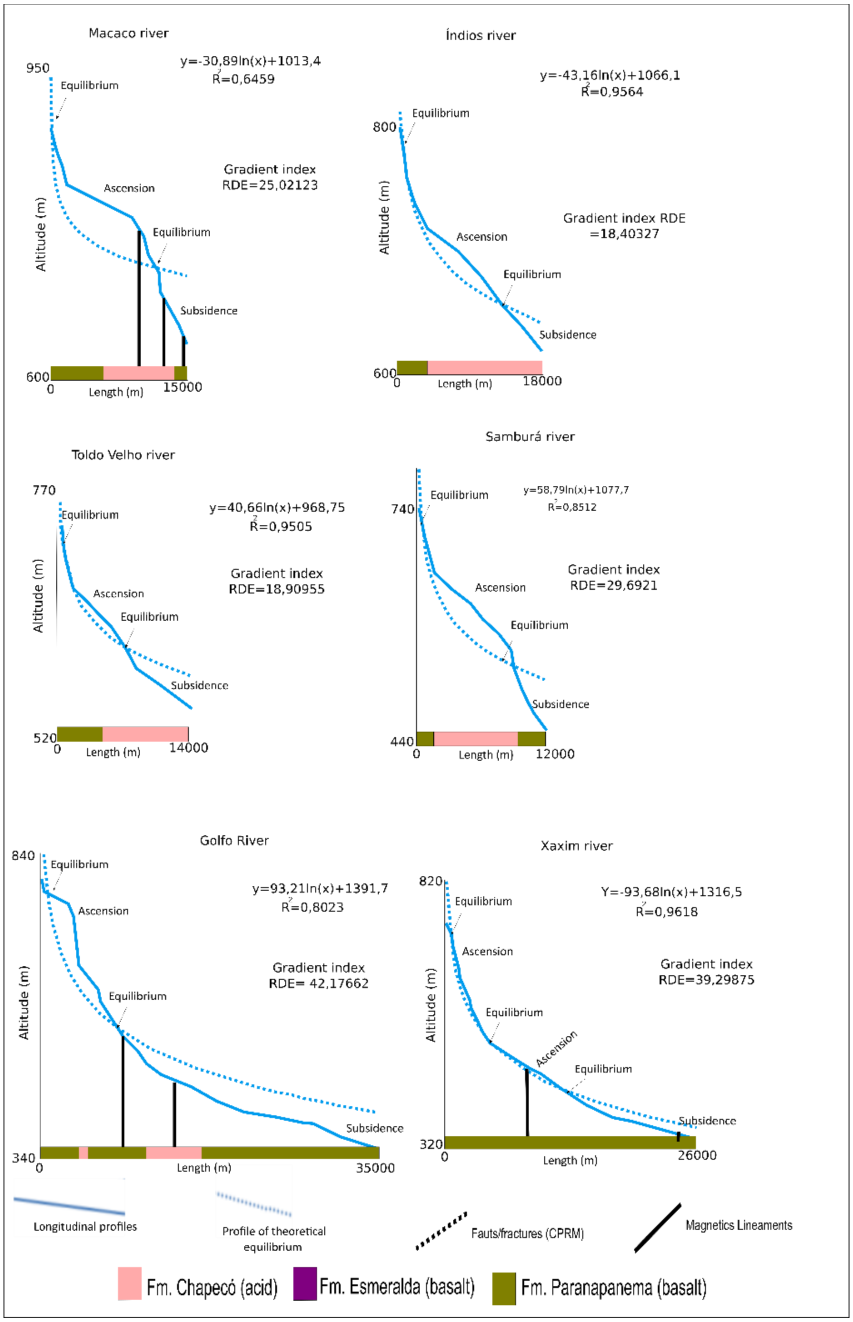

Figure 8. Longitudinal profiles of the left bank tributaries of the Chapecó River. (Elaborated by the authors)

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Comparing the tributaries on the right and left banks of the Chapecó River, it was possible to conclude that the signs of tectonic activity are stronger in the rivers on the right bank, since the slope breaks are more pronounced and have a better correlation with the structural lineaments.

The longitudinal profiles of the tributaries of the Chapecozinho River show few accentuated slope breaks, with the exception of the tributary Sanga Grande (Figure 9). In general, in the Chapecozinho basin, sections in subsidence and ascension are observed in all tributaries, but the distance between the theoretical equilibrium curve and the longitudinal profile is small; exceptions in this regard occur in the Sanga Grande and Pesqueiro. The greatest mismatch observed in these two tributaries is the result of tectonic influence. Sanga Grande, for example, is located in a sector of the study area where there is a rectangular drainage pattern associated with structural influence.

Comparing the results of the data observed in the other tributaries of the Chapecó River with the tributaries of the Chapecozinho, it was noticed that the tributaries of the left bank of the Chapecó and the tributaries of the Chapecozinho present longitudinal profiles with similar patterns. In all rivers, ascension and subsidence sections were identified, as well as relatively small distances between the longitudinal profiles and the theoretical equilibrium curves, and in general, slightly accentuated slope breaks. The data show that tectonic influence is more pronounced on the right bank of the Chapecó River, mainly upstream of the confluence with the Emigra tributary, in the municipality of Abelardo Luz (SC).

The basins of the rivers Irani, Monte Alegre and Chalana are neighbors of the Chapecó river basin on the left bank. In all the affluents analyzed, stretches in ascension and subsidence can be observed. Slope breaks are also common, with the largest associated, in general, to structural lineaments (see tributaries Ressaca, Xanxerê, Lajeado Tigre). The data suggest that these tributaries are out of adjustment in relation to the graded profile, when considering the low values of R^2 (Figure 10).

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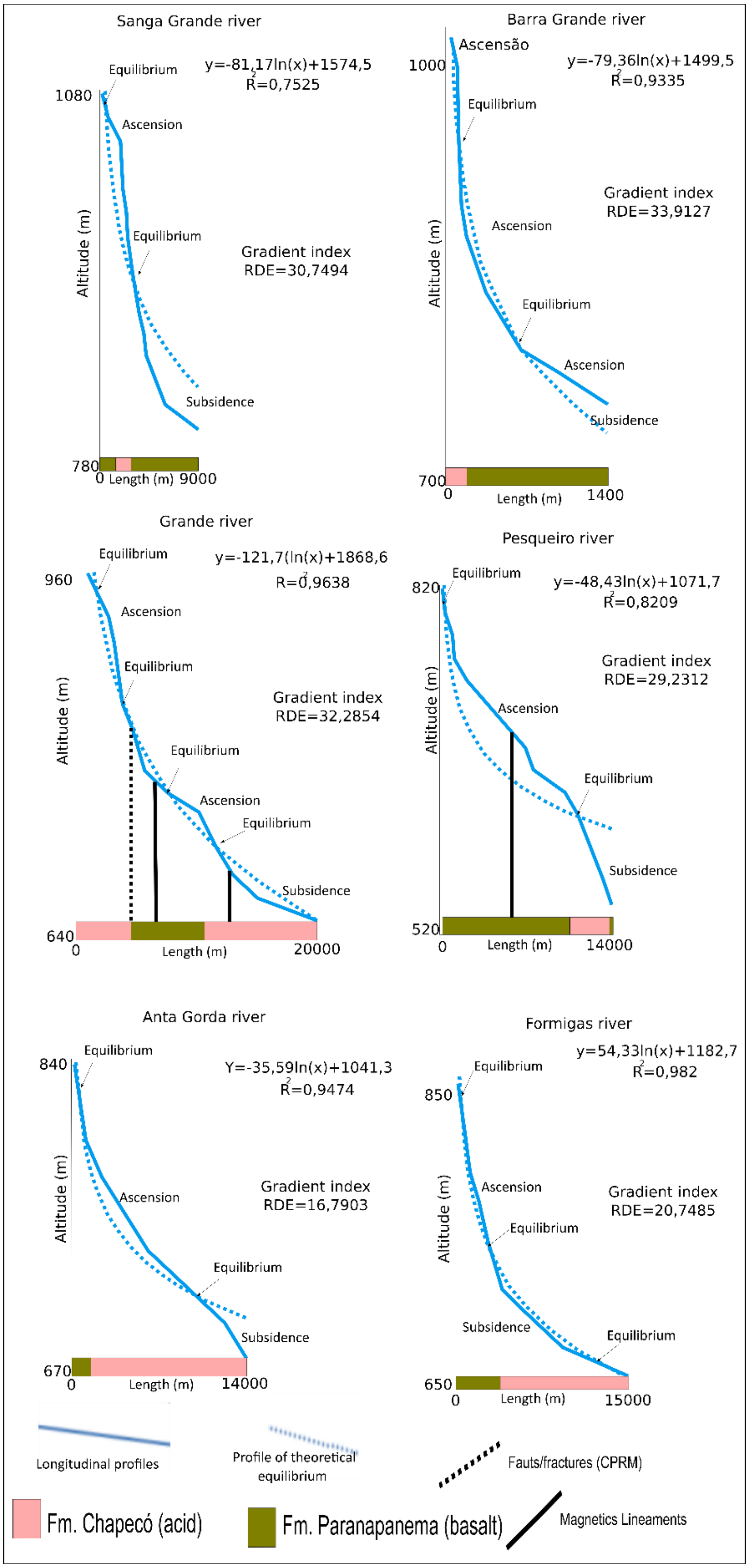

Figure 9. Longitudinal profiles of the tributaries of the Chapecozinho River (Elaborated by the authors)

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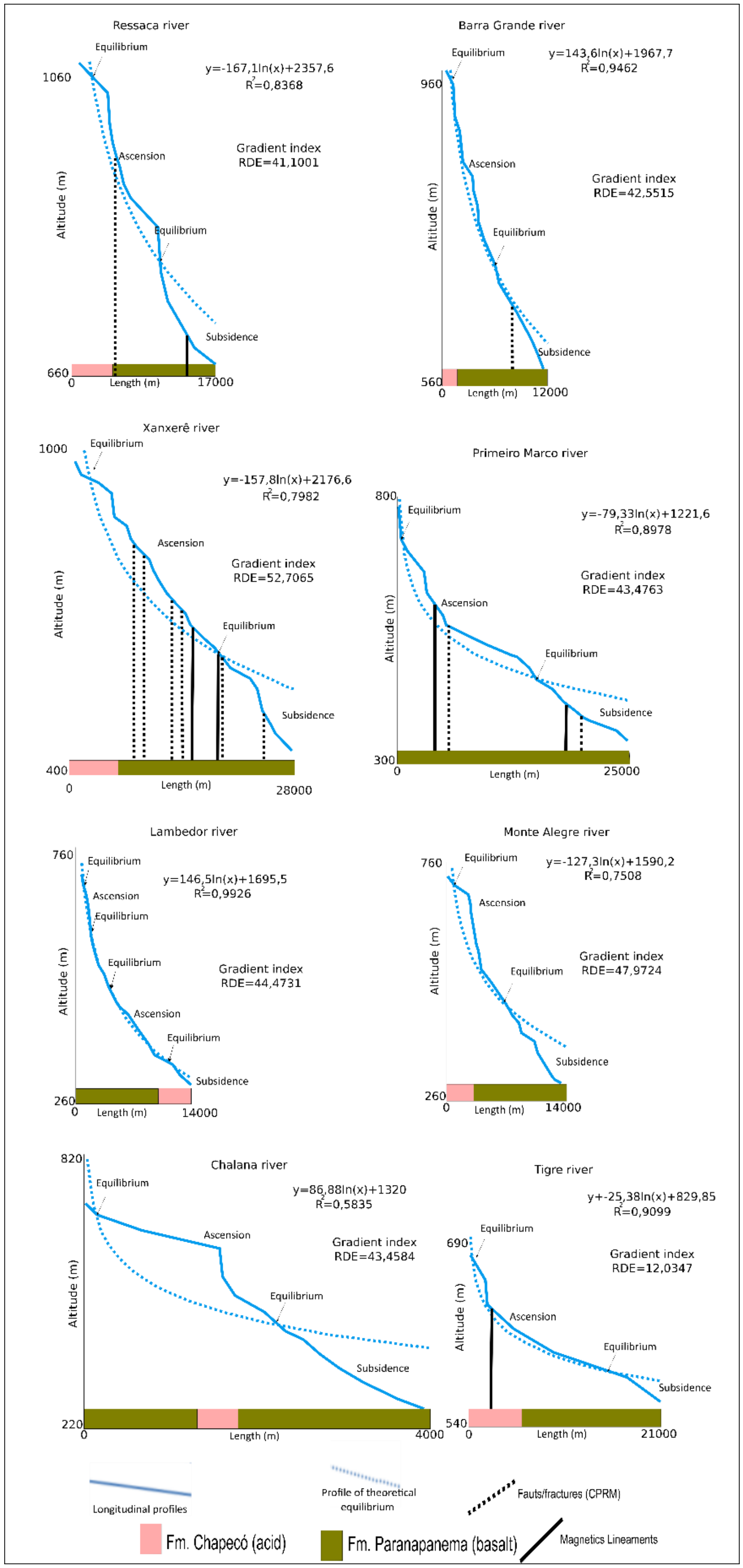

Figure 10. Longitudinal profiles of the tributaries of the basin of the rivers Irani, Chalana, and Monte Alegre. (Elaborated by the authors)

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On the left bank of the Irani River basin, there are the basins of the Ariranha, Ariranhazinha, Engano and Jacutinga rivers. The tributaries analyzed in these basins flow mostly over basic rock (Fm. Paranapanema). In general, their slope breaks are not very accentuated. The R^2 values were close to 1 and the longitudinal profile appears to be well adjusted to the theoretical profile, which indicates that they are close to the dynamic equilibrium state (Figure 11). In this context, even though there are sectors in subsidence and ascension, they are not so pronounced, with the biggest highlight being Lajeado Fragoso. In general, there are few structural lineaments. All this indicates that the tectonic influence on these rivers is smaller than, for example, on the Chapecó and Irani river basins.

On the left bank of the Uruguay River, 8 rivers that have their entire course in the study area were analyzed (Figure 12). The tributaries located on the left bank of the Uruguay River have characteristics quite similar to those of the tributaries of the Ariranha, Ariranhazinha, Engano and Chalana basins. They run mostly over the Paranapanema basalt, have longitudinal profiles with less pronounced ascension and subsidence sectors, and high R^2 values. This indicates that these tributaries are close to the dynamic equilibrium state. The number of structural lineaments is small in most of the tributaries; only in Lajeado Grande is this number more expressive. A steep slope break was identified only at Lajeado Jacutinga, in the upper third of the channel, possibly associated with lithological change from acid rock (Fm. Chapecó) to basic (Fm. Paranapanema). All these features suggest that the tectonic influence on the left bank of the Uruguay River was less than on the Chapecó and Irani Basins.

In addition to tributaries that run entirely in the study area, sections of the main rivers (Uruguay, Chapecó, Chapecozinho, Irani, Engano, Jacutinga and Passo Fundo) were also analyzed (Figure 13).

The Uruguay River in the study area runs entirely over basic rocky substrate. This analyzed stretch had the lowest value of R^2 (0.4264) when compared to the other analyzed rivers. Approximately half of this stretch is above the graded profile and half below (Figure 13). In this river, the ascending and subsidence sectors are separated by structural lineaments, specifically fault/fracture and magnetic lineament (km 90 – Figure 13). This suggests that this important slope break is probably the result of tectonic activity (LIMA et al., 2019).

The tectonic influence on the Uruguay River has already been considered. Studies suggest that the Uruguay River is embedded in an important tectonic lineament (BELLIENI et al. 1986; LIMA et al., 2019; LIMA et al., 2022). In addition, there are a large number of structural lineaments that intersect the longitudinal profile of the river, evidencing tectonic influence (LIMA et al., 2019; LIMA et al., 2022). The other stretches of rivers

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analyzed are segments of large tributaries of the Uruguay River, except for the Chapecozinho River, which is a tributary of the Chapecó. All these rivers run mostly over basic rock (Figure 13).

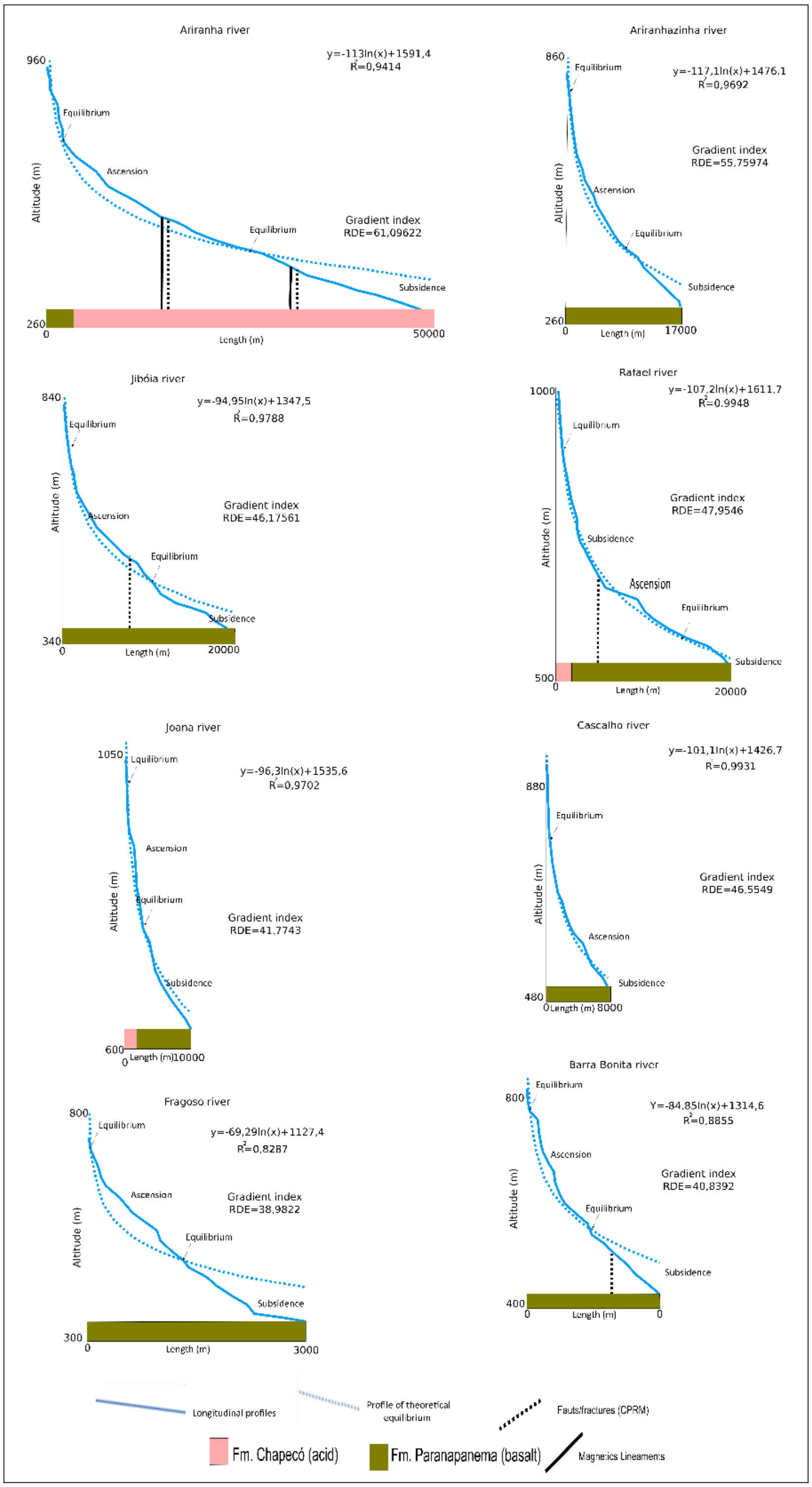

Figure 11. Longitudinal profiles of basin channels of the Ariranha, Ariranhazinha, Engano and Jacutinga rivers. (Elaborated by the authors)

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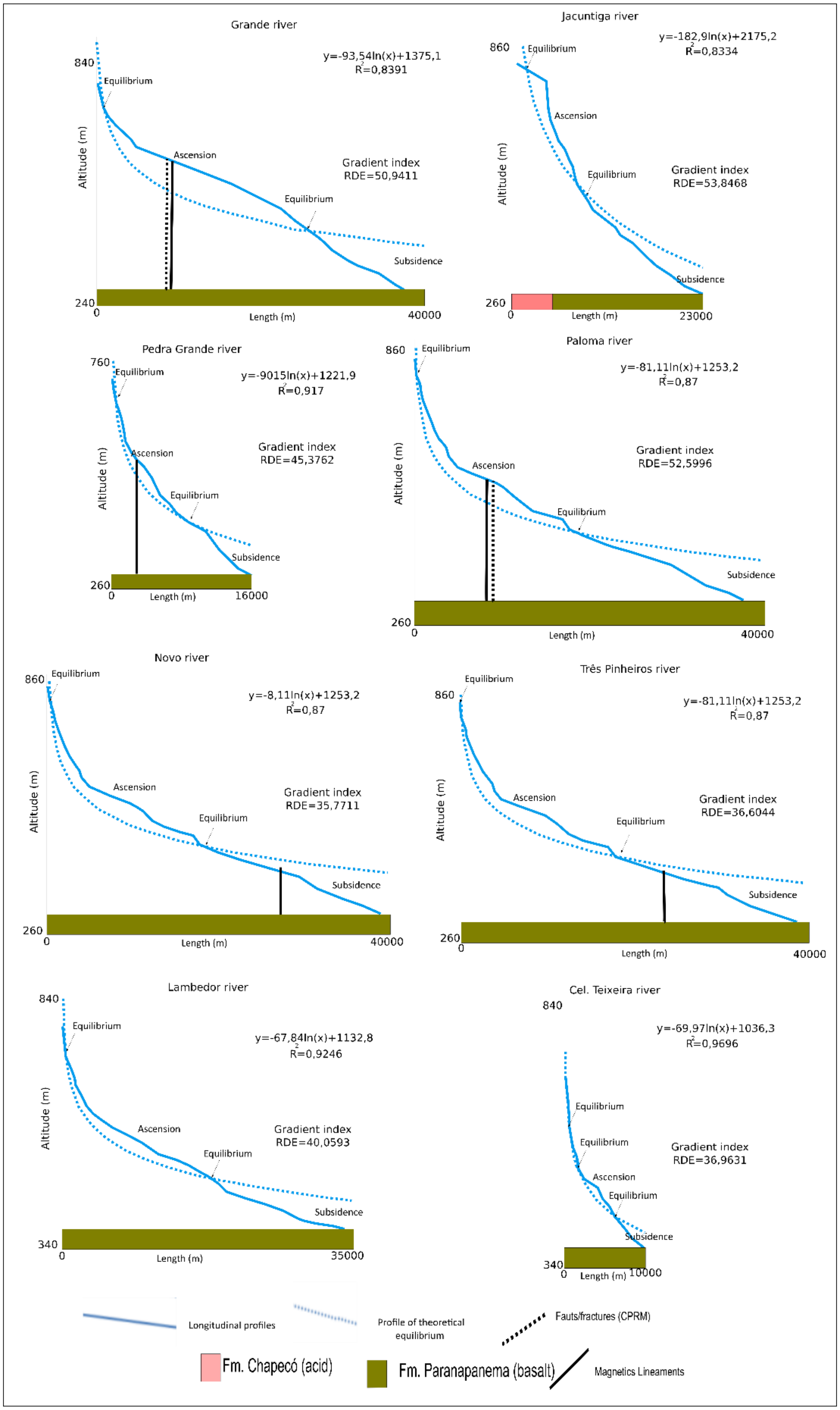

Figure 12. Longitudinal profiles of the rivers located on the left bank of the Uruguay River, that run entirely within the study área. (Elaborated by the authors)

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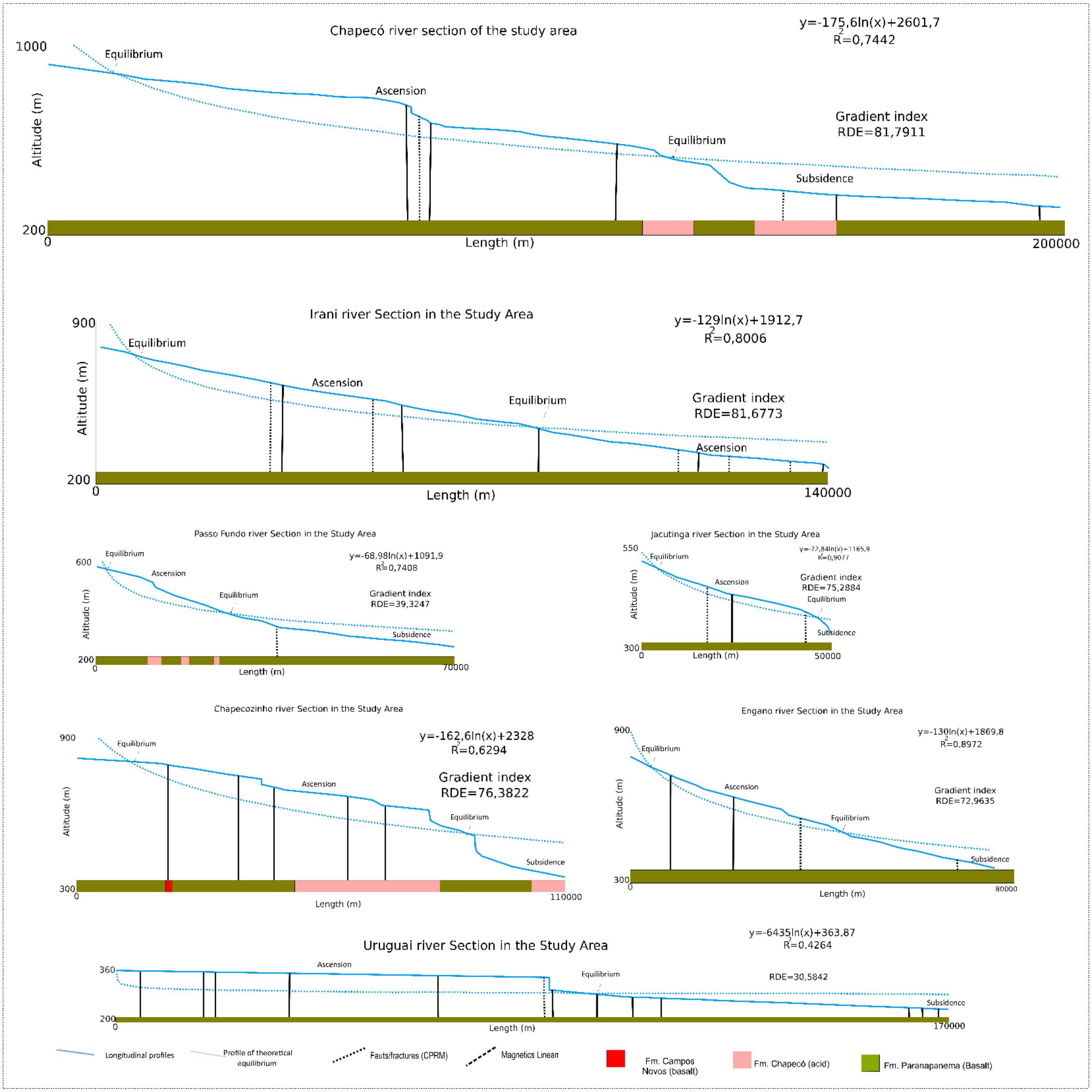

Figure 13. Longitudinal profiles of sections of the principal rivers that drain within the study área. (Elaborated by the authors)

All sections analyzed presented sectors in ascension and subsidence, most of which have a good correlation with structural lineaments, indicating that tectonics played an important role in the lowering and raising of these blocks. The most important slope breaks, which constitute base level changes, are present in the Chapecó River and its tributary Chapecozinho. This suggests that the Chapecó basin was the one that

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suffered the greatest tectonic influence, as already shown by Lima (2020), mainly in the sector upstream of the confluence with the Feliciano tributary. Corroborating these results, one can cite the work by Fujita et al. (2017) which showed that structural control was important in the compartmentalization of the Chapecó river basin, creating ascending and subsidence blocks.

In summary, it can be said that most of the longitudinal profiles of the rivers analyzed in this study area are in a state of dynamic disequilibrium. From the collected data, it is possible to observe the distance between them and the ideal theoretical curve and/or graded profile. In addition, in virtually all rivers, there are ascending and subsidence stretches. In numbers, one can have an idea of the level of maladjustment of a river considering the value of R^2. This adjustment factor shows that the closer to 1, the greater the equilibrium state of the river. In the analyzed rivers, the R^2 values varied from 0,43 in the section of the Uruguay River to 0,99 in the Lajeado Rafael, a tributary of the Engano River. It is possible to indicate that, in general, the smaller the R^2 values, the greater the slope breaks or ruptures in the longitudinal profiles.

IV. Conclusions

The analysis of the longitudinal profiles of the rivers in the central sector of the Araucaria Plateau suggests that when the rivers are on a single geological formation, they are more balanced, with R^2 values greater than 0.8. In these cases, slope breaks (knickpoints) are less pronounced, almost always corresponding to small waterfalls and rapids. On the other hand, profiles with lower R^2 values, therefore less balanced, occur in areas with greater lithological differentiation. Most of the time part of the flow runs over acidic rocks (Fm. Chapecó) and part of the flow over basic rocks (Fms. Paranapanema, Campos Novos, Esmeralda). Slope breaks are characterized as medium to large-sized waterfalls.

Lithological differentiation is not the only factor responsible for the formation of slope breaks in the longitudinal profiles of the analyzed rivers. Of the main breaks observed, around 50%, are associated only with the presence of structural lineaments (faults/fractures, magnetic lineaments). Of the other breaks, approximately 21%, are associated with structural lineaments and lithological differentiation. This fact has already been evidenced in other sectors of the Araucaria Plateau (LIMA, 2009; LIMA, 2012; FLORES et al. 2017).

The large number of slope breaks implies distancing from dynamic equilibrium. In all the analyzed rivers, ascending and subsidence stretches were observed. In most cases, these sections present a good correlation with the structural lineaments, indicating that tectonic factors were responsible for the tilting and lowering of

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blocks in different sectors of the study area. Quantifying this relationship, it is possible to conclude that about 52% of the stretches in ascension and subsidence are directly related to structural lineaments. The analysis of the data suggests that it is in the Chapecó river basin that the stretches in ascension and subsidence, in percentage terms, presented a greater correlation with structural lineaments (72%). In the other basins of the study area, the percentages were around 50%. The present work suggests that the study area was subject to morphostructural and morphotectonic influence. However, it is in the Chapecó river basin that this influence is most marked.

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