

# Geomorphological Structuring and Tectonic Control in the Southeastern Brazilian Stepped Reliefs: Relation with the Evolution of Crystalline Scarps



Roberto Marques Neto, Felipe Pacheco da Silva, Juliana Alves Moreira, Juliana Costa Baptista Barreto, and Matheus da Silva Frauches

**Abstract** The strong tectonic control acting on the relief evolution in the context of the southeastern Brazilian rift margin has been treated by several methodological prisms. The great escarpments of the Brazilian passive margin present important crustal elements acting in its geomorphological evolution and structuring, being the present work in charge of discussing the relations between the structural and tectonic control in the evolution of such geomorphological systems, focusing on specific compartments of Serra do Mar and Serra da Mantiqueira, the two main orographic steps of the Brazilian Atlantic margin. Through the elaboration of paleotopographic models and structural and geochronological analysis, the results pointed out strong neotectonic deformational effects superimposed on Precambrian structures reactivated in the Cretaceous-Paleocene, reinforcing the action of a post-Miocene tectonics influencing the maintenance of scarps and enhancing local and regional amplitudes.

## 1 Introduction

The geomorphological structuring of the crystalline terrains of southeastern Brazil conforms to relief systems characterized by well-marked regional scaling, controlled by different base levels that contain distinct organizations in terms of morphogenetic and surface processes. From the base level defined in the Atlantic Ocean to the more receded interfluvial basins that flow toward the oceanic level, there stands out a graded relief marked by high ridges in continuous *horsts*, structural hills, interplanaltic erosive depressions, tectonic depressions (*grábens*), and other geomorphic facts carved in ancient structures and in great measure influenced by neotectonic efforts.

---

R. M. Neto (✉) · J. A. Moreira · J. Costa Baptista Barreto · M. da Silva Frauches  
Federal University of Juiz de Fora, Juiz de Fora, Brazil  
e-mail: [roberto.marques@ufjf.edu.br](mailto:roberto.marques@ufjf.edu.br)

F. P. da Silva  
Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

The distensional tectonics that engendered the separation of the Afro-Brazilian paleoplate from the Mesozoic remobilized the Proterozoic structures inherited from the Brazilian-Pan African orogeny through epeirogenetic efforts that defined the plateau levels of the Atlantic margin, including the taphrogenic tectonics responsible for generating the Serra da Mantiqueira and Serra do Mar, as well as the Paraíba do Sul river tectonic depression. Such geodynamic event has been defined as the southeast Brazilian continental rift (Riccomini 1989). With the frank opening of the Atlantic Ocean, the evolution of the hydrographic basins that drain toward the oceanic level took course, and that in the context of the rift system under consideration has in the Paraíba do Sul river its main regional collector, whose base level is defined since the Eocene.

Despite the existence of a regional Paleogene base level, the base levels have not been stable in the region due to the effect of neotectonic deformational efforts (Hasui 1990; Saadi, 1991), with well-documented evidence in the context of the rift margin (Santos 1999; Chiessi 2004; Zalan and Oliveira 2005; Silva and Mello 2011; Marques Neto et al. 2019). Such structuring derives from a strong erosive imperative defined by the proximity to the Atlantic Ocean, partly differential due to lithostructural contrasts, but augmented by a morphotectonic control responsible for the reactivation of headwaters, re-hierarchical drainage, lateral migration of channels by block basculation, colluvialization on the slopes, among other processes.

Among the main results of this entanglement of controls, some of them are worth mentioning: (1) The Atlantic crystalline margin of southeastern Brazil is geomorphologically characterized by staggered plateau levels defined in successive regional base levels; (2) These base levels are not stable, having been subjected to the influences of post-miocene tectonics; (3) The coastal and sublittoral escarpments have their retraction processes conditioned by successive base levels delimited in different tectonostructural blocks, which repercusses in a distinct regional variation of the erosive dynamics; (4) The upward migration of *knickpoints* tends to be more evident in the rocky segments of the river channels, which has had an impact on the maintenance of slopes along the retreating scarps; (5) In the course of scarp retraction and morphogenesis of the interflaves, it has been common for the interception of channels by transversal drainage that enters the interior of the continent, promoting fluvial captures of various magnitudes as pointed out by authors such as Cherem et al. (2013), Rezende (2018), Salgado et al. (2018), Marent and Valadão (2019), among others.

Focusing on the premises listed above, this chapter discusses aspects related to the morphogenesis and geomorphological structuring of the great escarpments of the Brazilian passive margin, putting the magnifying glass on three regionally significant escarpment extensions positioned in different compartments and subjected to distinct base levels, conforming geomorphological specificities that are very representative of the regional geomorphogenesis: Serra dos Órgãos, in the context of the Serra do Mar, Serra do Ibitipoca, in the context of the Serra da Mantiqueira, and Serra do Relógio, a NNE-SSW alignment corresponding to the festooned structures of the so-called Northern Mantiqueira, cut in deep epigeny by the transverse drainages that trace back to the interplaneltic erosive depressions.

## 2 Materials and Methods

The selection of the geomorphological compartments collated in the present work took into account (1) the homologous character of the genesis of these structures, (2) the different evolutionary aspects linked to distinct regional base levels and to the conditioning of the Cenozoic tectonics, (3) the regional representativeness in the context of the southeast rift margin. In this sense, the structures analyzed were generated during the reactivations linked to the platform rifting but evolved as a function of specific controls engendered by their respective base levels and particular tectonostructural aspects. The methodological treatment employed coadunited cartographic techniques and paleotopographic, geochronological, structural analysis and field reconstitution.

First, a database was prepared for each area from Landsat images (OLIVIRS C1 Level 1) and SRTM (*Suttle Radar Topography Mission*) data from the shaded relief, available for download on the website of the USGS (*United States Geological Service*), as well as the planialtimetric bases provided by the Foundation Brazilian Institute of Geography and Statistics (IBGE) at the scale of 1/50,000. The remote sensing products served as a basis for generating baseline information on hydrography, slope, and hypsometry, with their respective cartographic documents processed in ArcGIS software. The planialtimetric bases, together with the base maps that were generated, served for the geomorphological compartmentalization and the generation of paleotopographic maps for the three geomorphological systems studied.

The extraction of the structural lineaments was performed to support the interpretation of the geomorphological structuring of the areas and their regional differences. The relief and drainage lineaments were defined from SRTM radar data in shaded relief. The interpretation took into account four angles of azimuthal illumination (45°, 90°, 315°, and 360°), since each one of these angulations emphasizes more forcefully some lineament orientations to detriment of others, thus allowing a more secure and comprehensive interpretation. The rosette diagrams were generated at 10° angular intervals, using the Georient© software.

The present relief was discussed in relation to the paleotopographic picture obtained from the application of the Sêppomen technique (Motoki et al. 2008), a cartographic approach that estimates the paleorelief from valley fills (Leverington and Teller 2003; Couto et al. 2014; Vargas 2017). The methodology consists of dividing the study area into quadratic cells superimposed on the planialtimetric bases at a scale of 1/50,000, in which the maps are generated. For each cell the highest level curve is considered, which implies the removal of the other curves and the consequent elimination of the effect of fluvial dissection, thus resulting in a geomorphological configuration prior to the most recent phase of drainage incision. The paleotopographic map is generated by interpolation procedures, here performed by the IDW protocol (*Inverse of Distance Weighted*) contained in the toolbox of the GIS software. For the present proposal, we opted for the modulation in an intermediate grid of 1 km × 1 km, which presumably indicates a more recent temporality of the

relief, emphatically nequaternary, but that reveals to satisfaction past situations of altimetry, density, and depth of dissection.

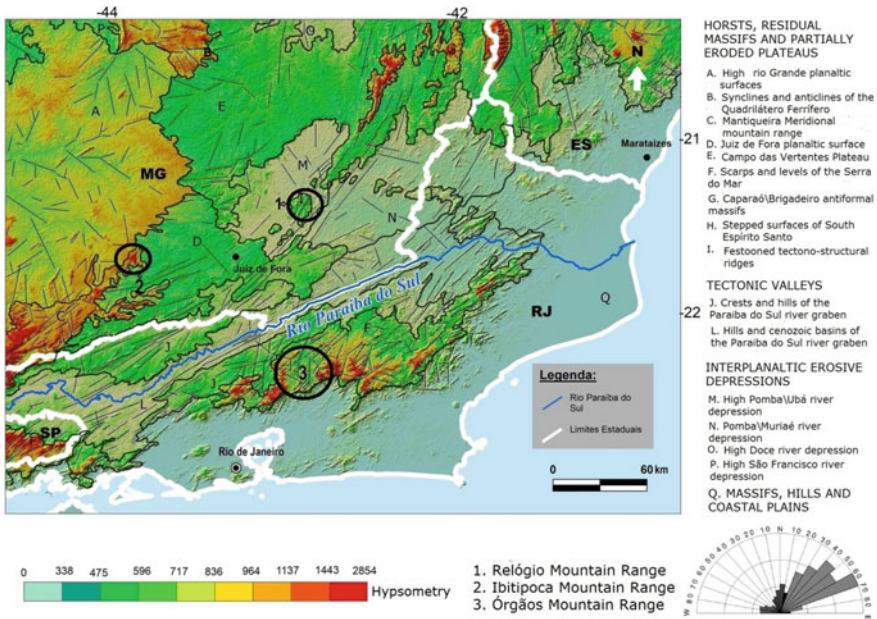
The comparison between the current and past topographic pictures was also subsidized by the interpretation of the existing fluvial captures along the three compared interfluvial segments, gauged from the evidence expressed in the topographic sheets at the scale of 1/50,000, in Google Earth Pro images, and from field control. The following criteria were considered: (1) presence of anomalous curve (*elbow of capture*) linked or not to a transcurrent displacement; (2) occurrence of blind valley (*wind gap*) visible in the planialtimetric bases *e*lou in the field; (3) same altimetric position along the surface where the capture occurred, between the captured basin and the capturing basin.

For the Serra do Ibitipoca context, the presence of terraces generated by the post-capture fluvial notch still preserved enabled the dating of the deposit by Optically Stimulated Luminescence (OLE), thus allowing to bring to light geochronological aspects of the local and regional Quaternary morphogenesis. The material collected in the field followed the usual protocols (Jacobs and Roberts 2007; Sallun 2007; Anderson and Anderson 2010; Bierman and Montgomery 2014), removing the sediment mass by incising a dark-colored, properly sealed PVC plastic tube. In this case, the collection was performed at a depth of 1.05 m. Then, the collected material was sent to the laboratory Datações, Comércio e Prestação de Serviços Ltda., where the dating test was performed from the SAR protocol (*Single Aliquot Regenerative Doses*) in fifteen aliquots.

### 3 Study Area

The region focused on in the present study comprises the area influenced by the southeast Brazilian continental rift (Riccomini 1989). The geomorphological structuring of the southeastern rift margin is driven by successively reactivated Precambrian structures of general NNE-SSW orientation, the dominant one in the continental rift system. Such structures intersect different geomorphic compartments that evolved throughout the Cenozoic and control regional base levels arranged at distinct altitudinal positions (Fig. 1). Indefectibly, they are the main structural conditioning factors in the current scalings as the main alignments correspond to the major regional geomorphological compartments defined in the *horsts* of Serra do Mar and Serra da Mantiqueira and the tectonic depression of the Paraíba do Sul river. Secondly, a tectonic control has favored the reaffirmation of the scarps and the generation of stepped landforms and, finally, a mainly erosive control is related to the retraction of the scarps and the consequent opening of interplanaltic depressions in the E-W orientation.

The selected geomorphological compartments comprise terrains inserted in different hydrographic basins of regional importance. The Piabanha river basin, fully attached to the Rio de Janeiro state, covers a large part of the stepped reverse of the Serra dos Órgãos, whose slopes facing the Baixada Fluminense are dissected



**Fig. 1** Regional geomorphological structure and compartmentalization

by smaller channels. Serra do Ibitipoca is positioned in an important interfluvial segment of the Peixe river basin, a direct affluent of Preto river. Regarding Serra do Relógio, its location in the central part of the Pomba river basin stands out, marking the limits between different altimetric levels of the interplanaltic depression linked to the alluded fluvial channel. The three mentioned hydrographic basins, directly or indirectly, imbricate in the Paraíba do Sul river, main regional collecting trunk.

Altimetric variation, slope orientation, lithology, and distance from the Atlantic Ocean are factors that define mesoclimatic differentiations and vegetation cover, dominated by the ombrophilous forests in the Serra do Mar (emphatically in the branch concerning Serra dos Órgãos) and the semideciduous seasonal forests in the interior orographic steps, as occurs in Serra do Relógio in the form of remaining fragments. Serra do Ibitipoca, on the other hand, appears as a higher structure sustained by quartzite, thus showing ombrophilous forests over schist on windward slopes with higher elevations, besides rock fields in the quartzite somites where they vary in different floristic and phytophysiognomic arrangements.

## 4 The Regional Geomorphological Structuring and the Erosive Control on the Evolution of Scarps

The tectonostructural arrangement in the southeastern Brazilian rift margin, as highlighted, comprises high reliefs of general NE-SW orientation and transversal drainage of copious NW-SE orientation, besides E-W orientations linked to more recent transcurrent regimes. Such structuring, therefore, responds to a complex framework linked to different tectono-erosive controls operating throughout the Cenozoic in different degrees of tropicality. Figure 2 summarizes the main evolutionary events that cover the regional context, serving as a temporal reference for the present discussion.

The three compartments analyzed in a more vertical way replicate the regional typicality, as is explicit in the observation of the structural lineaments extracted for the areas under consideration (Fig. 3), mainly those concerning the relief, pointing to the strong control of the NE-SW shear zones in the regional geomorphological organization. The NW-SE structuring, in its turn, is explored in a more recurrent way by the drainage of lower hierarchical level that demands the main collecting trunks linked to the rift, among which is the Paraíba do Sul river itself. Such structures are dominantly neotectonic (Silva and Mello 2011), and reveal the superposition of post-Miocene stress fields on the Precambrian structures reactivated in the Cretaceous-Paleocene. In Serra dos Órgãos and Serra do Ibitipoca, the relief forms assume a prominent N50E orientation, and in Serra do Relógio N30E.

It is also explicitly noticed that the drainage orientation inherited from the rift, aligned in the NE-SW direction parallel to the great escarpments, diminishes in the direction of the continental interior, being conspicuous in the Serra dos Órgãos and inexpressive in the region of the interfluves bordering the Rio Grande basin where the

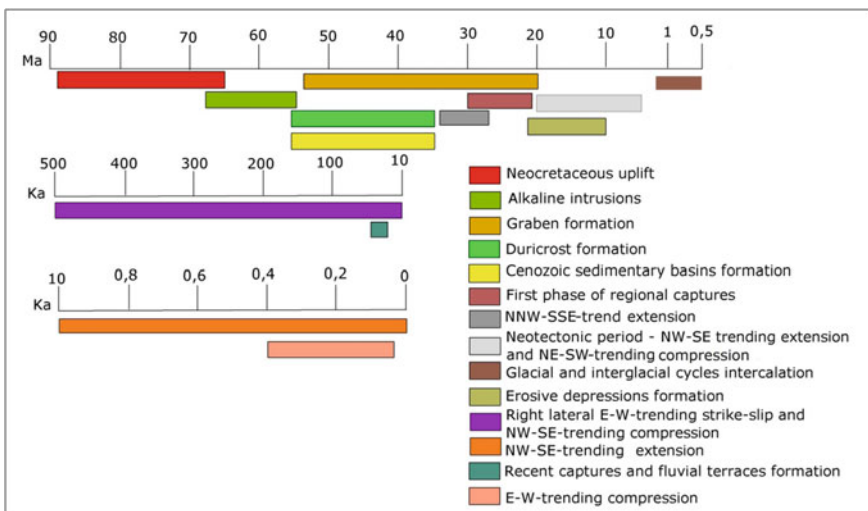


Fig. 2 Main evolutionary events that have affected the region since the Neocretaceous



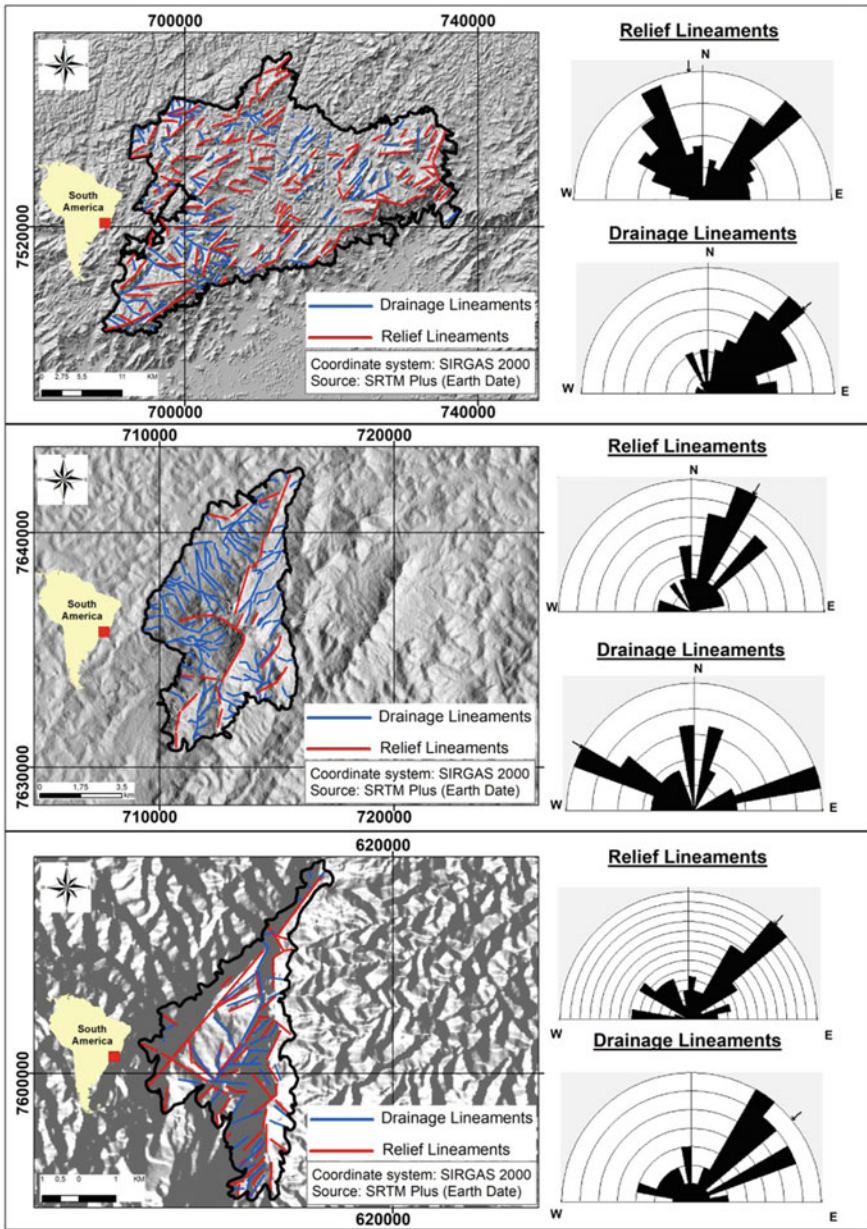


Fig. 3 Topography and drainage lineaments extracted for Serra dos Órgãos (above), Serra do Ibitipoca (below) and Serra do Relógio (in the middle)

rivers are confined to the regional faults until they enter the interplanaltic depression of the Pomba river when the drainage begins to run transversally to the structures genetically linked to the continental rift.

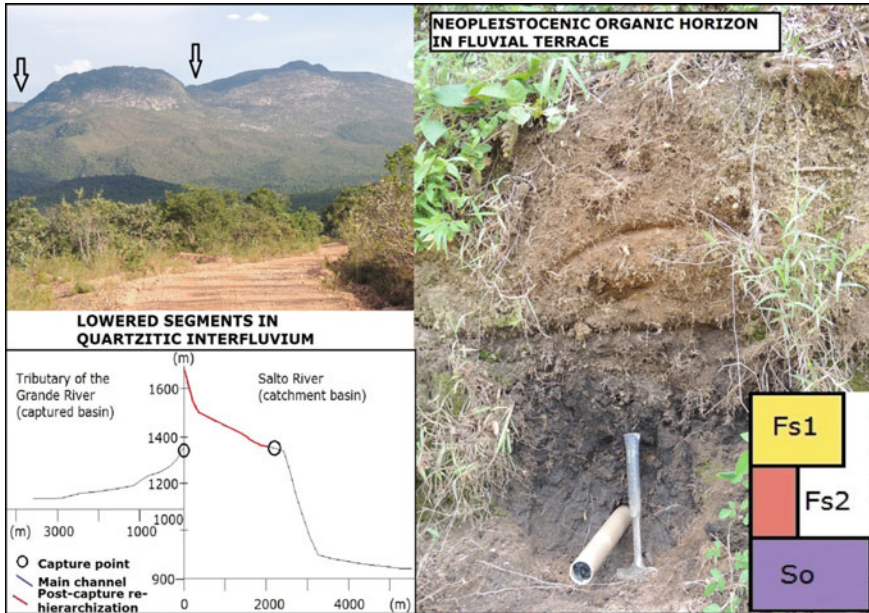
The units presented in greater detail figure as three surfaces of common tectonic genesis given by the platform uplift positioned in different sectors of the continental rift and, therefore, submitted to different base levels that have been imposing distinct conditions for the morphological evolution of these areas. The erosional organization of Serra dos Órgãos is controlled by the general base level of the Atlantic Ocean in its southeast face and by the tectonic depression of the Paraíba do Sul river in the interior plateaus; In Serra do Relógio, the denudational processes are leveled at the second level of the interplanaltic depression of the Pomba river, at an altitude of 300 m; in Serra do Ibitipoca, the regional base level is given by the Peixe river, which in the vicinity of the block dissects the relief at an altitude of 900 m before stabilizing its plain at the threshold of 700 m. These different positions in the landscape denote the regional scaling convergent to the Paraíba do Sul river valley, where the intermingling of the staggered reverses of the Serra do Mar and the Mantiqueira escarpments takes place.

In the central part of the area covered in this study the main regional erosive front opens, which according to Paixão et al. (2020) decreases from NE to SW. This can be well observed in Fig. 1, which also points out the E-W direction erosive wave festooning transversally the NNE-SSW oriented structural highs, to include the Serra do Relógio.

The SW expansion of the alluded erosive entrance is hindered by the tectonic sill of the Paraíba river, positioned at the southeastern limit of the hemigraben that the aforementioned river dissects in its middle course, as well as by *knick-points* along the Peixe river and other tributaries. Even though, the Peixe river presents a pronounced erosive aggressiveness capable of entering the interfluves of the Mantiqueira mountain range, forming large retractive arcs in gneissic-granitic lithologies that differ from the morphologies of the rectilinear scarps in the quartzite mountains, among which the Ibitipoca mountain range appears as the highest block. In spite of the support propitiated by the resistant quartzite, the dissection is very active on the somite surfaces, promoting the capture of a channel originally belonging to the Grande river basin and that nowadays appears as the main watercourse dissecting the summits in question. The transposition of the immense threshold favored the entrenchment of the channel and the formation of terraces with preserved organic horizons, dated by Optically Stimulated Luminescence (OLE) at 23,000 years (Fig. 4).

The reversal of drainage by fluvial catchments has been common in the evolution of large regional interfluves. The preponderance of catchments draining toward the Atlantic Ocean subtracting areas of basins facing the continental interior has been observed in several works (Cherem et al. 2013; Rezende 2018; Salgado et al. 2018; Marent and Valadão 2019). The capture processes occur, therefore, in the high ridges that mark the interfluves between the Paraíba do Sul river basin and the Rio Grande, Doce, and São Francisco river basins, and there are also important downstream





**Fig. 4** River catchment in Serra do Ibitipoca with terrace generation in the catchment. Textural distribution. Fs1—Sandy-clay facies referring to the most recent coverings with superficial enrichment of organic matter; Fs2—Sandy-clay facies with greater loss of organic matter; So—sandy facies markedly organic (buried glei horizon)

rearrangements related to the evolution of the relief in the eastern basins directly or indirectly connected to the Atlantic Ocean.

The alluded eastward projection of the capture lines is due to the natural retreat of the mountain escarpments, being the fluvial captures are also quite recurrent in the interfluvial morphogenesis of Serra dos Órgãos, a compartment of Serra do Mar that shows abundant evidences of active tectonic control. The capture front follows the interfluvial lines that separate the basins of the rivers Piabanha and Paquequer (tributaries of the Paraíba do Sul river) from the small channels that drain directly toward the Baixada Fluminense. The two cited rivers dissect deeply the relief, accompanied by the strong incision of its tributaries and of diverse rearrangements for capture in the interior of these basins, that assume thus a strong aggressive condition capable to capture segments of small opposing channels directed directly toward the Atlantic. Figure 5 is representative of the catchment patterns in Serra dos Órgãos, sampling a situation in which the catchment turns toward the Paraíba do Sul river and another in which the catcher condition is from the opposite basin facing the Atlantic base level.

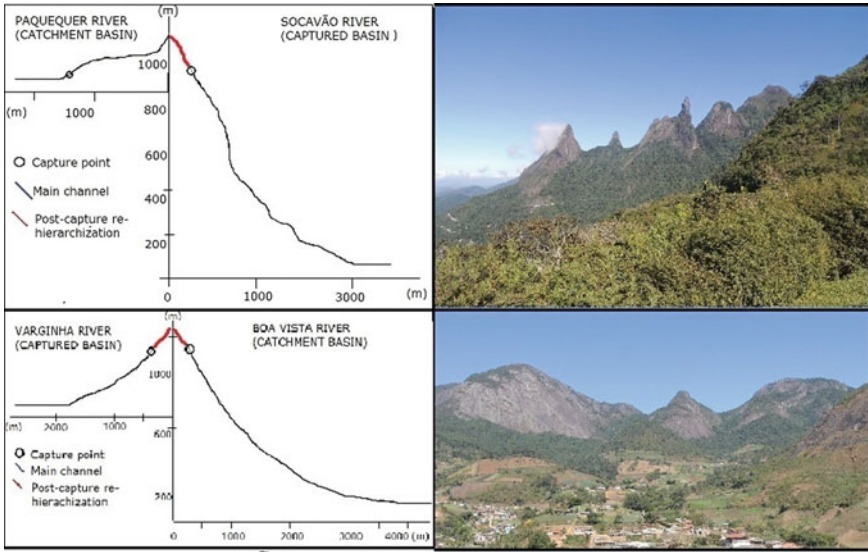
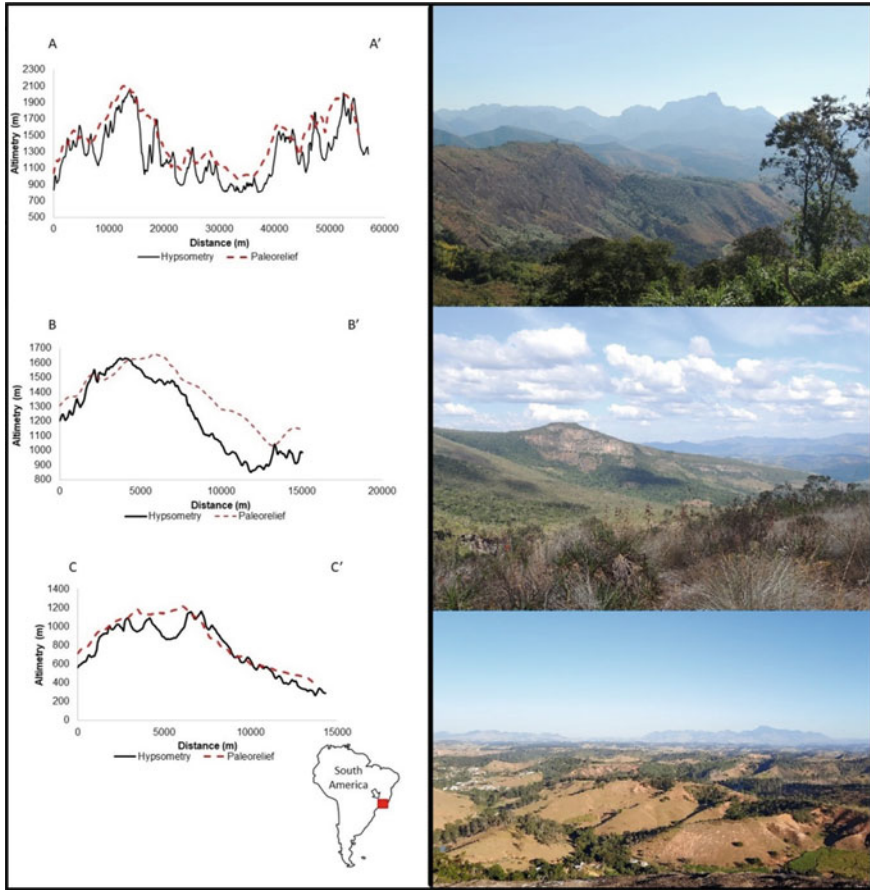


Fig. 5 River catches in the interfluvial strip of Serra dos Órgãos

## 5 Neotectonic Conditioning

Besides erosional and structural aspects, evidence of morphotectonic control also abounds in the region, especially in Serra do Mar (Riccomini 1989; Gontijo 1999; Hartwig 2006; Nascimento et al. 2013) and Serra da Mantiqueira (Saadi 1991; Santos 1999; Morales 2005; Marques Neto 2017). The presence of facets on different surfaces, both on high escarpments and on structural hills of intermontane surfaces, is associated with other geomorphological evidence of tectonic control, such as *shutter ridges*, outcrops on terraces and low slopes, lateral migration of channels by block basculation, strangulation of fluvial plains, hanging valleys disarticulated from local base levels, misalignment of interfluves, etc.

The retractive morphogenesis of scarps and interfluves, associated with tectonic uplift and reactivation of headlands, have been shared in the Cenozoic evolution of the regional relief. Structural and geochronological interpretations have been associated with geochemical denudational approaches (Rezende et al. 2013) for a more comprehensive understanding of the regional morphological evolution. Paleotopographic reconstructions are a cartographic technique that spatializes a previous altimetric organization and dissection, providing important morphometric and morphographic elements to support the interpretation of the relief evolution. The paleotopographic reconstructions performed in the three interfluvial alignments under consideration were accompanied by the elaboration of current topographic profiles superimposed on the profiles generated from the paleo-model (Fig. 6) to aid the visualization of the current compartments and their past projection from transects.



**Fig. 6** Overlapping topographic and palaeotopographic profiles for the three interfluvial alignments compared. A-A'—Serra dos Órgãos, B-B'—Serra do Ibitipoca, C-C'—Serra do Relógio

Neotectonic processes visibly affect the geomorphological structure of Serra dos Órgãos, which shows morphological evidence of such effects in the form of deep and embedded valleys, sills, and high-mountain valleys, scarps with trapezoidal facets, etc. The paleotopographic map generated for the area (Fig. 7) denotes the maintenance of the altimetry in spite of the retractive processes of the scarps, which have presented a marked conservation of the slopes and a tendency of remnant migration of the *knickpoints*, with dominance of rocky bed rivers in the interior of the alluded compartment.

Currently, the altimetric levels of Serra dos Órgãos exceed 2100 m in the culminating plateaus, figuring as one of the highest compartments of the entire Serra do Mar. The paleotopographic map suggests a pattern in which the evolution of the valleys tends to maintain and even increase the slopes, due to the predominance of *bedrock rivers* within this compartment. Synchronously, the sustaining of the slopes

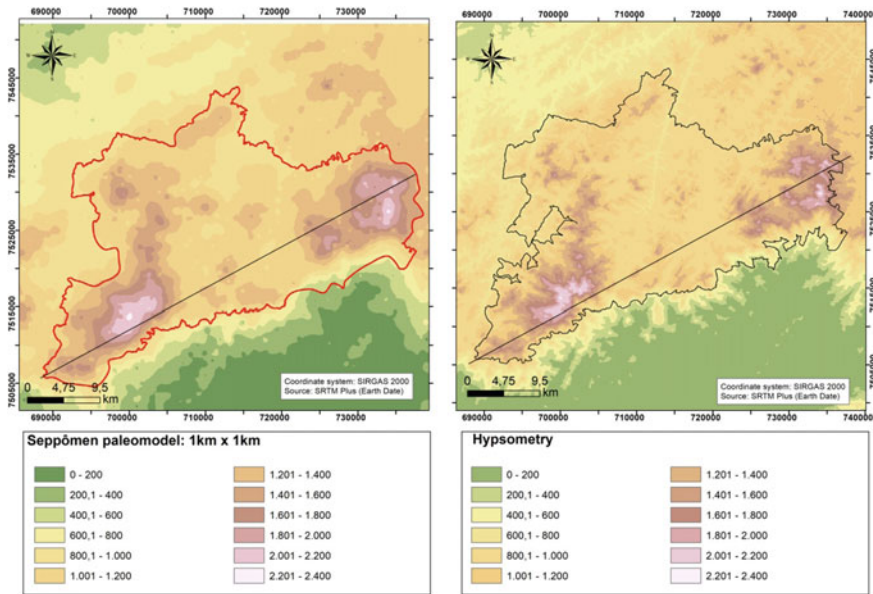


Fig. 7 Paleotopographic reconstitution of Serra dos Órgãos (RJ) compared to present altimetry

is accompanied by the increase of the dissection density, revealing intense rehierarchization and vertical notching in higher-order channels due to the regional *uplift*, a configuration that converges with other research that points to regional morphotectonic control, both in Serra dos Órgãos (Hartwig 2006) and in the Paraíba do Sul valley (Silva and Melo 2011). The very lineaments linked to the Piabanha river and its main formers, well marked on the current hypsometric map, do not appear well defined on the paleotopographic map, suggesting a relatively recent intensification of the vertical notch that favored the formation of deep low-order valleys, many of them suspended.

The maintenance of the interfluvial lines associated with the high slopes suggests vertical evolution of the landscape commanded by the fluvial carving, and the reworking of the headwaters by the main channels has partially reworked the interfluves sustained by uplift. On the other hand, the staggering levels reveal local controls exerted by several thresholds arranged in steps, controls that overlap the regional *trend* and influence the interfluvial erosive remodeling not only from the slopes facing the Guanabara Bay but also from those facing the Paraíba do Sul valley. Such geomorphological organization is reflected, for example, in the superimposition of Paquequer River on a NW–SE structure well marked in the relief that lines up in the interior extensions of the scarp ridges of the reverse of Serra dos Órgãos, showing the existence of a higher plateau in the upstream confining an altimontane depression limited by a local sill that was obliterated by the epigenetic cut of superimposition. In the current topographic configuration, the referred process resulted in a greater leveling of the valley bottom and reattached the crest spur in local hills.

In spite of the strong tectonic conditioning of Serra dos Órgãos, the comparison of the present topography with the paleomodel shows that the main slope breaks that delimitate the compartment did not suffer significant alterations, differently from what occurred in the interior blocks that climb in the direction of the tectonic valley of the Paraíba do Sul river, where a strongly controlled drainage has been aggressively dissecting the relief. Possibly, this is due to the differential resistance of the lithotypes that compose the granite-gneissic batholith of Serra dos Órgãos.

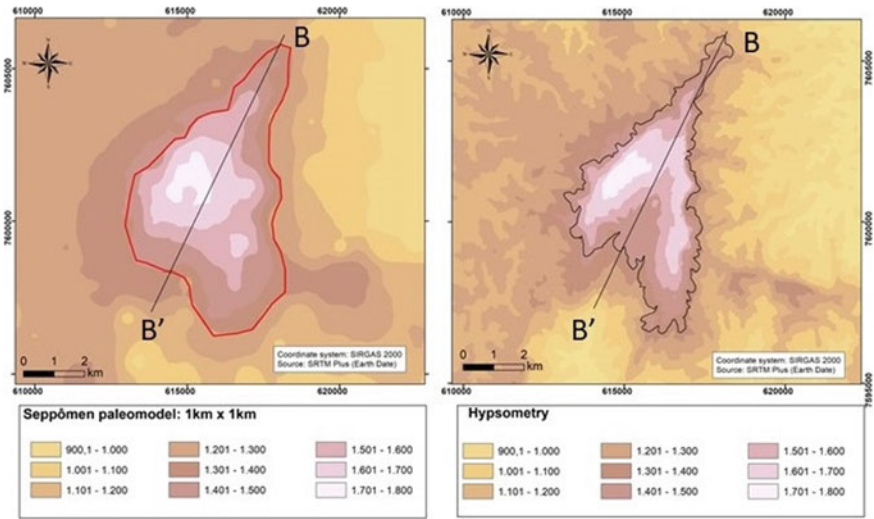
Once the Serra do Mar is transposed, the *horst* of Serra da Mantiqueira stands out as the second orographic step of southeast Brazil. Serra do Ibitipoca is positioned in the northeastern extremity of this important regional geomorphological compartment, one of the continuously higher structures of the whole Brazilian territory. Its limit is given by a structural sill that represents a strong erosive obstacle for the drainage that has been causing the retreat of this sector of the Mantiqueira mountain range controlled by the base levels imposed on the rivers captured by the basins that drain into the Paraíba do Sul river. The high altimetries are sustained by quartzite, which flanked by biotite-gnaisses and schists establish local amplitudes above 700 m. The Salto River is the main channel that dissects the block, crossing stepped sills until it flows into the Peixe river, the first base level that rises in the regional scaling until the Atlantic Ocean. Together with the Conceição stream, the upper course of the channel in question integrated an organized drainage toward the Grande river, sharing the hydrographic basins that drain inland, having been captured by the erosive wave that has been forcing the retraction of the escarpments of the Mantiqueira mountain range, as reported in the previous section.

Although the quartzite landscapes are markedly resilient, thus presenting a strong structural significance, evidence of neotectonic diastrophic effects are present in Serra do Ibitipoca as in the entire regional context. As occurs in Serra dos Órgãos, ridges with preserved facets incarcerating hanging valleys and disarticulated local and regional base levels are common, associated with vertical notches that deepen the structural canyons. The paleotopographic reconstitution of the block under consideration (Fig. 8) indicates sectors in which the present altimetry is higher than its previous correspondents, suggesting a preferential uplift of this block limited by craggy fronts. On the other hand, it is clear the erosive entrance of the Salto River, whose incision in the escarpment forms an inverted “V” that is not observed in the pale-model, suggesting an accentuated post-capture resurfacing.

In this case, the importance of the capture processes can be endorsed by the appreciable resurfacing unleashed on a relief sustained by quartzite, even if the underlying shale levels favor preferential alteration fronts and more forceful erosive inputs. Notoriously, the southern and eastern faces of the Serra do Ibitipoca facing the catchment basin present indentations and sinuosities that are much more prominent compared to its western side, facing the Rio Grande basin.

The block corresponding to the Serra do Ibitipoca clearly marks the limits of continuity of the elevated relief of the Serra da Mantiqueira and the passage to the hills of the lower plateau levels that climb up to the Paraíba do Sul river plateau. On the geomorphic surface in question, the regional NE-SW orientation is maintained, but elevated ridges are much more discontinuous, missing in the Paraíba do Sul river basin





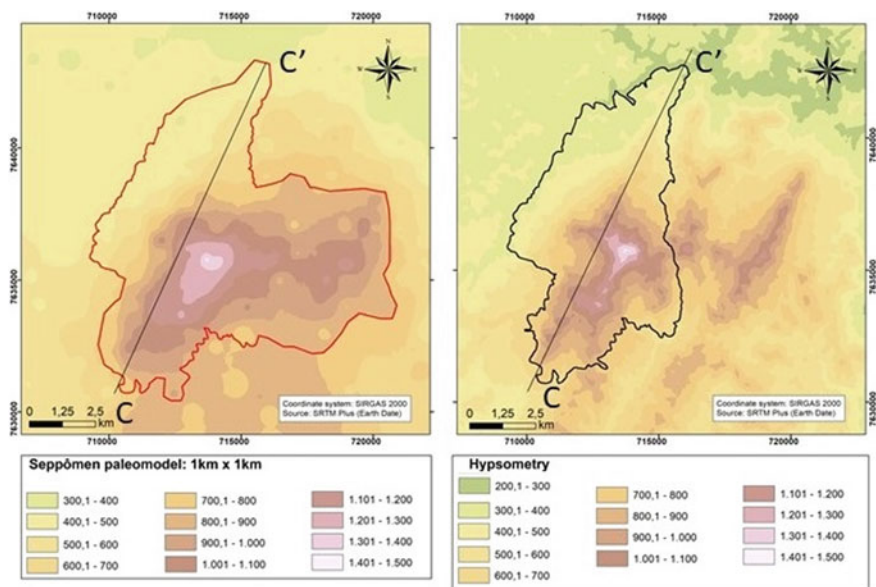
**Fig. 8** Paleotopographic reconstitution of the Serra do Ibitipoca (MG) and surroundings compared to the present altimetry

and standing out in the medium Pomba river basin, where they are festooned by the passage of the Pomba and Novo rivers. In this context is the Serra do Relógio, a gneissic-granitic massif that appears as a geomorphological heritage of more continuous alignments quite denuded by the hydrographic network that was arranged in the interplanatic depressions.

The Serra do Relógio marks the contact of two geomorphological plateaus with approximately 200 m of unevenness, which concern the two main levels of the interplanatic depression of Pomba river. The higher one is elevated at about 500 m of altitude in the backyard of the structural highlands and the lower one at medium altitudes of 300 m, closer to the Paraíba do Sul river and figuring as a functional base level for the higher compartment positioned upstream of the epigenetic cut.

Convergently to what was verified in the other two structures analyzed, the paleotopographic reconstitution suggested that the dissection of Serra do Relógio did not imply altimetric loss, despite the advance of the lowered surfaces in its surroundings (Fig. 9), suggesting tectonic influence in the sustaining of the structure in question. This behavior is in revelation of its position in the main regional erosive fronts verified in the Pomba river depression compartments, being sustained, inclusively, by the same lithotypes that frame the hills of the depression compartment to west (Fig. 10), given by the enderbitic gneisses of the Juiz de Fora Complex (Soares et al. 2002). In contrast, in the southernmost branch of the Mantiqueira, although the Peixe river itself presents a transversal behavior and a position very close to the interfluvial line of the Grande river basin, the great sills were not yet cut by superimpositions in this sector, leaving the relief more preserved in comparison with the festonations





**Fig. 9** Paleotopographic reconstitution of the Serra do Relógio and surroundings compared to the present altimetry



**Fig. 10** View of the Serra do Relógio. Around it, the originally forested hills of the Pomba river Depression, dominant form pattern in the Zona da Mata region of Minas Gerais

verified in the northeast, context in which Serra do Relógio and a set of NE-SW and NNE-SSW ridges are inscribed (see Fig. 1, brought at the beginning of this chapter).

The erosive aggressiveness around Serra do Relógio can be appreciated both in the map in Fig. 9 and in the image in Fig. 10, which shows the erosive depressed surfaces. The generated paleomodel suggests a past connection between the main alignment that is presently known by the toponymy Serra do Relógio (Fig. 9) and more residual hills and ridges to the east, connections that reveal the existence of a more continuous past somite surface consumed by the opening of interplanaltic depressions, which obliterated surfaces underlain by both the biotite-gnaisses of the Andrelândia Complex and the enderbites and charnockites of the Juiz de Fora Complex. The regional view of the great escarpments of southeastern Brazil (see again Fig. 1) points out the structural heritages and their relations to the present-day morphology that underlies these more residual dividers.

## 6 Some Trends in Regional Evolution

Considering what has been presented, the region of the great escarpments of the southeastern Brazilian rift margin houses geomorphological systems of genetic linkage, both erosional and tectonic. The compartments analyzed more specifically share a tectonic genesis that is still influential in their respective evolutions, although erosional forces have acted differently in the present and in the past in each one of them, as well as bequeathing profound regional geomorphological differentiations.

In a summarized way, it can be considered that the morphogenesis of the interfluves and the intermontane areas in the domain of the great escarpments of southeastern Brazil is markedly controlled by tectonic uplift associated with the retreat of the escarpments, indicating that it is not only the reequilibrium by mass balance that influences the maintenance of high topographies but also distensive, compressive and transpressive crustal efforts well marked in the relief forms, in the drainage arrangement and in the structures present in the outcrops.

The results show a regional differentiation in the tectono-erosive processes, with a lowered area within the interplate depressions that surround Serra do Relógio contrasted with the relief of the great regional tectonic pillars—Serra do Mar and Mantiqueira, characterized by the recurrence of fault scarps with deep, confined and markedly rectilinear valleys. The major downdip in the surroundings of Serra do Relógio indicates that the most aggressive denudation zone that is established between the erosional depression of the Pomba river and the tectonic depression of the Paraíba do Sul river can be relatively old and refers to superimposition processes that engendered epigenetic cuts in the NNE-SSW structures, in agreement with the age of the alteration coverages estimated in this region by Antonioli et al. (2005) as Miocene to Pliocene age. The remaining interfluves are much more residual, and fluvial catchments currently operate in the intermountain sectors, as the catchment front is already receding into the São Francisco and Doce River basins.

Entering the tributary basins of the Paraíba do Sul river that dissect the Serra da Mantiqueira (Peixe and Preto rivers), the erosive input has not yet reduced the topographic volumetry as in the Pomba river basin. In this way, the interfluvial morphogenetic processes present more recent arrangements, with nequaternary captures as dated in the quartzite block summits, which signals the erosive imperative of these basins and the advance of denudation on the planar surface of Juiz de Fora toward the interfluves of the Grande river basin. The continuity of erosive regression, in short, can set back the Peixe river to the point of consummating a process of capture of the upper Grande river upstream of its intersection, which is quite probable given the morphogenetic imperative ascertained here. Undoubtedly, this prelude of regional capture, once consummated, would mark a new phase in the geomorphological organization of the great escarpments of the Brazilian rift margin.

## References

- Almeida FFM, Carneiro CDR (1998) Origin and evolution of the Serra do Mar. *Rev Bras de Geociências* 28(2): 135–150
- Anderson RS, Anderson SP (2010) *Geomorphology: the mechanics and chemistry of landscapes*. Cambridge University Press, Cambridge
- Antonoli L, Tupinambá M, Gracia MJ, Dino R (2005) Palynology and age of Neogene (Upper Miocene/Pliocene) sediments from the Pomba-Muriaé River depression (MG). Symposium on Geology of the Southeast, p. 63
- Bierman PR, Montgomery DR (2014) *Key concepts in Geomorphology*. Freeman and Company, New York
- Couto EV, Fortes E, Sordi MV, Marques MJ, Camolezi BA (2012) Seppômens maps for geomorphic developments analysis: the case of Parana Plateau border, Faxinal, State of Parana, Brazil. *Acta Scientiarum Technology* 34(1): 71:81. <https://doi.org/10.4025/actascitechnol.v34i1.9944>
- Chiessi CM (2004) *Tectônica Cenozoica no Maciço Alcalino de Passa Quatro (SP-MG-RJ)*. Dissertação (Mestrado em Geologia). Instituto de Geociências, Universidade de São Paulo
- Cherem LF, Varajão CA, Magalhães Jr A, Varajão AFDC, Salgado AAR, Oliveira LAF, Bertolini, WZ (2013) O papel das capturas fluviais na morfodinâmica das bordas planálticas do sudeste do Brasil. *Revista Brasileira de Geomorfologia* 14(4): 299–308
- Gontijo AHF (1999) *Morphotectonics of the middle Paraíba do Sul River valley: Serra da Bocaina region, São Paulo and Rio de Janeiro states*. D. thesis, Institute of Geosciences and Exact Sciences, Paulista State University
- Hartwig ME (2006) *Mesozoic-Cenozoic ruple tectonics in the Serra dos Órgãos region, RJ*. Dissertation (master's degree), Institute of Geosciences, University of São Paulo
- Hartwig ME, Riccomini C (2010) Morphotectonic analysis of the Serra dos Órgãos region, southeastern Brazil. *Rev Bras de Geomorfologia* 11(1): 11–20
- Jacobs Z, Roberts RG (2007) Advances in optically stimulated luminescence dating of individual grains of quartz from archeological deposits. *Evolutionary Anthropology*, 1(6): 210–223. <https://doi.org/10.1002/evan.20150>
- Leverington DW, Teller JT (2003) Paleotopographic reconstructions of the eastern outlets of glacial Lake Agassiz. *Canadian Journal Earth Science* 40: 1259–1278. <https://doi.org/10.1139/e03-043>
- Marques Neto R (2017) The southern Mantiqueira *horst*: proposed morphostructural compartmentalization for its mining portion. *Revista Brasileira de Geomorfologia* 18(3): 561–577

- Marent, B Valadão, RC (2019) Contribuição aos estudos da evolução da escarpa entre as bacias hidrográficas dos rios Doce e Paraíba do Sul, na Serra da Mantiqueira-MG-Brasil. *Geosp – Espaço e Tempo* (26)2: 417–434.
- Marques Neto R, Ferraro BV (2018) Regional geomorphological cartography and morphogenesis: methodological contributions. *Brazilian Journal of Geomorphology* 19(2): 267–281
- Marques Neto R, Moreira JA, Silva FP (2019) Evolution of escarpments in rift margins: a discussion on soerguation and denudation in southern Mantiqueira from paleotopographic maps and geomorphometric parameters *Revista Brasileira de Geomorfologia*. 20(4): 877–890
- Morales N (2005) Neotectonics in intraplate environment: examples from southeastern Brazil. Ph. D. thesis, Institute of Geosciences and Exact Sciences, Paulista State University
- Motoki AG, Petrakis H, Sichel et al (2008) Origin of the Mendanha syenitic massif reliefs, RJ, based on geomorphological analyses and its relation to the Nova Iguaçu volcano hypothesis *Geosciences*. 27(1): 97–113
- Nascimento ER, Salamuni E, Queiroz GL et al (2013) Evidence of morphotectonic and neotectonic determination in the relief of Serra do Mar in Paraná State. *Revista Brasileira de Geomorfologia*. 14(3): 287–299
- Oliveira, LAF Quaternary fluvial dynamics and landform configuration at the contact between the Rio Pomba Depression and the Campos das Vertentes Plateau (2012) Dissertation (master's degree in Geography) Institute of Geosciences, Federal University of Minas Gerais
- Paixão RW, Salgado AAR, Freitas MM et al (2020) Possibility of endorheism and fluvial captures in the morphogenesis of the Paraíba do Sul river basin *Revista Brasileira de Geomorfologia* 21(4): 821–834
- Rezende E, Salgado A, Silva AAR et al (2013) Controlling factors in landform evolution on the NNW flank of the continental rift of southeastern Brazil: an analysis based on the measurement of long-term denudational processes *Revista Brasileira de Geomorfologia*. 14(2): 221–234. <https://doi.org/10.20502/rbg.v14i2.416>
- Rezende EA (2018) O papel da geodinâmica espaço-temporal da rede hidrográfica na evolução geomorfológica da alta/média bacia do Rio Grande, sudeste brasileiro. Tese (Doutorado em Geologia Ambiental e Recursos Naturais), Escola de Minas, Universidade Federal de Ouro Preto
- Riccomini C (1989) The continental rift of southeastern Brazil. Ph.D. thesis, Institute of Geosciences, University of São Paulo
- Saadi A (1991) Ensaio sobre a morfotectônica de Minas Gerais: tensões intraplaca, descontinuidades crustais e morfogênese. Ph. D. thesis, Institute of Geosciences, Federal University of Minas Gerais
- Sallun AEM (2007) Aloformation Paranavaí: Quaternary colluvial deposits of the upper Paraná River basin (SP, PR and MS). Ph. D. thesis, Institute of Geosciences, University of São Paulo
- Salgado, AAR Cherem, LFS Sordi, MV (2018) Grandes capturas fluviais no Brasil: síntese das novas descobertas. *Estudos do Quaternário* (19): 23–31
- Santos M (1999) Serra da Mantiqueira and Planalto do Alto Rio Grande: the Tertiary basin of Aiuruoca and morphotectonic evolution. Ph. D, thesis,- Institute of Geosciences and Exact Sciences, Paulista State University
- Silva FP (2019) Role of post-Miocene tectonics in the morphological configuration of hydrographic systems - morphotectonic assessment in the context of rift margins. Dissertation (Master in Geography), Federal University of Rio de Janeiro, Institute of Geosciences
- Silva TP, Mello CL (2011) Neotectonic reactivations in the Paraíba do Sul River Shear Zone (southeastern Brazil). *Journal of the Institute of Geosciences*. 11(1): 95–111. <https://doi.org/10.5327/Z1519-874X2011000100006>
- Soares ACP, Noce CM, Trow R, et al (2002) Projeto Sul de Minas. COMIG-UFMG-UFRJ-UERJ
- Vargas KB (2017) Geomorphological surfaces in the north central Paraná and regional relief evolution. Ph.D. thesis, Centro de Ciências Humanas, Letras e Artes, Universidade Estadual de Maringá
- Zalan PV, Oliveira JAB (2005) Origin and structural evolution of the Cenozoic Rift System of Southeastern Brazil *Boletim de Geociências da Petrobrás* 13(2): 269–300