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The endorheic – Exorheic transition and later stage of fluvial incision in a wet tropical margin setting: The Atlantic draining Paraíba do Sul River basin (Brazil)

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ABSTRACT

Present-day endorheic drainage systems are rare in tropical humid regions and/or close to the coast. During the late Cenozoic, under a humid tropical climate, the Paraíba do Sul River basin (SE Brazil) has developed along the South America passive margin. This basin currently drains into the South Atlantic Ocean, but it preserves landforms that are indicative of previous endorheic paleodrainage. This study examines the possibility that this region was endorheic for most of the Neogene, prior to the establishment of the present-day drainage to the Atlantic and discusses the transition from an endorheic to an exorheic system. Data was obtained through analysis of geomorphological features identified by remote-sensing techniques and verified by fieldwork, as well as the interpretation of landscape evolution models elaborated by the Seppômen method. Five drainage convergence areas and possible endorheic paleobasins, previous to the Quaternary (or to the Pliocene) have been identified within the present-day Paraíba do Sul River basin. Each area is associated with a Cenozoic graben and is separated by structural highs which would have formed paleodrainage divides. The mechanism for the transition endorheic-exorheic is the overspill, the inland regressive erosion or, more probable, a combination between these two processes. In fact, these two processes often occur concomitantly and both contribute to the same result: the expansion of an exorheic basin by the incision of a permanent channel into the endorheic basin infill. The geological evolution of the ancestral Paraíba do Sul River, draining to the Atlantic Ocean, was later strongly controlled by the very low sea levels during the Quaternary which determined the stage of fluvial incision. No numerical dating has been yet obtained for the proposed endorheic-exorheic transition; nonetheless, published regional denudation rates suggest that this transition occurred sometime in the interval between 21 and 5 Ma (Miocene to Pliocene). This transition was controlled by a previous decrease in subsidence within the aforementioned grabens and by a much wetter climate that promoted overspill and connection to the Atlantic.

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1. Introduction

Endorheic basins generally occur in intramontane regions, quite far away from the coast, where tectonic activity and/or low precipitation (arid or semi-arid climates) hinders an exorheic organization of the drainage systems (Sobel et al., 2003). Thus, for passive margins such as the Atlantic South America, a dry climate is considered essential for the occurrence of this type of drainage system (Nichols, 2007).

In fact, nowadays there are no current endorheic basins along the tropical and humid subtropical passive margin of South America. Nonetheless, the Paraíba do Sul River basin (SE Brazil) displays geomorphic characteristics that are indicative of previous endorheic paleodrainages (Paixão et al., 2020; Negrão et al., 2020). However, the literature concerning the evolution of rivers in South America is very limited.

In recent years, several studies have been published suggesting that many present-day, exorheic basins were previously endorheic (e.g., Cunha et al., 1993, 2019; Pingel et al., 2013; Soria-Jáuregui et al., 2018; Antón et al., 2018; Cunha, 2019; Struth et al., 2019; Bridgland et al., 2020). Different mechanisms have been proposed for triggering the fluvial incision that drives the transition of a basin from endorheic to exorheic conditions, namely river capture/piracy (Craddock et al., 2010; Antón et al., 2014; Vacherat et al., 2018), spillover (Heidarzadeh et al., 2017; Cunha et al., 2019), antecedence or superimposition (Douglass et al., 2009). Overspill occurs when a basin fills with sediment and water and breaches the lowest hard rock sill (outlet of the basin) leading to river incision upstream from this point. This process of fluvial incision can lead to a final morphology similar as that resulting from a lowering of the sea level of an exorheic system (Struth et al., 2019). Fluvial incision can be triggered by tectonic uplift, by climate change (to a wetter climate) or by the lowering of the base level; either individually or through these factors acting in concert.

There are relatively few studies of drainage rearrangements in the humid tropical and subtropical regions of the South America's passive margin (e.g. Ab'Saber, 1957; Cherem et al., 2012; Salgado et al., 2014, 2016; Sordi et al., 2018; Souza et al., 2021). The principal objective of these studies was to understand the importance of river capture processes leading to escarpment retreat in a passive margin. They showed that over time the Atlantic-draining rivers of the South America passive margin have pirated areas from interior drainage basins which has led to an inland retreat of the coastal escarpments/hydrographic divides, namely the Serra do Mar and Serra da Mantiqueira. Nonetheless, none of these previous studies have investigated the possibility of previous endorheic paleodrainages, under tropical climates, in this passive margin. In the study area, significant tectonic activity during the Cenozoic led to the formation of a system of failed continental rifts along part of this margin which are collectively known as the Continental Rift of Southeast Brazil (CRSB - Riccomini, 1989; Riccomini et al., 2004; Zalán and Oliveira, 2005; Heilbron et al., 2016; Negrão et al., 2020). The CRSB is currently drained by the Paraíba do Sul River; however, despite its proximity to the Atlantic Ocean (~100 km) the tectonic setting is favourable to the formation of endorheic basins. Indeed, it is the lack of previous studies carried in the area that prompts this research. To understand the long-term landscape evolution of the present-day, Paraíba do Sul River basin, we will investigate the hypothesis of endorheic conditions within this region prior to the current exorheic conditions. The mechanisms by which a transition from an endorheic to exorheic system took place will also be discussed. Morphological evidence has provided a basis for understanding the endorheic – exorheic transition of a very large area leading to transcontinental drainage to the Atlantic Ocean. The investigation of evidence from this area is thus of considerable value for understanding the controls on the formation of endorheic basins in a passive margin setting.

The results of an analysis of the drainage network including morphological and morphometric characteristics, support the hypothesis that part of the Paraíba do Sul River basin underwent a transition from an endorheic to exorheic system at the end of the Neogene by the successive incorporation of endorheic sub-basins. Extensive fieldwork over the very large study area underpins the data and interpretations made. Given that the sub-basins (grabens of the CRSB) only preserve Eocene sediments, this hypothesis is for now only supported by morphological observations and interpretations. That is, we searched by remote sensing and fieldwork, drainage anomalies and morphological evidences that prove that the Paraíba do Sul River basin had endorheic paleo sub-basins from the late Cretaceous to, probably, the middle-Pliocene.

2. Geological and geographical characteristics of the study area

The Paraíba do Sul hydrographic basin is located at SE Brazil, extends for some 1,100 km and covers a total area of 61,570 km^2 (Fig. 1). For most of its length the Paraíba do Sul River flows through an intermontane plateau of hills (*Mares de morro*) that comprises the "floor" of a series of aligned grabens that form part of the CRSB. Most of the tributaries of the Paraíba do Sul River drain the prominent scarps formed by the horsts that bound the CRSB. To the SE of the main river valley is the Serra do Mar (Bocaina and Orgãos ranges) that reaches elevations of nearly 2300 m, whilst in the NW lies the Serra da Mantiqueira which contains peaks with altitudes higher than 2700 m. The main structure of the CRSB is thought to have developed between 60 and 35 Ma (Paleocene and Eocene); however, faults and distensive joints evidence that some tectonic activity persisted through to at least the end of the Pliocene (Riccomini et al., 2004; Negrão et al., 2020).

The Paraíba do Sul River basin is underlain by lithologies of the Ribeira Belt, one of several mobile belts formed during the Late Neoproterozoic–Cambrian/Ordovician, Brasiliano/Pan-African Orogeny which led to the amalgamation of western Gondwana (Heilbron et al., 2000). The geology of this mobile belt is complex but in simple terms it consists of a series of high-grade metamorphic terranes which includes granulites and both ortho- and paragneisses with a principal NE trending foliation; it was intruded by pre-, syn- and post-collisional magmatic bodies. The principal foliation forms an axial plane foliation to the majority of folds in the Ribeira Belt, which is also characterised by reverse faulting and ductile shear zones with evidence for multiple phases of deformation (Heilbron et al., 2016).

From the Eocene to the end of Miocene, the CRSB was structurally developed within the Neoproterozoic basement and several sedimentary formations were placed within the depocentres of its various grabens; these grabens formed endorheic basins with sedimentation in anastomosing rivers and lacustrine systems (Ramos et al., 2006). The morphology of the Paraíba do Sul River valley reflects the geological history of the region with a wide river valley within the grabens but steep-sided, narrow valleys and gorges found where the river crosses the structural highs between grabens.

At present, most of the river valley has a wet tropical climate whilst a humid subtropical climate prevails in elevated areas of the surrounding ranges/scarps (horsts). Precipitation is relatively well distributed throughout the year with an average annual precipitation of nearly 2500 mm due to the orographic rains caused by Serra da Mantiqueira and Serra do Mar (Sant'anna Neto, 2005). The present-day climate favours the development of a dense tropical forest - the Atlantic Forest; however, since the 19th century much of the natural vegetation has been cleared along the Paraíba do Sul River valley to make way for cultivated and grazing land. It is worth noting that Brazil's south-eastern plateau experienced several climate changes throughout the Quaternary, with drier and colder periods, interspersed with hotter and more humid periods (Barros and Magalães, 2020).

3. Materials and methods

The central valley of the Paraíba do Sul River basin was mapped in detail from the coastal river plain to the mountainous areas at its

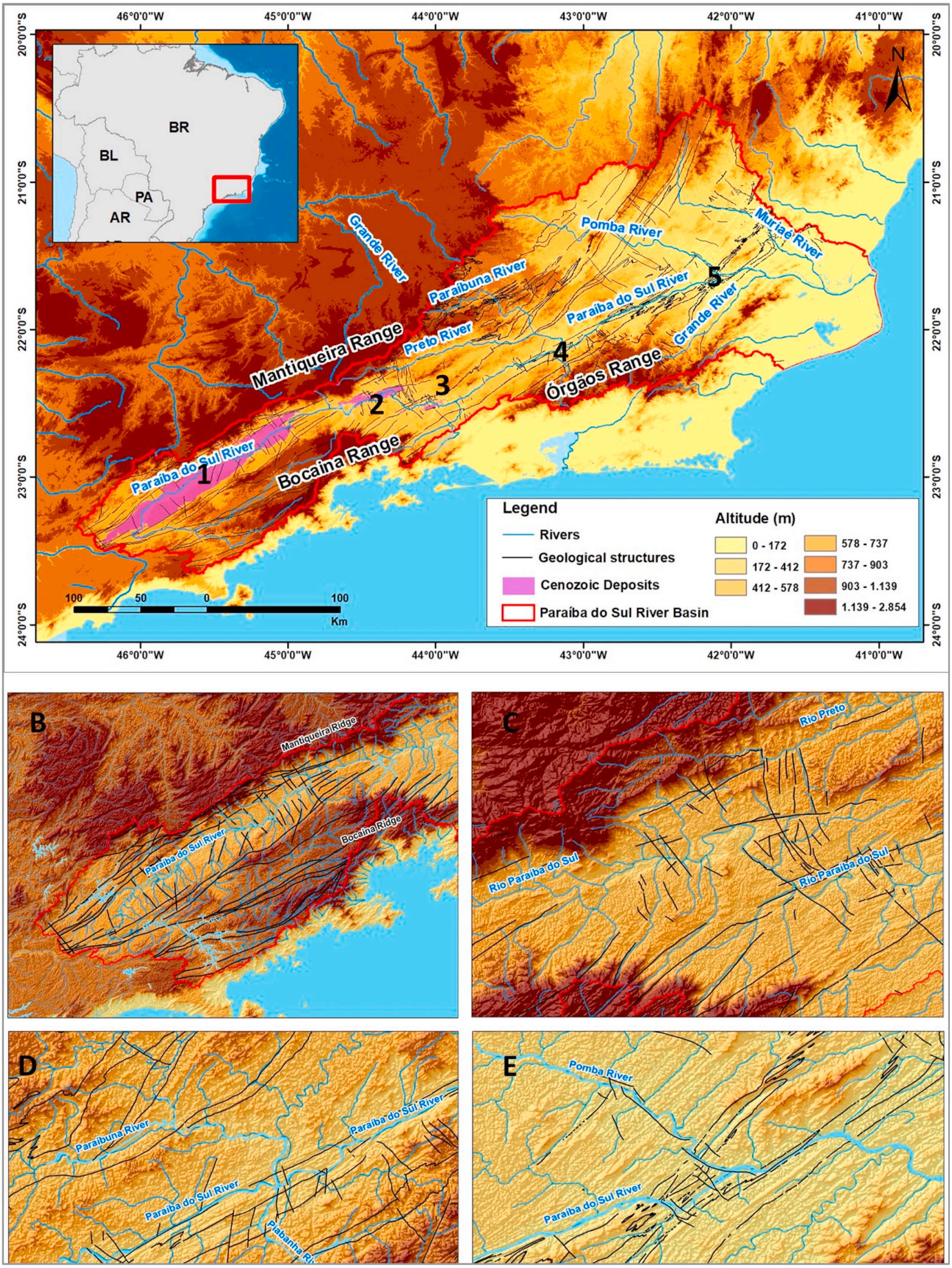

Fig. 1. A) Digital elevation model of the region showing the location of Paraíba do Sul hydrographic basin. Grabens in the region: B) – Taubaté (1); C – Resende (2)/ Volta Redonda (3); D - Três Rios (4); E – Itaocara (5). Modified: Paixão et al. (2020).

headwaters; with a focus on the structural highs that separate the grabens of the CRSB and the series of open valleys where drainage convergence was identified. Field work was conducted with focus on morphological evidence related to drainage system. As part of the fieldwork, converging drainage areas were identified, characterised and mapped. A Digital Elevation Model (DEM) and other derived maps of the study area were developed using processed SRTM radar images (Shuttle Radar Topography Mission) with spatial resolution of 30 m from the TOPODATA project (Valeriano and Rossetti, 2012). A shaded relief map was generated from the DEM using the Hillshade tool in ArcGIS 10.5 and with illumination from the northwest at 45°. Altimetry and derived morphological and morphometric data were extracted from the SRTM, with a focus on identifying drainage anomalies and narrowing of river valleys in topographic profiles. The spatial distribution of the drainage network within the Paraíba do Sul basin was characterised, that is their orientation, organization and relative equilibrium was described.

The focus was placed on the identification of centripetal drainage patterns, which is where drainages converge towards the centre of a region with flow directions often opposing that of the principal drainage. Such patterns are considered evidence of prior endorheic drainage systems. Transverse topographic profiles were traced across the Paraíba do Sul River in order to allow morphological analysis of changes in relief along the river valley and to understand the formation of gorges.

Paleotopographic maps were generated in order to show the topographic relief of the study area prior to fluvial dissection (stage of fluvial incision) by the Paraíba do Sul River. Different procedures were used to prepare the topographic maps, following Antón et al. (2018). However, in this study, the Seppômen routine (Motoki et al., 2008) was chosen to reconstruct the topography, as it enables the generation of paleotopographic maps for large regions through geoprocessing and data interpolation methods. Its limitations are associated with the cell size defined, being unable to detail the topography more than its cell size. These maps were generated using the Seppômen methodology developed by Motoki et al. (2008) which is based on a valley fill technique involving the interpolation in a GIS environment of the maximum elevation values in a DEM through the use a sampling grid with a specified cell size (Couto et al., 2012). The cell size used has a direct influence on the obtained results; with larger cell sizes resulting in greater valley fill representative of moments in times further in the past, whilst smaller cell sizes generate maps that reflect the paleotopography closer to the present-day (Marques Neto et al., 2019). Paleotopographic maps were generated for the study area using different cell size: 5 × 5 km, 4 × 4 km, 3 × 3 km, 2 × 2 km and 1 × 1 km. These maps allowed the identification of topographical depressions along the intermontane plateau which are evidence of past endorheic systems. The volume of material eroded from paleotopographic data was estimated subtracting the current topographic surface (DEM) and paleosurfaces shown in the Seppômen map that was generated using a 5 × 5 km cell size (vol. = DEM surf. – Paleotopographic xn), pixel by pixel. The total eroded volume calculated was divided by the Paraíba do Sul catchment area to obtain the mean denudation depth in meters. By dividing the inferred average denudation depth by the average erosion rates (Table 1) for the Paraíba do Sul River valley determined by Cherem et al. (2012), Rezende et al. (2013), and Salgado et al. (2016); the time between the two moments was estimated by comparing the 5 × 5km estimated paleotopography and the present day relief. The papers by Cherem et al. (2012), Rezende et al. (2013) and Salgado et al. (2016) measured denudation rates in three different basin sectors of the two horsts of Paraíba do Sul River. Considering: (1) the reliability of the long-term denudation rates obtained by 10Be cosmogenic nuclides and; (2) the good distribution and the high number of the samples (22 samples); we consider these three papers as a good basis for trying to calculate the age of the transition (endorheic/exoreic). We also estimated the maximum and minimum age for this transition using the two extremes values for denudation rates calculated by the cited authors. Finally, fieldwork focused on the characterization of slope morphology and of river terraces and alluvial plains along the Paraíba do Sul River valley.

Table 1
Erosion rates used to calculate the probable age for the endorheic–exoreic transition.

Catchment (Range) (Fig. 1)	Paper	Erosion Rates
Pomba River (North Mantiqueira Range)	Cherem et al. (2012)	20.1 ± 0.2
Pomba River (North Mantiqueira Range)	Cherem et al. (2012)	23.1 ± 0.3
Pomba River (North Mantiqueira Range)	Cherem et al. (2012)	17.8 ± 0.3
Pomba River (North Mantiqueira Range)	Cherem et al. (2012)	14.4 ± 0.2
Pomba River (North Mantiqueira Range)	Cherem et al. (2012)	15.2 ± 0.1
Pomba River (North Mantiqueira Range)	Cherem et al. (2012)	12.8 ± 0.1
Preto River (Central Mantiqueira Range)	Rezende et al. (2013)	26.5 ± 0.8
Preto River (Central Mantiqueira Range)	Rezende et al. (2013)	12.9 ± 0.4
Preto River (Central Mantiqueira Range)	Rezende et al. (2013)	18.1 ± 0.6
Preto River (Central Mantiqueira Range)	Rezende et al. (2013)	12.1 ± 0.5
Preto River (Central Mantiqueira Range)	Salgado et al. (2016)	29.4 ± 0.9
Preto River (Central Mantiqueira Range)	Salgado et al. (2016)	12.9 ± 0.4
Preto River (Central Mantiqueira Range)	Salgado et al. (2016)	19.7 ± 0.6
Preto River (Central Mantiqueira Range)	Salgado et al. (2016)	18.9 ± 0.6
Preto River (Central Mantiqueira Range)	Salgado et al. (2016)	15.2 ± 0.5
Preto River (Central Mantiqueira Range)	Salgado et al. (2016)	26.8 ± 1.9
Preto River (Central Mantiqueira Range)	Salgado et al. (2016)	23.3 ± 1.8
Rivers that drain to Rezende Graben (North Bocaina Range)	Salgado et al. (2016)	27.4 ± 1.6
Rivers that drain to Rezende Graben (North Bocaina Range)	Salgado et al. (2016)	22.3 ± 1.4
Rivers that drain to Rezende Graben (North Bocaina Range)	Salgado et al. (2016)	22.9 ± 1.3
Rivers that drain to Rezende Graben (North Bocaina Range)	Salgado et al. (2016)	21.4 ± 2.4
Rivers that drain to Rezende Graben (North Bocaina Range)	Salgado et al. (2016)	22.3 ± 1.1
Springs of the Paraíba do Sul River (Central Bocaina Range)	Salgado et al. (2016)	7.7 ± 0.2
Springs of the Paraíba do Sul River (Central Bocaina Range)	Salgado et al. (2016)	6.7 ± 0.2
Springs of the Paraíba do Sul River (Central Bocaina Range)	Salgado et al. (2016)	12.3 ± 0.4
Springs of the Paraíba do Sul River (Central Bocaina Range)	Salgado et al. (2016)	8.7 ± 0.3
Springs of the Paraíba do Sul River (Central Bocaina Range)	Salgado et al. (2016)	10.7 ± 0.4

4. Results

4.1. Geomorphological analysis

Several gorges and narrowing reaches of the river valley can be observed along the course of the Paraíba do Sul River. Expressive areas of convergent drainages and low relief can be found directly upstream of these gorges and “narrows” (Fig. 2); and tributaries of the Paraíba do Sul River are contained within wide valleys. Field observations in these areas reveal a morphology of open valleys with low altitudinal range, characterised by rounded hills. A number of these secondary drainages

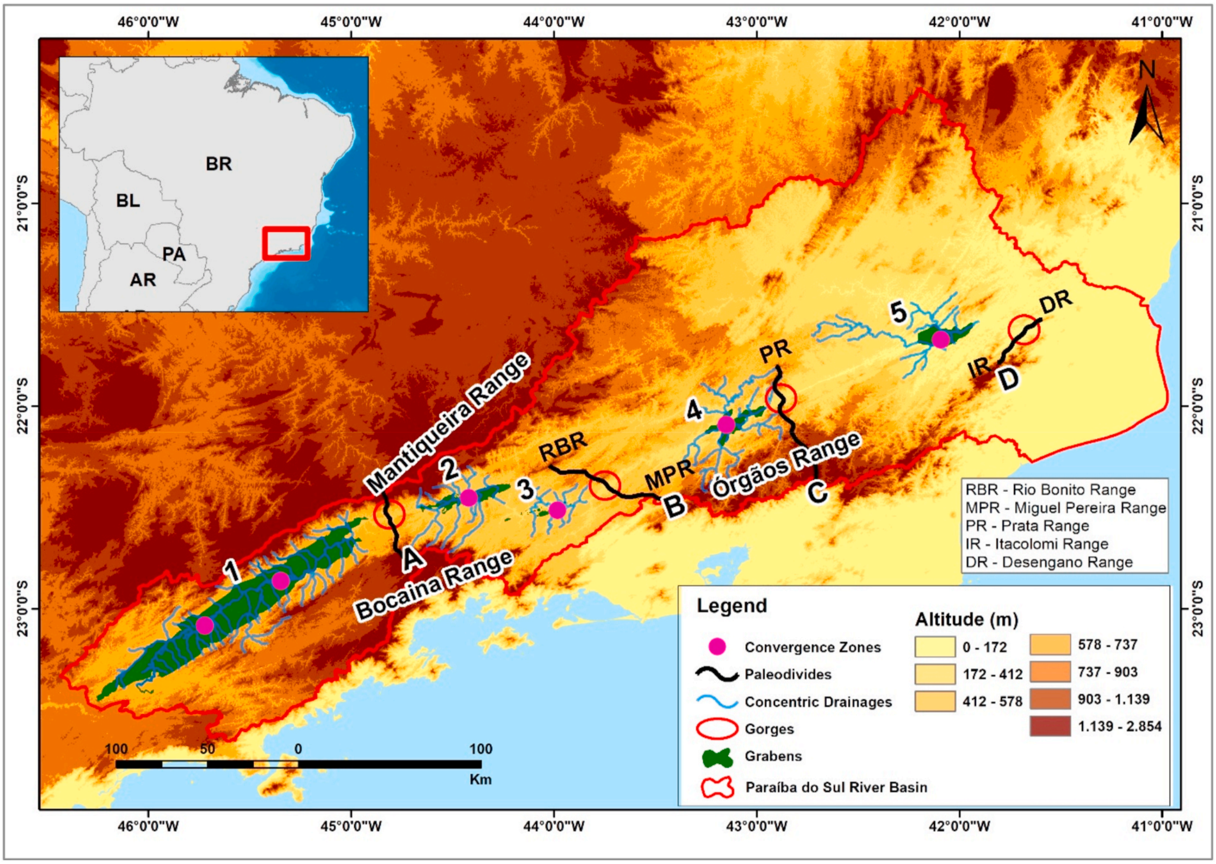

Fig. 2. Hydrographic basin of the Paraíba do Sul River showing the location of areas with convergent drainage patterns, paleodivides and gorges. Convergent drainage areas: 1. Taubaté; 2. Resende; 3. Volta Redonda; 4. Três Rios; 5. Itaocara. Paleodivides with transversal topographic profiles given in Fig. 3: A - Queluz; B - Miguel Pereira; C - Sapucaia; D - Desengano. Modified: Paixão et al. (2020).

flow in the opposite direction to the Paraíba do Sul River and drain into depocentres or sub-basins which correspond to grabens of the CRBS, which defines the regional depression along which the Paraíba do Sul River flows. The structural highs that separate these grabens coincide with the gorges and "narrows" of the Paraíba do Sul River (Fig. 2). In field surveys changes in morphology were noted, in which the main valley of Paraíba do Sul River transitions into a narrower valley with steep slopes within almost mountainous relief.

The areas displaying convergent drainage are characterised by centripetal patterns and are located within grabens with structural highs separating them from other rift basins. The Paraíba do Sul currently connects all of the paleobasins to form the current exorheic, hydrographic basin. Five sections along the Paraíba do Sul display these characteristics: 1 - Taubaté; 2 - Resende; 3 - Volta Redonda; 4 - Três Rios; 5 - Itaocara (Fig. 2).

Topographic profiles across narrow sections of the Paraíba do Sul River valley are shown in Fig. 3. Fluvial incision has led to a formation of narrow gorges in several locations as show in profiles C and D. Both profiles display significant differences in elevation between the river bed and the tops of the surrounding slopes, namely 600 m and 400 m for profiles C and D, respectively. Whilst the river valley is not as steeply sided in profiles A and B (Fig. 3), it is still narrower than where the Paraíba do Sul River flows through the grabens which display convergent drainage patterns (Fig. 2).

4.2. Seppômen paleotopography maps

The Seppômen map generated using a 5 km cell size represented the oldest "snapshot" of the area currently occupied by the Paraíba do Sul drainage basin. The paleotopography was strongly controlled by faulting related to the formation of the CRSB (Fig. 4A) and the region contained a number of small endorheic basins with drainages convergent on the depocentres of the aforementioned grabens: 1 - Taubaté, 2 - Resende, 3 - Volta Redonda, 4 - Três Rios and 5 -Itaocara (Figs. 2 and 4). Landscape evolution by fluvial dissection was simulated through a reduction in the cell size used to generate successive paleotopography maps of the study area (Fig. 4B, C, D and E). It was observed that despite this (ongoing) fluvial dissection the five areas (grabens) have maintained their convergent drainage patterns through to the present day (Figs. 2 and 4). The series of Seppômen maps shows that continued headward erosion by the Paraíba do Sul River lead to repeated drainage capture through the breaching of the topographic divides between grabens and the incorporation of each successive endorheic system into the ever expanding exorheic drainage basin (Fig. 4). These maps also demonstrate that as fluvial incision and dissection advanced upstream from the Atlantic, prominent valleys in the areas of convergent drainages were widened (Fig. 4).

The longitudinal profile of the present-day Paraíba do Sul River can be compared with the paleotopography along the same profile at moment "A" as per the Seppômen map generated using a cell size of 5 × 5 km (Fig. 5). The paleotopographic profile shows the presence of several structural high such as at Queluz and Sapucaia (Fig. 5) which have previously been described in the text and are also shown in Figs. 2–5. These structural highs had a strong influence on past drainage patterns within region (Fig. 4). This structurally controlled drainage pattern was later modified by the ongoing development of the exorheic Paraíba do Sul hydrographic basin (Figs. 2, 4 and 5).

Volumetric estimates of landscape dissection based on the Seppômen paleotopographic map that was generated using a cell size of 5 × 5 km suggest that a total volume of ~7340 km^3 was removed from across the

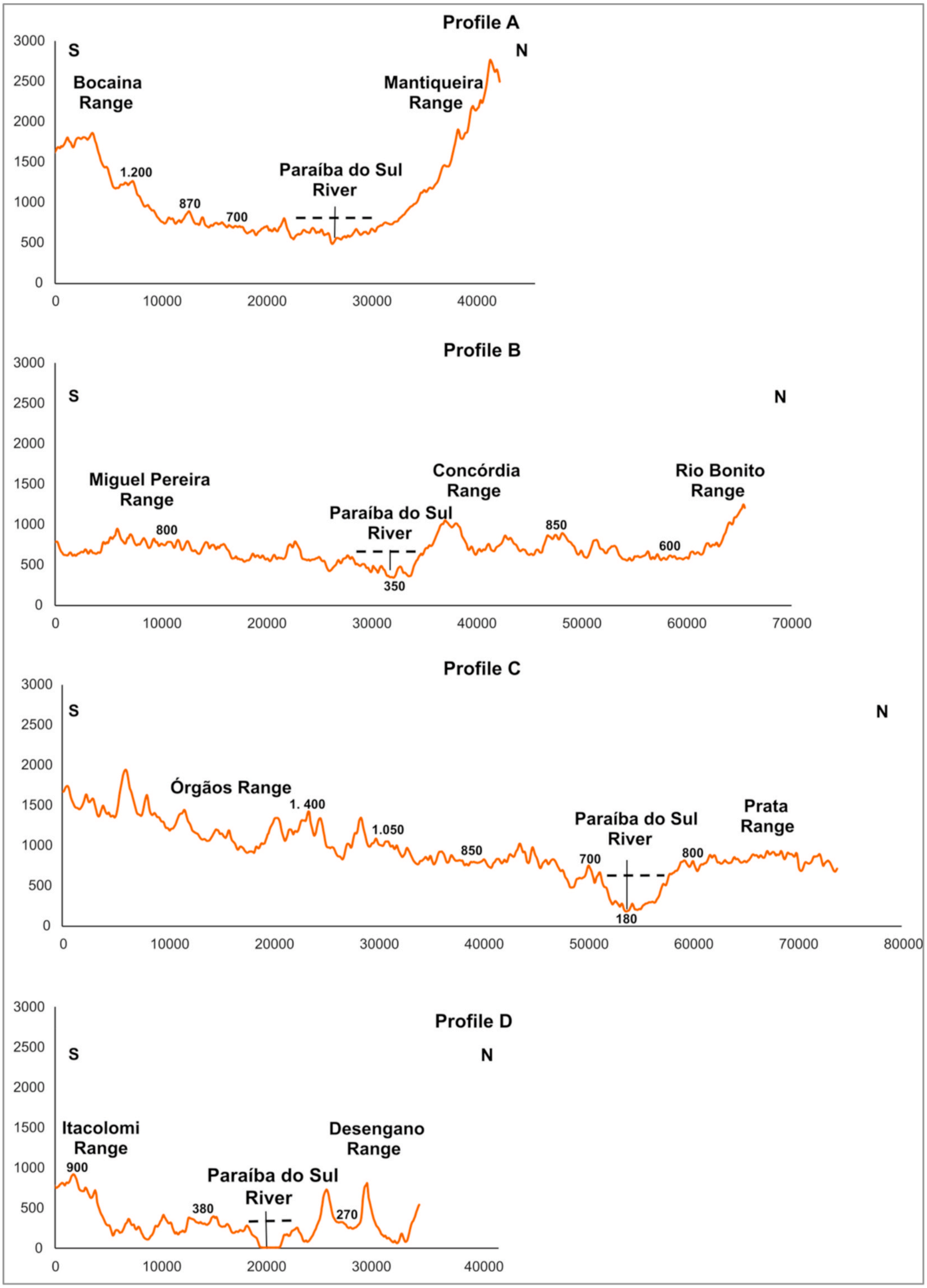

Fig. 3. Transversal topographic profiles across narrow sections of the Paraíba do Sul River valley. The dashed lines indicate the likely elevation of paleodivides between possible endorheic paleobasins which equate to areas of convergent drainages. The locations of the profiles are shown in Fig. 2.

current extent of Paraíba do Sul drainage basin (an area of 61,570 km^2). It is calculated that approximately 141.6 m' depth per km^2 was denuded from the Paraíba do Sul River basin. According to the denudation rates obtained by cosmogenic isotope Beryllium-10 (10Be) mentioned in Table 1, the average value for the study area is 18 m/Ma, while the maximum value is 29.4 m/Ma and the lowest value is 6.7 m/Ma. Based on denudation rates and the volumetric erosion values of the Paraíba do Sul River Basin, it is estimated that the mean required duration of denudation is approximately 7.9 Ma, and may vary between 5 Ma and 21 Ma, for the highest and lowest denudation rate respectively. Considering these estimated ages for denudation of Paraíba do Sul River Basil, it is assumed that the endorheic-exorheic transition occurred at Pliocene-Pleistocene transition.

5. Discussion

The Paraíba do Sul River basin has a segmented nature; with the principal drainage alternating between flowing within steep-sided

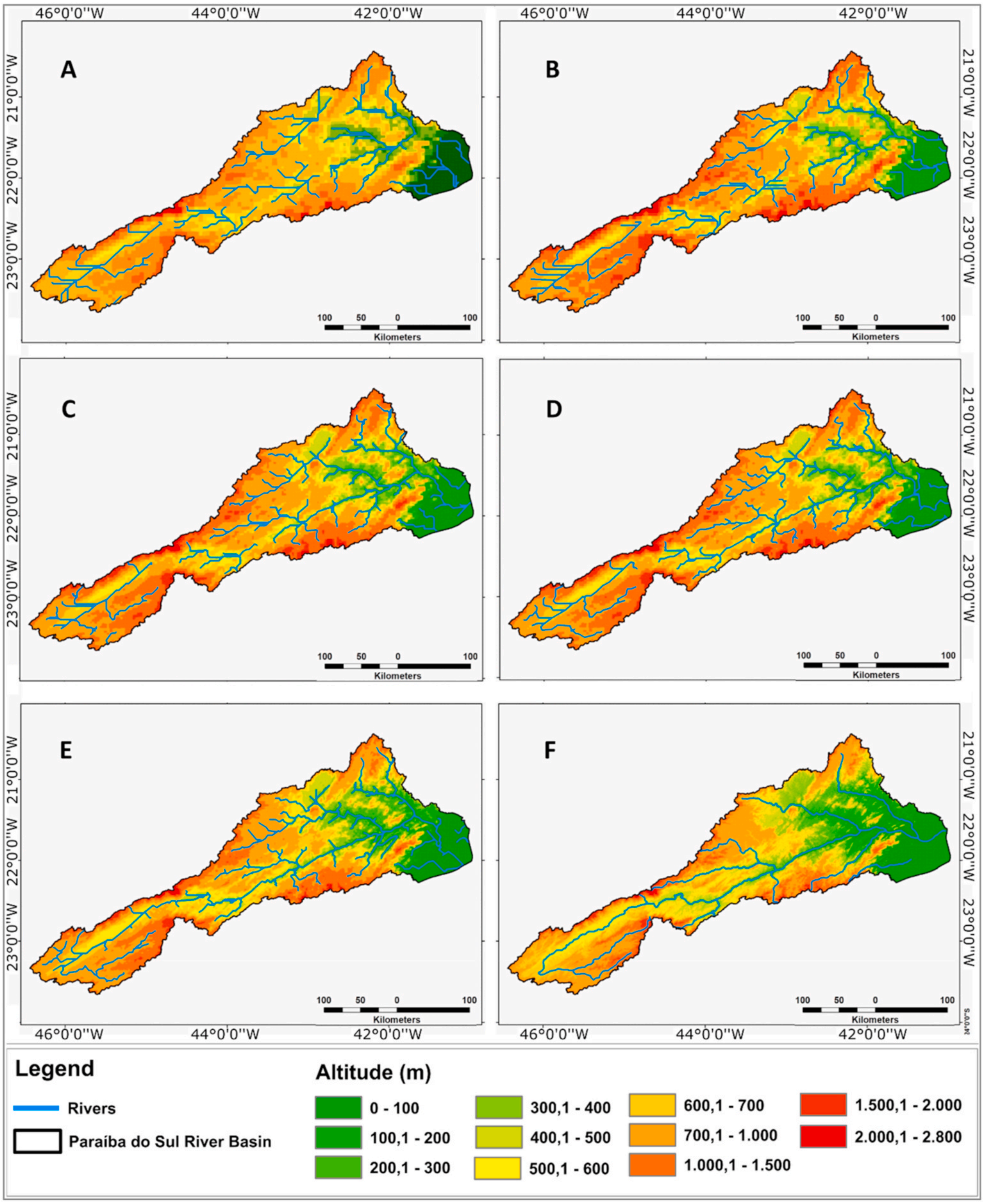

Fig. 4. Paleotopographic (Seppômen) maps of the Paraíba do Sul River basin generated using varying cell sizes (km): A - 5 × 5; B - 4 × 4; C - 3 × 3; D - 2 × 2; E – 1 × 1; F -Present-day relief (DEM).

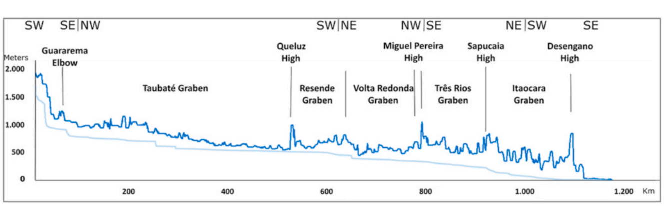

Fig. 5. Longitudinal profile (pale blue) of the Paraíba do Sul River showing the location of grabens and structural highs of the CRSB. The dark blue lines shows the paleotopography along the same profile extracted from the Seppômen map that was generated using a 5 × 5 km cell size. This profile shows the estimated paleo-relief that separated the different grabens into enclosed areas of convergent drainages.

valleys/gorges to passing through broad river valleys with low surrounding relief and convergent drainage patterns (Fig. 2). This is typical of a drainage that developed through the incorporation of endorheic paleobasins (Fig. 4).

Some tributaries within these paleobasins often flow in directions opposite to that of the ENE-flowing Paraíba do Sul River. Other drainages display abrupt inflections (elbows) in their channels, evidence of river capture events. Elevated river terraces and active gully erosion of old valley floors can also be seen in the areas of convergent drainages demonstrating recent changes in the local base level (Figs. 6 and 7). Some tributaries of the Paraíba do Sul River descend steeply from plateaus adjacent to the main river valley by a series of rapids and waterfalls in their final stretches before flowing into the principal drainage in the vicinity of gorges along the latter (Fig. 6e).

These aforementioned landforms are associated with past deposition centres within the grabens. Subsidence within these grabens during the Neogene and periods of drier climate (Ledru et al., 2005), favoured the development of endorheic basins. Despite the limited sedimentary record; the centripetal drainage patterns within the grabens and the structural framework of the grabens (Riccomini, 1989; Riccomini et al., 2004; Zalán and Oliveira, 2005) support the hypothesis that each of the

Fig. 6. (a) and (b) Large gullies within the Paraíba do Sul River basin; this accelerated erosion is a response to the lowering of the regional base level. **(c) and (d).** Elevated river terraces, suspended above the level of the current floodplain are evidence of fluvial incision. Detail of stratigraphic section in one such river terrace demonstrates the highly dynamic nature of fluvial systems with alternance between high- and low-energy conditions. **(e)** Extensive floodplain of the Paraíba do Sul River and low surrounding relief within the Resende graben. **(f)** Detail of rapids (knickpoint) in the final stretches of the Pirapetinga River before it converges with the Paraíba do Sul River close to the Itaocara graben.

identified areas within the Paraíba do Sul River basin were endorheic in the past.

As such the structural highs that separate the grabens of the CRSB and currently feature gorges and steep-sided valleys along the course of the Paraíba do Sul River; constituted hydrographic divides between the endorheic paleo sub-basins (Figs. 2 and 4). Cenozoic sediments preserved in the Resende (2) and Volta Redonda (3) paleobasins display sedimentary features consistent with deposition in an alluvial environment. This supports the hypothesis of isolated endorheic systems in each graben. As such basins are characterised by the inward flow of drainage and the subsequent accumulation of sediments and water in the lowest part of the landscape. In the case of the Taubaté (1), Resende (2) and Volta Redonda (3) basins this led to the deposition of sediments in a lacustrine environment.

According to the interpretation of the evolution of successive headward erosion pulses in the Paraíba do Sul River basin, surfaces that result from dissection and sculpting of relief at different tectono-stratigraphic stages generated different surface at different times (Fig. 7). The understanding of these evolutionary processes permits ascription of the problabe age of these surfaces, because each evolutionary stage corresponds to a specific base level within the drainage network. During the Cretaceous, before the tectonic events, the drainage system flowed into the interior of Brazil and the drainage system sculptured an extensive surface related to the ancient sea level of Paraná Basin. The beginning of rifting, which involved the entire SE passive margin, led to reorganization of the endorheic basins inside the graben systems, at a new base level. The erosional surface corresponding to this evolutionary stage probably dates from the Miocene to the Pliocene, because the sedimentary records of the Taubaté, Resende and Volta Redonda Basin are from this age. The final process is related to the capture of Paraíba do Sul drainage system by the Atlantic Ocean drainage, which occurred through erosive headward pulses related to the different sea levels. In this respect, a map has been generated that illustrates the phases of evolution (Fig. 7), based on morphological evidence. The highest surface corresponds to a moment in the Cretaceous period relative to a topography remaining from the dissection process of a hydrographic system that drained into the interior of the continent, long before the opening of the Atlantic Ocean. The Paleocene/Eocene to Miocene surfaces correspond to sedimentary filling events in the endorheic basins. The probable Late Pliocene to early Pleistocene surfaces records the transition of endorheic-exorheic drainage and the formation of a major river draining to the Atlantic. Finally, the middle-late Pleistocene to Holocene surfaces record the stage of fluvial incision, mainly determined by the low base levels of the Atlantic Ocean.

As previously discussed, these endorheic basins developed as the direct result of the tectonically controlled topography of the CRSB. It should be noted that this rift system is poorly studied east of the Volta Redonda basin (3); in the downstream portion of the Paraíba do Sul River basin (Zalán and Oliveira, 2005). This portion of the hydrographic basin contains two areas of convergent drainages at Três Rios (4) and Itaocara (5). The latter area has been described as the Itaocara graben which is characterised by a rhombic system of NE-SW and NW-SE trending faults and fractures (Tupinambá et al., 2003). The convergent drainage areas at Três Rios have not been characterised as a graben, but this area has the most well-developed centripetal drainage pattern of the Paraíba do Sul basin.

The structurally controlled topography of the CRSB with structural highs and grabens led to the development of isolated endorheic drainage basins which are preserved today as convergent drainage systems. Over time the region's predominantly endorheic drainage systems were

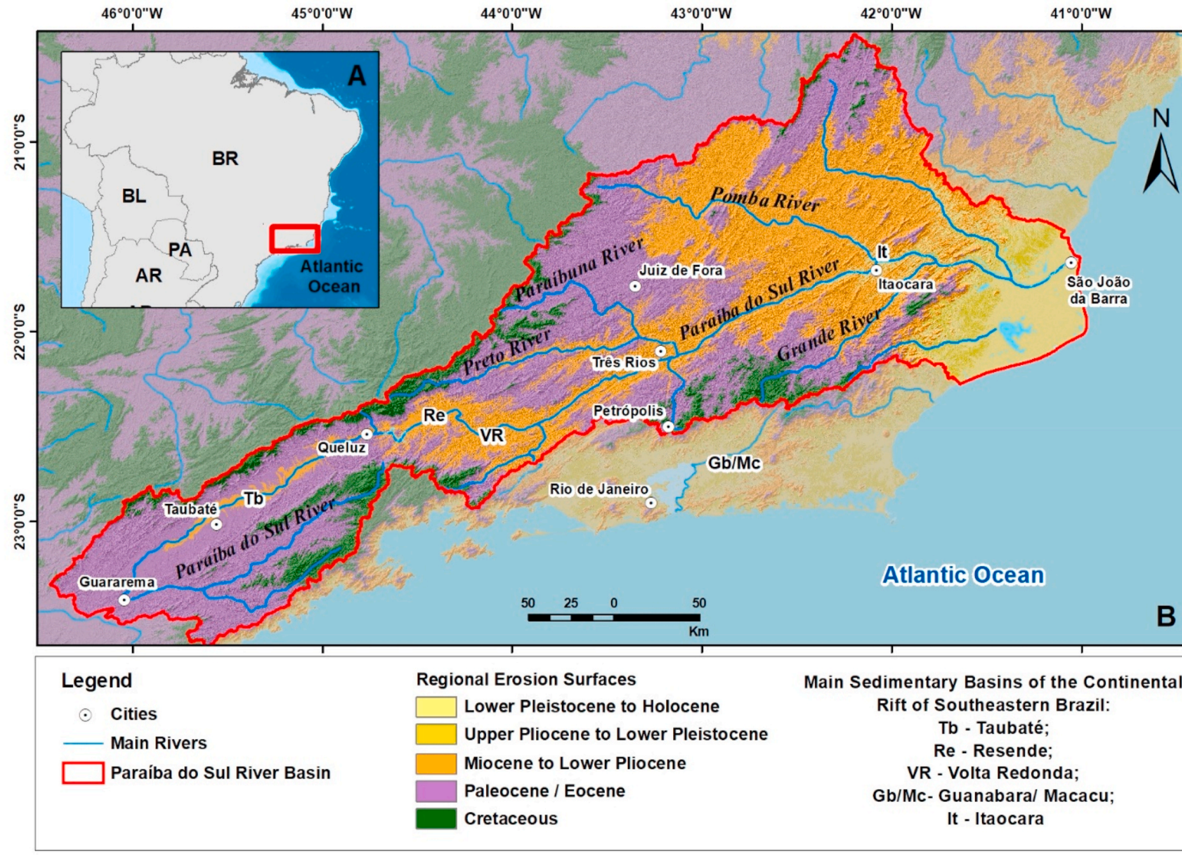

Fig. 7. Regional erosion surfaces in Paraíba do Sul River basin.

modified by headward erosion of the Paraíba do Sul River. This initially led to the breaching of the Desengano paleodivide (D) and subsequent capture of the endorheic, Itaocara paleobasin (Figs. 2 and 4B). Continued fluvial dissection resulted in the successive breaching of the Sapucaia (C), Miguel Pereira (B) and Queluz (A) paleodivides and associated capture of the Três Rios, Volta Redonda, Resende and Taubaté paleobasins respectively (Figs. 2, 4 and 5).

The most probable driving mechanism for the endorheic to exorheic drainage transition is by spillover/overflow across a paleodivide which can trigger fluvial incision downstream and accelerated headward erosion due to the abrupt change in the local base level. The Sapucaia paleodivide (C) is considerably higher than the Miguel Pereira (B) located further inland (Fig. 3). Hypothetical overflow from the endorheic Três Rios paleobasin (4) across the Sapucaia paleodivide would have led to greater fluvial incision across and downstream of this divide leading to the incorporation of the Três Rios paleobasin into the expanding exorheic system of the Paraíba do Sul River basin. Fluvial dissection and accelerated headward erosion would also have assisted with the successive capture of endorheic paleobasins further inland. This hypothesis is supported by the present extension of the Paraíba do Sul hydrographic basin, which is greater than 1000 km length. A long time is required for headward erosion to advance over such a distance; breach each of the paleodivides which are composed of resistant bedrock and capture all endorheic paleobasins.

Nonetheless, for a spillover event to occur the endorheic basin would need to be filled up with sediment and water and there is no sedimentary evidence for this to have been the case for the Três Rios paleobasin. The present-day gorges along the Paraíba do Sul River are evidence of thee paleodivides that separated the endorheic drainage systems. The erosion of these paleodivides and the overall fluvial dissection of the Paraíba do Sul River valley is controlled to a large extent by geological structures such as faults, fracture sets and foliation. The gorges are characterised by knickpoints with rock outcrops forming rapids and waterfalls (Fig. 6f) along the course of the river. The knickpoints manifest as abrupt changes in channel slope along the longitudinal profile of the Paraíba do Sul (Fig. 5). Steep-sided sections of the Paraíba do Sul often contain outcrops of basement within and along the margins of the active channel which is surrounded by elevated plateaus and dissected mountain ranges (Fig. 3). This current relief reflects the increased erosion caused by the abrupt change in base level that followed each successive breach of a paleodivide; by either overflow or headward erosion. Over time this led to capture of all of the endorheic paleobasins by the Atlantic-draining Paraíba do Sul River.

Based on the arguments presented above, we propose a new model of landscape evolution of the Paraíba do Sul drainage basin from the end of Neogene to the present day. The region was initially characterised by a series of grabens that contained small endorheic basins, with the western portion of the area containing headwaters of the Tietê River which drained inland towards the Paraná River (Figs. 1A and 4A).

The transition from an endorheic drainage to an exorheic Atlantic system maybe was driven by overflow (spillover) events (cascading) acting in conjunction with headward erosion by the ancestral Paraíba do Sul River. On its own, headward erosion underwent by a small Atlantic river can take several million years to erode through the resistant basement of the paleodivides in order to capture all the described endorheic paleobasins. On the other hand, a particularly humid climatic period would be necessary to fill up the endorheic paleobasins with water and sediments to the point of provoking an overflow event. The current phase of fluvial incision within the Paraíba do Sul River basin is being driven by the low base levels of the Atlantic Ocean during Quaternary which has resulted in significant headwater retreat and associated stream piracy.

The endorheic paleobasins developed within the aligned grabens of the CRSB which are separated from each other by structural highs.

However, the capture of these basins by the Atlantic-draining Paraíba do Sul drainage basin was influenced by older geological discontinuities (zones of weakness), namely shear zones as well as less resistant basement rocks, which have strongly controlled the general course of the Paraíba do Sul (Fig. 4 B, C and D.

The most recent drainage capture occurred inland of the Queluz structural high, where headward erosion by the Paraíba do Sul River led to the capture of headwaters of the Tiete River, which is an important tributary to the Paraná River (Ab'Saber, 1957). Headwater retreat in Paraíba do Sul drainage basin continues to advance towards the São Paulo graben and associated sedimentary basin.

Based on these denudation rates we suggest that the endorheic-exorheic transition occurred somewhere between 21 and 4 Ma. More probably it occurred between 7.9 and 5 Ma; i.e., in the Late Miocene or in the Pliocene. However, this age interval could be narrowed as climate records suggest that between ~4 and 3 Ma the study area experienced a much wetter climate (Haywood et al., 2016) which may have triggered perennial overflow as well as increasing regressive erosion and consequent fluvial piracy.

Reconstruction of drainage rearrangement that occurred in past times is not an easy task. Numerical models, such as those proposed by Forte and Whipple (2018), are in evidence, but are not applicable to this study, as they show only present and future trends and should not be used to reconstruct the past. In parallel, the humid tropical climate and the high erosive rates in the study area did not allow the preservation of sedimentary deposits. Therefore, the only available methods are remote sensing of morphological evidence and the use of Seppômen model. These two methods, although not conclusive and not allowing definition of the transition process, strongly indicate that the Paraíba do Sul River Basin was endorrheic until, at least, the late Miocene. The five drainage convergence areas, all associated with grabens and separated from each other by structural highs, cannot be explained by an exorheic drainage network. These are anomalies in the drainage network that, if they were only related to the tectonic formation of the RCSB, would no longer be preserved in the landscape. The comparison with the Seppômen model and the denudation rates seems to confirm this interpretation and show a probable transition between the Miocene and the Pliocene.

Considering our new perspective of late endorrheism in the Paraíba do Sul River Basin, there is clear potential for further research in the area. This would require new methods of analysis that would build on the ones used here. Previously, passive margins in humid tropics were understood as areas where drainage rearrangement only occurred as a consequence of escarpment recession, but our study shows that the phenomenon is much more complex.

6. Conclusions

The results of this study allow us to propose a new model for the morphogenesis of the Paraíba do Sul drainage basin: (1) the grabens of the CRSB defined a series of isolated, endorheic basins until the end of the Miocene or mid-Pliocene; (2) probably, by middle Pliocene an endorheic-exorheic transition occurred by successive captures that can have been driven by overflow/spillover from the endorheic paleobasins, followed by headward erosion by the ancestral Paraíba do Sul River or only by regressive erosion to inland; (3) the connection of these formerly isolated endorheic basins increased fluvial dissection and headward erosion; (4) probably by ~2 Ma, the Atlantic low sea levels during the Quaternary lead to the stage of fluvial incision, with periods of river deep down-cutting and regressive erosion advancing inland from the Atlantic Ocean, by successive erosion waves, further widening and expanding the Atlantic-draining Paraíba do Sul River basin.

It is likely that the main causes of the transition from an endorheic to an exorheic drainage were the decreasing subsidence in the CRBS grabens and a change to a much wetter climate during middle Pliocene. The later general lowering of the Atlantic base level during the Quaternary has also strongly increased headward erosion and subsequent drainage captures.

The Paraíba do Sul River basin advanced inland from the Atlantic coast by the successive captures of: the Itaocara (5), Três Rios (4), Volta Redonda (3) and Resende (2) paleobasins. These areas of convergent drainages lie to the east of the Queluz structural high and paleodivide, which prior to its breaching separated the drainage basins of the Paraíba do Sul and Paraná rivers. The Taubaté (2) paleobasin lies to the west and after it was incorporated into the Paraíba do Sul drainage basin, continued headward erosion leading to the capture of drainage areas further inland. In fact, the western limits of the Paraíba do Sul drainage basin includes the Guararema region; where the Paraíba do Sul River captured a significant drainage system which previously formed the headwaters to the Tiete River, a major tributary of the Paraná River (Fig. 1).

Considering that the study area has a tropical wet climate and is located less than 100 km from the coast along a passive margin, the results of this research suggest that river systems under humid tropical/subtropical climates in other passive margin settings may also have undergone similar endorheic-exorheic transitions at the end of the Neogene.

CRediT authorship contribution statement

Marcelo Motta de Freitas: Conceptualization, Formal analysis, Investigation, Resources, Project administration, Methodology, Writing – review & editing, Writing – original draft, Visualization, Supervision, Validation. **Rodrigo W. Paixão:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Data curation. **André A.R. Salgado:** Methodology, Investigation, Formal analysis, Data curation, Supervision, Writing – review & editing, Writing – original draft, Validation. **Luiz G. Eirado Silva:** Conceptualization, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. **Pedro P. Cunha:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Antonio A.T. Gomes:** Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **António A. Martins:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Julio C.H. Almeida:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Miguel A. Tupinambá:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Marcelo Dantas:** Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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