PALAEOSURFACE ANALYSIS ON THE CRETACEOUS BASALTIC PLATEAU ON THE UPPER RÍO URUGUAY BASIN (NE ARGENTINA AND SOUTHERN BRAZIL)

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ABSTRACT – First results of a geomorphological research on the Cretaceous basaltic plateau of the Upper Río Uruguay basin (NE Argentina and southern Brazil) are presented. DEM data from SRTM and field data were used for the morphometric analysis. Generation of hypsometric curves in five representative tributary basins of the Río Uruguay basin and also in one small basin tributary of the Río Paraná permitted to identify, classify and map the main Cenozoic palaeosurfaces of the plateau. Other morphometric parameters such as longitudinal profiles and isobase lines were produced also to delimit such surfaces. The identification of palaeosurfaces was extended on the Paraná and Uruguay rivers watershed in order to identify palaeosurface remnants and to correlate them to those described previously in southern Brazil. Palaeosurfaces 1 and 1b in this work are equivalent to King's "*Sul-American Surface"*. Both surfaces 1 and 1b (> 883 m a.s.l.) are well represented in the Río Pelotas sub-basin. If the Upper Río Uruguay basin corresponded to the lower segment of the palaeosurface, a predicted base level value would be estimated around 840 m a.s.l. The higher remnant surface of the plateau at the northeastern area of the province of Misiones (Argentina) is interpreted as Palaeosurface 2b (676-883 m a.s.l.). King´s *"Velhas Palaeosurface"* is correlated with Palaeosurface 2, which in Misiones comprises the plane-top watershed between the Paraná and Uruguay river basins (436- 676 m a.s.l.). This surface is widespread in the Upper Río Uruguay basin in Brazil and it is represented by a landscape of gentle and well rounded hills. The identified lower surfaces 3 and 4 correspond to the Apóstoles Surface (around 200 m a.s.l.), which would be generated by King´s *Paraguaçú cycle*, represented by valley incision.
Keywords: Morphometric analysis; palaeosurfaces; basaltic plateau; upper Río Uruguay basin; South America.

RESUMEN – *D. Kröhling, E. Brunetto, G. Galina, M.C. Zalazar - Análisis de paleosuperficies de la meseta basáltica cretácica de la alta cuenca del Río Uruguay (NE de Argentina y sur de Brasil).* Se presentan los primeros resultados de la investigación geomorfológica de la meseta basáltica cretácica de la alta cuenca del Río Uruguay (NE de Argentina y sur de Brasil). Modelos digitales de elevación SRTM y datos de campo fueron utilizados en el análisis morfométrico. La generación de curvas hipsométricas en cinco cuencas tributarias representativas de la cuenca del Río Uruguay y en una pequeña cuenca tributaria del Río Paraná permitieron identificar, clasificar y mapear las principales paleosuperficies cenozoicas de la meseta. Otros parámetros morfométricos tales como perfiles longitudinales y líneas de isobases fueron también producidos para delimitar dichas superficies. La identificación de paleosuperficies fue extendida a la divisoria de cuencas de los ríos Paraná y Uruguay a fin de identificar remanentes de superficies y correlacionarlas con aquellas descriptas previamente en el sur de Brasil. Las Paleosuperficies 1 y 1b en este trabajo son equivalentes a la *"Superficie Sul-Americana"* de King. Ambas Superficies 1 y 1b (> 883 m s.n.m.) están bien representadas en la subcuenca del Río Pelotas. Si la alta cuenca del Río Uruguay corresponde al segmento más bajo de la paleosuperficie, un nivel de base predictivo es estimado alrededor de los 840 m s.n.m. La superficie remanente de mayor cota de la meseta en el área noreste de la provincia de Misiones (Argentina) es interpretada como Paleosuperficie 2b (676-883 m s.n.m.). La "*Paleosuperficie Velhas"* definida por King se correlaciona con la Paleosuperficie 2, la que en Misiones comprende la divisoria plana entre las cuencas de los ríos Paraná y Uruguay (436-676 m s.n.m.). Esta superficie es amplia en la cuenca del Río Uruguay en Brasil y está representada por un paisaje de colinas bien redondeadas y de pendientes gentiles. Las superficies identificadas de menor cota 3 y 4 corresponden a la Superficie Apóstoles (ca. 200 m s.n.m.), las que habrían sido generadas durante el *ciclo Paraguaçú* de King, representado por la incisión de valles.
Palabras clave: análisis morfométrico; paleosuperficies; meseta basáltica; cuenca superior del Río Uruguay, América del Sur.

INTRODUCTION

Palaeosurfaces identification at a regional scale is useful on the analysis of the landscape evolution of basaltic plateaus and particularly on fluvial studies. According to Widdowson (1997), palaeosurfaces represent time intervals long enough for distinctive correlated features to develop, and must be distinguished among themselves by their descriptive attributes.

The break-up of the Gondwana supercontinent is represented by the Paraná continental basaltic flood province (the Serra Geral Formation). It was formed during the opening of the South Atlantic Ocean in the Early Cretaceous, covering more than 1.2 million km^2 in southern Brazil, northeastern Argentina and northern Uruguay, with maximum registered thickness of 1,700 m (Almeida, 1986). The Upper Río Uruguay basin (Río de la Plata basin) is developed on the basaltic plateau, forming part of the Southern Brazilian Plateau.

The region is under subtropical humid conditions, with mean annual temperatures between 19°C and 21°C and rainfall ranges between 1,700 and 2,200 mm/yr. The vegetation is represented by savanna and tropical forest. Taking in account the work of Ab'Sáber (2000), vegetation stocks closely related to the present inter- and subtropical vegetation were developed after Mid-Tertiary times. During the Quaternary, such floras fluctuated in space, controlled by successive climatic changes.

In general, the morphology of passive margins is related to intraplate tectonics and climate (mainly sea-level change). These margins would have been uplifted and remained elevated since their rift phase (Japsen et al., 2006). King (1956) interpreted the landscape evolution of the eastern South American passive margin by the interplay between long-term denudation and regional uplift. For many authors, King´s model has played a significant role in explaining tectonic activity (or their absence) and climate as both driving mechanisms of morphogenesis in passive margins (Bezerra et al., 2008).

First studies on palaeosurfaces in Brazil begun with the Davisian model (Davis, 1899) of concordant mountain tops for defining levels of erosion. Stepped systems of planation surfaces as a result of cyclic evolution related to the regional uplift induced by break-up of the Gondwana supercontinent were investigated by King (1956, 1967) in southern Brazil. King (1956) identified the *Gondwana Surface* (Upper Cretaceous), as a result of generalized planation. It is considered as the oldest surface of Brazil, occupying the highest position and exposed from the Cretaceous to the present times. All previous surfaces are exhumed or fossil. Following King (1956), the general landscape of Brazil is represented by a vast pediplain, generated by denudation between the Lower Cretaceous and Middle Tertiary. It was later reduced to a plateau dissected by polycyclic erosion (stream incision) that excavated valleys almost on the entire surface, with maximum coincident heights on the interfluves.

The Sul-American erosion cycle of King (Lower Tertiary) is represented by remnants of the *Sul-American Pediplain*. The erosion cycles, after the post-Cretaceous uplift, are marked by the opening of valleys that destroyed a large part of that pediplain. Locally these subsequent cycles included an advanced stage of planation. The *Velhas erosive cycle* of the Upper Tertiary is represented by valleys that dissected the Sul-American Surface. Locally, this cycle includes a phase of generalized planation that generated a *Velhas Surface*, represented by an undulating landscape, with pediments. Velhas surface penetrated along the main rivers, destroying most of the Sul-American Surface. The typical landscape is a surface on which the two cycles are involved. Pleistocene erosion cycle (*Paraguaçú*), is characterized by the opening of fluvial valleys (King, 1956).

According to King (1956), two planation surfaces, juxtaposed at different levels, are separated by relatively steep scarps. These have the characteristics of erosion escarpments (their contours, relationships with the upper and lower planation levels and relationship with parent rock), and allow the definition and mapping of cyclical erosion units represented by planation surfaces. The cited escarpments are undergoing recession by headward erosion. This is evident from the existence of pediments, also showing the way in which the peneplain was generated (by development and coalescence of isolated pediments). The stepped landscape then shows that it evolved from the regression of scarps and pedimentation. In King's (1956) opinion, each planation surface remains virtually unchanged until it is destroyed by the scarp of the subsequent erosion cycle.

The foundation of King's model (mainly developed north of the Upper Río Uruguay basin) is based on the following premises: (1) continental areas uplift episodically, almost synchronously, and uniformly; (2) parallel-scarps retreat prevails over down-wearing, which is regarded as a minimum; this retreat propagates inland as denudation makes progress; (3) knick-points retreat inland over long distances along rivers and slopes. The approach used in this model favors the spatial correlation of erosion (or planation) surfaces, usually widely scattered, which would be based on their elevation and relative position in the landscape. This correlation would eventually lead to an estimated age of erosion surfaces, especially if a link could be established between the erosion surface and a sedimentary deposit of known age (Bezerra et al., 2008).

Subsequent investigations in the Southern Brazilian Plateau proposed four periods of morphogenesis related to uniform uplift, following planation process proposed by King. Bigarella and Becker (1975) suggested important internal morphological differentiations, which are associated to the influence of local factors in the regional evolution. Generally, the structural platforms are very frequent in basaltic terrains. Erosion processes gave origin to a stepped morphology with development of numerous “cuestas”, but a tabular morphology predominates. The elevations of the basaltic plateau range between 300 to 1400 m a.s.l. Waterfalls are associated to structurally controlled reaches, where sub-horizontal and very resistant bodies outcrop. The large pediplanation surface (Middle Tertiary) is known in Brazil as *Pd3* (Ab´Sáber, 1969; Bigarella et al., 1965). *Pd2* and *Pd1* pediplanes (Bigarella and Andrade, 1965) are equivalent to the surfaces generated by the Velhas and Paraguaçú cycles of King, respectively.

Recently, the pediplanation model of King has been questioned by some authors in both eastern South America and western Africa (Bezerra et al., 2008). Post-rift tectonics has played a significant role in shaping different morphologies and sedimentary basins along both margins. Differences in tectonic styles along the eastern South American margin are now explained by different response of previous structures to post-rift stress fields. Also, post-breakup denudation does not present a similar pattern in western Africa and eastern South America; denudation rates varied significantly along both passive margins. The climatic factor played an important part in the evolution of both margins (Bezerra et al., 2008).

Between the Brazilian landscape and macroecological domains differentiated by Ab’Sáber (2000), the Upper Río Uruguay basin in Brazil is included in the *Domain of the Araucaria Plateau.* It is characterized by medium altitude plateaus, 800-1,300 m a.s.l., covered with Araucaria forests of diverse density, including mosaics of mixed prairies. Depth of weathering is very variable, with imperfectly developed convex hills. There is eventual colluvium on slopes, covering sub-recent topography, with large microrelief irregularities, corresponding to a drier climate. In part of the region comprising the Upper Río Uruguay basin in Brazil, Justus et al. (1986) have recognized the three palaeosurfaces of the landscape identified by King (1956) and designated them as: *Região Geomorfológica Planalto das Araucárias (Sul-Americana), Região Geomorfológica Planalto das Missões (Velhas) and Região Geomorfológica Planalto da Campanha (Paraguaçú).*

From a morphotectonic point of view, the Argentine sector (Misiones province) of the Cretaceous basaltic plateau is considered by Popolizio (1972) as a transitional area between the uplift of the Brazilian plateau to the northeast and the subsiding style of the middle-lower Paraná basin southwestward of the province of Corrientes (Argentina). For this reason, table-like landscape has remained unchanged in the Misiones province, with appreciable uplift, compared with the morphology of the province of Corrientes, characterized by a structural style represented by vertical faults that generated differential tectonic blocks movements (Popolizio, 1972). This author suggests that the fracture tectonics that affected the basaltic plateau in the Misiones province (represented by fracture systems without vertical displacements -NE-SW main direction; NW-SE and E-W systems with minor frequencies-) played a secondary role respect to the morphoclimatic processes that modeled the region.

The morphometric analysis method has been used as an auxiliary tool in many geological investigations in different regions of the world. Golts and Rosenthal (1993), Zuchiewicz and Oaks (1993), Grohmann (2004) and Grohmann et al. (2007), among others, discussed the development of this method. The availability of digital elevation data and processing capacity today stimulate the use of hypsometric curves and digital elevation to represent relief forms and models as basic mapping tools (Soares and Riffel, 2006). These authors demonstrated for three neighboring hydrographic basins in southern Brazil that hypsometric curves can be used to identify palaeosurfaces in multi-history landscapes by manipulating their attributes. Palaeosurface remnants are large areas with relatively similar elevations that appear in hypsometric curves as rather flat segments. Hypsometric curves generated for each drainage basin permit to compare the landscape evolution for basins that differ in extent and steepness, for evaluating the geomorphic maturity of catchments and landforms (Strahler, 1952a). The shape of a hypsometric integral (Strahler, 1952b) changes from concave-convex to concave as the basin reaches the equilibrium (mature) stage; concave curves indicate planations. Reinterpretation of the stepped topography, combined with the analysis of palaeolandforms, drainage anomalies and structural controls, was made by many authors in different areas of Brazil.

The main purpose of this study is to apply morphometric analysis techniques to the basaltic plateau in the Upper Río Uruguay basin (26°30‘ to 28°45‘ lat. S and 49°15‘ to 56° long. W), covering a large part of the states of Rio Grande do Sul and Santa Catarina , Brazil and a minor area comprising the province of Misiones and northeastern of Corrientes province in northeastern Argentina (Figure 1), focusing the study in the Argentine territory (Misiones province; 29,800 km^2). The investigation began with the identification of palaeosurfaces in selected tributary stream basins of the larger Río Uruguay basin. The analysis is extended on the Paraná and Uruguay rivers watershed in order to identify palaeosurface remnants and to correlate them to those described by other authors in southern Brazil. Geomorphological and stratigraphical field data of the Río Uruguay basin are integrated in the work of Iriondo and Kröhling (2008). First results of morphometric analyses of the basaltic plateau were previously presented by Kröhling et al. (2009).

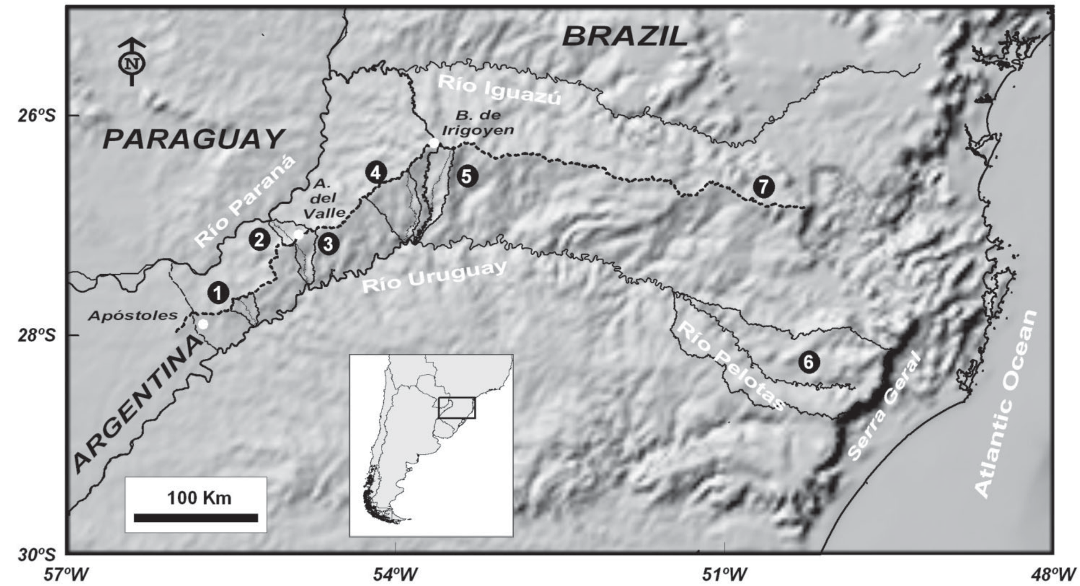

FIGURE 1. Location map of Upper Río Uruguay basin. Sub-basins in Misiones (Argentina): **1** – Río Itacaruaré; **2** – Río Cuña Pirú; **3** – Río Acaraguá; **4** – Río Yabotí; **5** – Río Pepirí Guazú. In Brazil: **6** – Río Pelotas basin. **7** – Location of the longitudinal profile from the watershed between Paraná and Uruguay fluvial systems (see Figure 8).

MATERIALS AND METHODS

The availability of digital terrain elevation data from Shuttle Radar Topographic Mission (SRTM, distributed at horizontal resolution of 3arcsec -approximately a 90×90 m grid-¸ Jarvis et al., 2008) for the development of digital elevation models (DEMs) and the advantages for integrating Geographical Information Systems (GIS) and statistics provided the base for the morphometric analysis. Also, field data taken during many previous years of studies on geomorphology and Quaternary geology of the Upper Río Uruguay basin supported the necessary base (Iriondo and Kröhling, 2004; 2008).

DEMs for selected hydrographic sub-basins were extracted from the generated DEM for the region comprising the Upper Río Uruguay basin. The method of morphometric analysis was applied to the following tributary river basins in Misiones province: Itacaruaré, Acaraguá, Yabotí and Pepirí Guazú. Also a tributary basin of Río Paraná (Río Cuña Pirú basin) was considered. The Río Pelotas basin (the main tributary of the Upper Río Uruguay), with its watersheds near the Serra Geral scarp in southern Brazil, was also analyzed for a comparative study (Figure 1).

Altitude frequency histograms for each tributary basin were produced from the extracted SRTM data, using the ENVI program. Hypsometric curves for these sub-basins were generated also from SRTM data; respective curves represent the relationship between altitude and cumulative areas under given contour intervals around watersheds. According to Soares and Riffel (2006), the region under a hypsometric curve (being a summation of area intervals per altitude), represents the amount of rock between a river outlet and the erosion surface. The procedure followed in this work is presented in detail by Soares and Riffel (2006): "The histograms for the several classes of H are constructed and the cumulative frequency is converted to area (A) between the highest point and the H level. A hypsometric curve represents the cumulative frequency of points with altitude H within class intervals, from the highest to the lowest point. In order to compare different basins, the H and A values are converted to fractions of their respective maximum values to give comparable hypsometric curves. The experimental hypsometric curves are segmented between minimum (H_{omin}) and maximum (H_{omax}) observed values of altitude in histograms; the minimum (H_{omin}) is taken from the modal lower class boundary, because this modal class represents the larger area of altitude interval; this class therefore represents the lower mean slope interval and as a consequence, the closest preserved level to the early (eroded) base level of the hydrographic basin. The operation is taken in order not to consider altimetry data related to erosion events governed by successive base levels".

The relief gradient in a hydrologic basin dominated by fluvial erosion base level can be modeled by a logarithmic function. This model is fitted to each segment by regression analysis using the least-squares method:

$$H = a - b \ln(A)$$

where, H is the minimum altitude to which area A is circumscribed; a and b are the estimated parameters (a is the maximum predicted altitude, and b is a coefficient that is proportional to the average declivity in the altitude interval).

This allows calculating the minimum palaeosurface altitude.

For each investigated basin, the simulation of a stream network was carried out by using DEM data. Also longitudinal profiles of the collectors were extracted through ArcGIS program.

The isobase map was generated by free-software GRASS-GIS (GRASS Development Team, 2005), following the methodology proposed by Grohmann et al. (2007). Steiner (2007) compared different GIS software platforms (GRASS-GIS and ArcGIS) for production and manipulation of morphometric data, slope, aspect and surface roughness maps, and concluded that the DEM-derived products are equivalent. Also, the author concluded that isobase surface maps generated by GRASS present smoother shapes and contours.

The DEM was smoothed with a 7x7 filter to minimize the effects of possible noises. An isobase represents the line that marks an erosion surface, by stream incision. Filosofov (1960) defines isobase surface as a hypothetical surface determined by the intersection of drainages of similar order with an erosion surface, associated with the reorganization of the drainage networks. It can be considered as a simplified surface of the original topography, where the elevations above the isobase surface are discarded. According to Golts and Rosenthal (1993), the resulting surface is related to similar stages of erosion and can be considered as a product of recent tectonic-erosive events.

Stream channel network was extracted from a 90x90 SRTM-DEM using the Single Flow Direction (SFD -D8) algorithm (r. watershed command). The stream Strahler order (1952a) has been assigned to polylines of the streams in the attribute table. The elevation isobase map was made from the intersection of contours with 1st, 2nd and 3rd order stream channels. The resulting raster was interpolated in order to obtain the hypothetical map (Wobbe, 2007).

RESULTS

Stepped Surfaces of the Upper Río Uruguay Basin

Remnants of three extensive erosion surfaces have been recognized and described in the basaltic plateau of the province of Misiones by Iriondo and Kröhling (2008), mainly on basis of field data. The higher remnant surface exposed of the plateau in Argentina is restricted to the area of Bernardo de Irigoyen, northeastern Misiones province, and found at altitudes around 800 m a.s.l. This area has undergone intense physical and chemical weathering and persistent erosion action; small circular depressions in the basaltic rocks (200-300 m in diameter and 5-10 m depth, named "dales" in Brazil) presently occupied by peat bogs are frequent.

According to Iriondo and Kröhling (2004), most of the landscape of the province of Misiones is formed by the intermediate surface, mostly below 300 m of the Bernardo de Irigoyen surface, forming a plateau or narrow butte tops at the edges and expressed by the top of the known Sierra de Misiones. The surface is represented by rounded hills and mature fluvial valleys and it is correlated to the surface generated by the *Velhas erosive cycle* of King (1956) in Brazil. The *Velhas Palaeosurface* of Misiones (or *Pd2* of Bigarella et al., 1965*)* comprises the plane-top watershed between the Paraná and Uruguay basins, with a NE-SW direction in the central part of the province (Figure 1). Because of the proximity of these large fluvial collectors, pediplanation and pedimentation processes leaved a narrow remnant that locally are restricted to ridges of planned tops.

The lower level of the general landscape (close to 200 m a.s.l) forms a peripheral area in southeastern Misiones province that is locally named *Apóstoles*

Pediplain. It would have been generated by the King´s *Paraguaçú cycle* (or Bigarella´s *Pd1),* destroying the intermediate surface by the regression of erosion scarps and a deep incision and widening of fluvial valleys. A rim of ferricrete was formed by subsurface flow along the southwestern limit of the *Apóstoles Surface* in the northeastern of the province of Corrientes.

Remnants of the King's *Sul-American Surface* are well-developed in the headwaters of the Río Uruguay (on the sub-basins of the Pelotas and Canoas rivers) at around 1,000-1,200 m.a.s.l. and located immediately westward from the large Serra Geral erosion scarp. The *Velhas Paleosurface* is widespread in the Upper Río Uruguay basin in southern Brazil and it is represented by a landscape of gentle and well rounded hills (locally named as "coxilhas").

Hypsometric Curve Analysis

Table 1 summarizes the main modes of the statistical distribution of altitudes for each studied tributary basins, taken from the respective frequency histograms. The histograms of Figure 2 correspond to the two basins with main headwaters in the upper level of the landscape in Misiones province. Main mode of the Río Pepirú Guazú basin, at the Argentine-Brazilian border, is at 512 m a.s.l.; secondary modes are at 692 m a.s.l. and 806 m a.s.l. The Río Yabotí basin shows a main mode at 524 m a.s.l., close to the main mode of the Pepirí area. Histograms generated for the adjacent Cuña Pirú and Acaraguá river basins (tributaries of the Paraná and Uruguay basins, respectively) are presented in Figure 3. Main mode of the Cuña Pirú basin is at 184 m a.s.l., with a secondary mode around 453 m a.s.l. The Acaraguá basin shows a polymodal distribution (Mo: 451, 316 and 181 m a.s.l.). The Itacaruaré basin distribution is bimodal, with the main mode close to 144 m a.s.l. and secondary modes around 225 and 275 m a.s.l. (Figure 4). The main mode in the highest altimetry value considering the six tributary basins investigated was obtained in the Río Pelotas basin (Mo: 922 m a.s.l.), with the secondary mode at 1139 m a.s.l. (Figure 4).

Hypsometric curves generated for each basin allow identifying significant low gradient surfaces or terraces (see an example in Figure 5). Such relatively flat segments are indicative of palaeosurfaces that could be related to ancient base levels. From regression analysis (see Table 1) the adjustment of the low gradient segments permits to reconstruct two hypothetical hypsometric curves and consequently to estimate the elevation for the former base levels. In order to compare the different basins, each area is converted to fractions of their respective maximum values to obtain normalized hypsometric curves (Figure 6 and Table 1). Three groups of hypothetical hypsometric curves are deduced from proximal value sets for predicted base levels. Using this approach, three main palaeosurfaces are defined (named palaeosurfaces 1,

TABLE 1. Modal elevation, minimum and maximum elevation and predicted base level for the palaeosurfaces identified for each tributary river basin (the lower value for each palaeosurface was remarked).

Hydrographic basin	Modal elevation (m.a.s.l.)	Minimum elevation (m.a.s.l.)	Maximum elevation (m.a.s.l.)	predicted base level (m.a.s.l.)	Log. Model	R²
Pelotas						
palaeosurface 1	922,1	882,6	981,2	840,9	y = -223,81Ln(x) + 2967,2	0,9915
palaeosurface 1b	1138,9	1079,8	1276,9	903,6	y = -181,3ln(x) + 2626,1	0,9910
Pepirí Guazú						
palaeosurface 2	512,4	479,70	594,02	425,1	y = -150ln(x) + 1583,2	0,9913
palaeosurface 2b	692	675,68	708,35	548,8	y = -72,44ln(x) + 1108,1	0,9854
Yabotí						
palaeosurface 2	523,8	492,34	555,15	424,1	y = -76,63ln(x) + 1010	0,9833
Acaraguá						
palaeosurface 3	180,5	165,48	225,61	134,7	y = -401,1ln(x) + 2780,2	0,9995
palaeosurface 3b	315,8	255,67	360,89	206,8	y = -175ln(x) + 1361	0,9878
palaeosurface 2	451,1	436,05	481,14	377,4	y = -37,92ln(x) + 627,54	0,9849
Cuña Pirú						
palaeosurface 3	183,6	168,61	213,55	161,1	y = -129,4ln(x) + 965,04	0,9895
palaeosurface 2	453,2	453,22	498,16	402,7	y = -28,11ln(x) + 577,33	0,979
Itacaruaré						
palaeosurface 4	143,8	111,39	182,57	105,8	y = -119,2ln(x) + 838,88	0,9963
palaeosurface 3	225,3	211,04	282,20	157,4	y = -62,47ln(x) + 541,62	0,9811

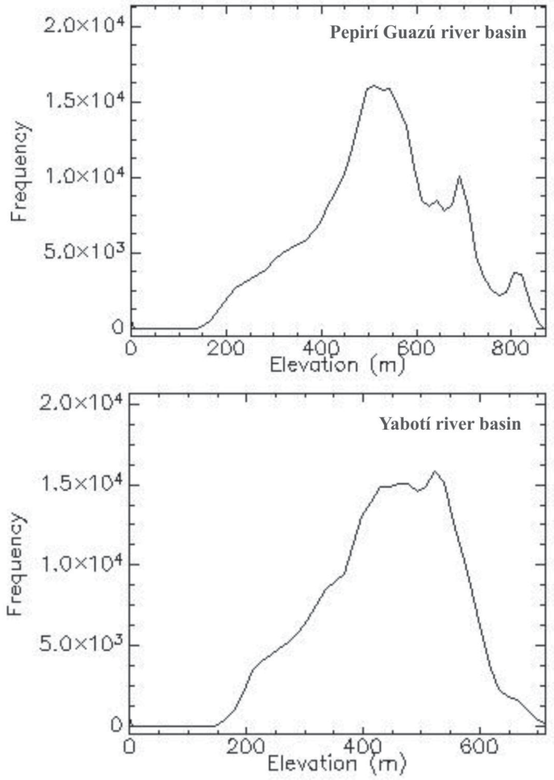

FIGURE 2. Frequency histograms of Pepirí Guazú and Yabotí river basins, obtained from SRTM (90 m) - DEM data and calculated by using ENVI 4.0 software.

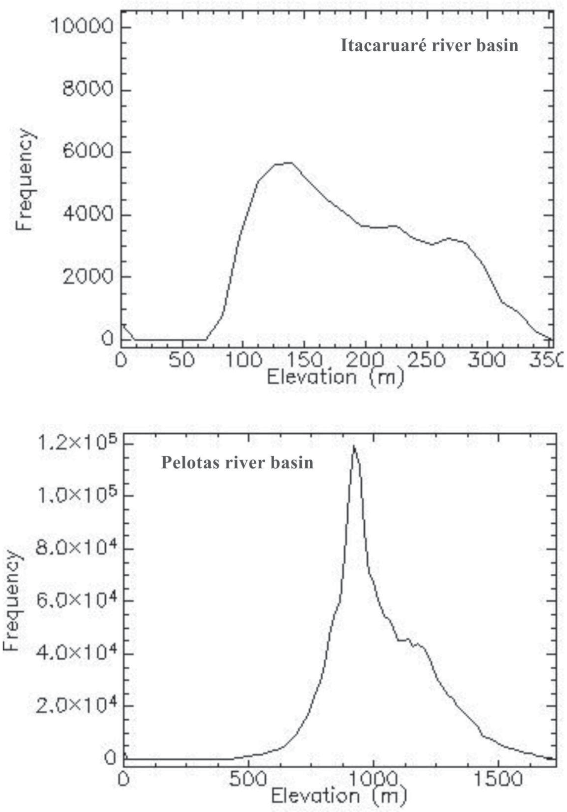

FIGURE 4. Frequency histograms of Itacaruaré and Pelotas river basins, obtained from SRTM (90 m) - DEM data and calculated by using ENVI 4.0 software.

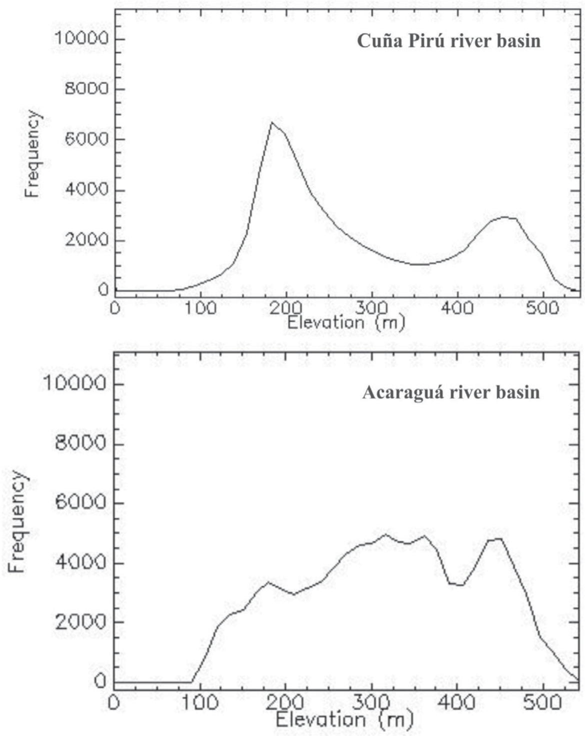

FIGURE 3. Frequency histograms of Cuña Pirú and Acaraguá river basins, obtained from SRTM (90 m) - DEM data and calculated by using ENVI 4.0 software.

2 and 3) and complementary intermediate or secondary palaeosurfaces also appear from the analysis (1b, 2b, 3b and 4). Therefore, each mapped palaeosurface was considered between the minimum H_{min} for correlative surfaces and the H_{min} of the next higher surface (Table 1 and Figure 7). These altitudinal ranks can also be observed in the watershed area along the Uruguay and Paraná fluvial systems (Figure 8). Inflections in the longitudinal profile of the watershed roughly point out the limits between the different palaeosurfaces.

In the Río Pepirí Guazú basin, the main palaeosurface 2 is dominant (Figure 9). Steps or knickpoints are easily seen in the longitudinal profile of the collector in coincidence with the lower limits defined for palaeosurfaces 2 and 2b. Similarly, the palaeosurface 2 covers the largest area in the Río Yabotí basin, although the palaeosurface 3b influences subtly (around 400 m a.s.l.) on the longitudinal profile of the collector (Figure 10). Figure 11 shows that palaeosurface 3 has a larger representation in the Río Cuña Pirú basin; conversely, surface 3b occupies most of the Río Acaraguá basin. The main controls on the respective longitudinal profiles of the collectors are palaeosurfaces 3 and 4 (around 140 and 180 m a.s.l., Figure 11). Palaeosurface 4 is mainly preserved in the Río Itacaruaré basin (Figure 12) and

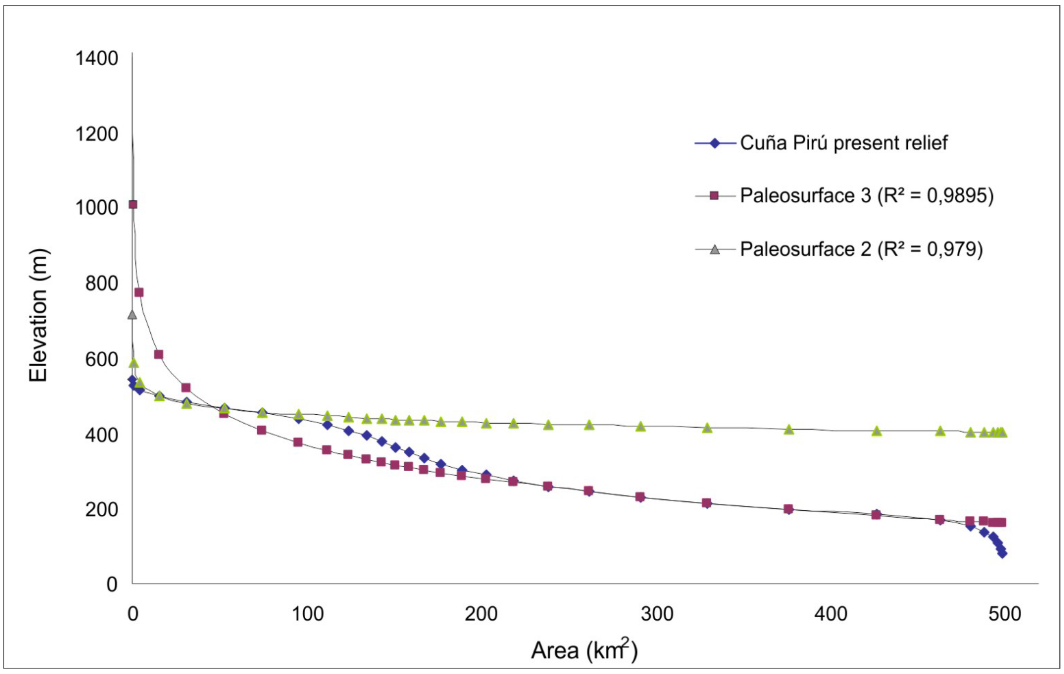

FIGURE 5. Hypsometric curves of the Río Cuña Pirú basin. Diamond plots represent the present relief. Hypothetical hypsometric curves obtained from regression analyses, by fitting the low gradients segments, correspond to triangle and square plots. They represent palaeosurfaces and the relatively flat segments are considered as their remnants.

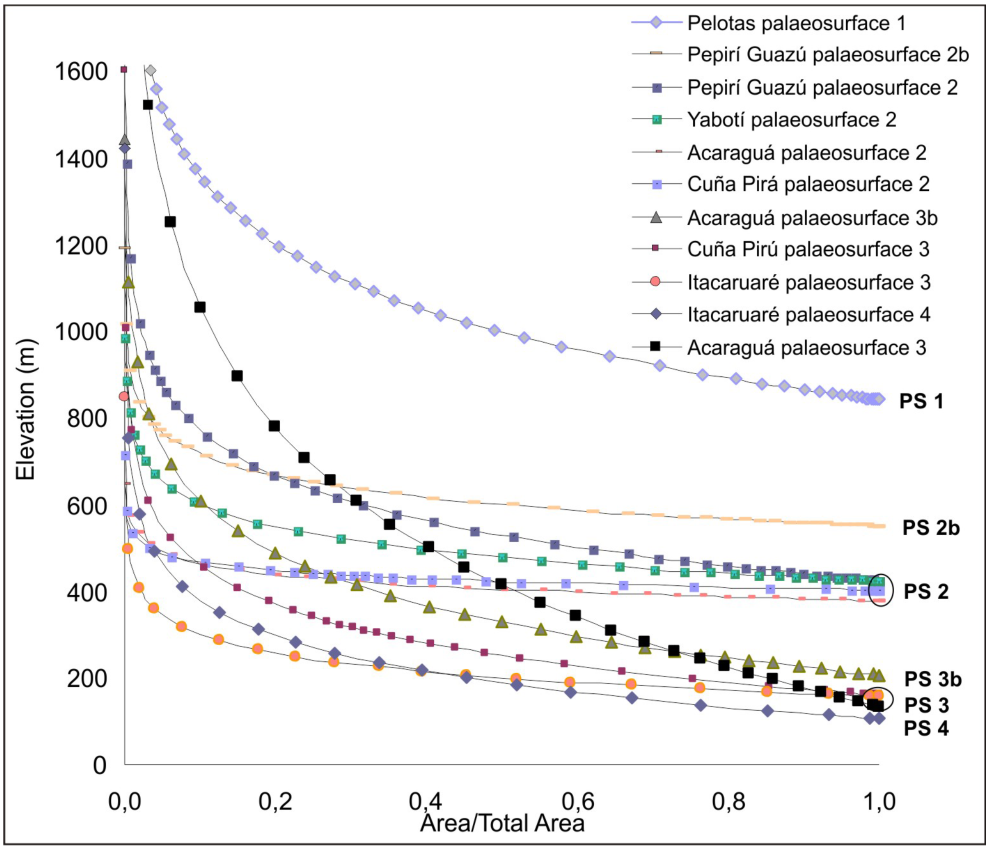

FIGURE 6. Modeled hypsometric curves, with elevation values (H) and cumulative areas (A), re-scaled to 1: area above altitude H divided by the total area. Predicted base level elevations allow grouping hypsometric curves and defining three main palaeosurfaces and several secondary ones.

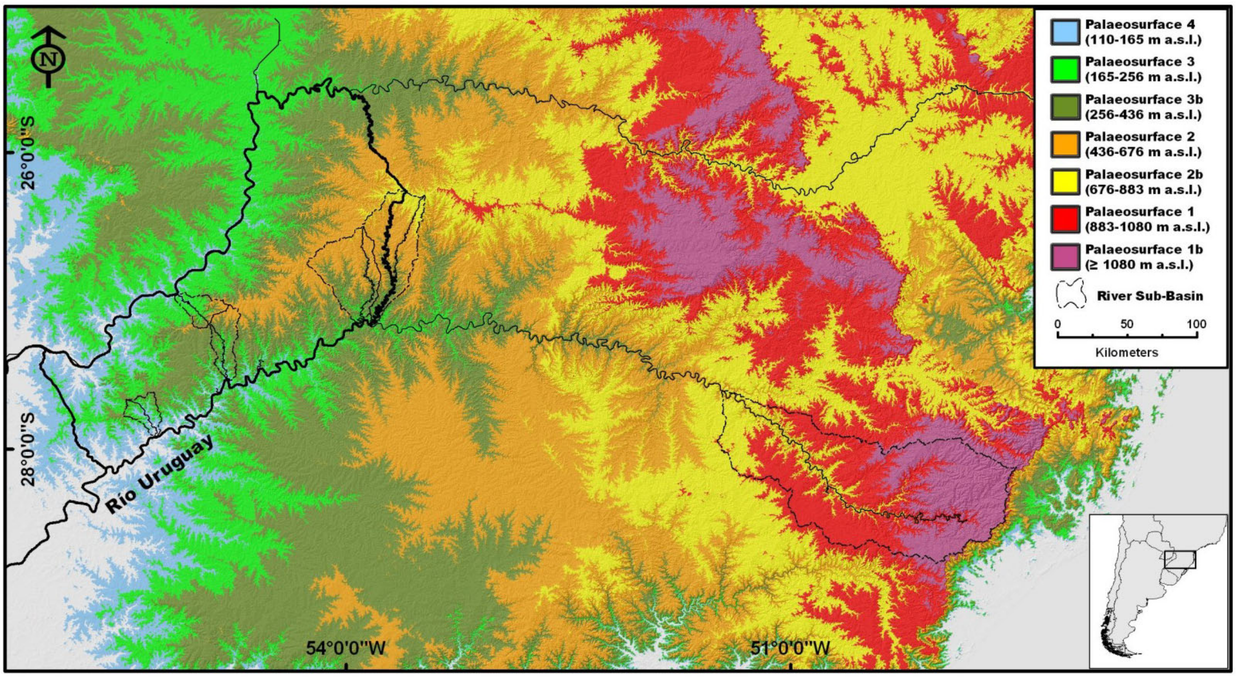

FIGURE 7. Palaeosurfaces map defined from morphological analyses. Observe the elevation intervals for each surface in Figure 8.

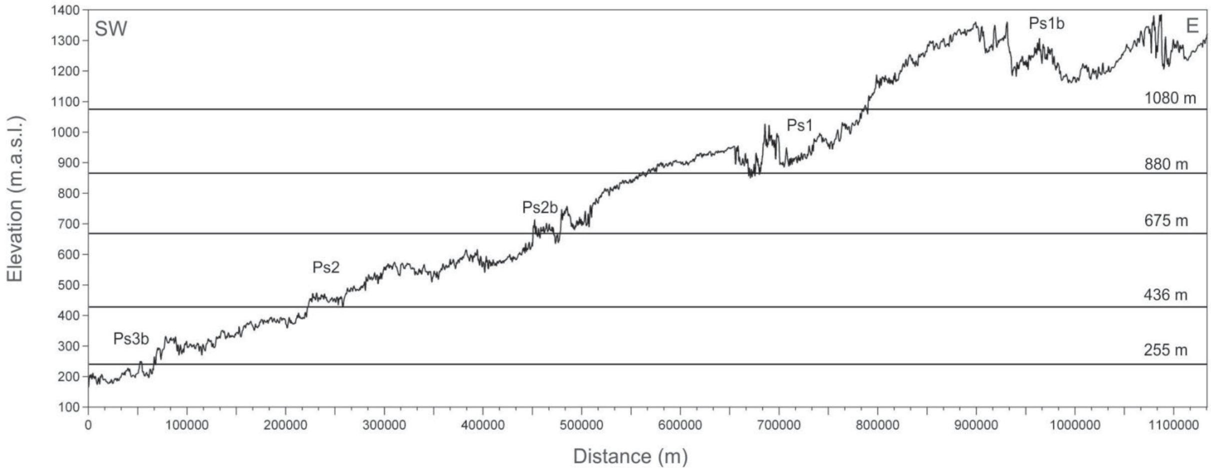

FIGURE 8. Longitudinal profile from the watershed between Paraná and Uruguay fluvial systems. On the right of the plot are the elevation intervals for each surface, projected on the watershed.

the stream longitudinal profile is also controlled by palaeosurfaces 3 and 4 (see the inflections in 120 and 180 m a.s.l.). The Río Pelotas basin is almost totally developed on palaeosurfaces 1 and 1b (Figure 13); an important control, represented by a knick-point in the longitudinal profile of the river, corresponds to palaeosurface 1b (around 1080 m a.s.l.). The extension of each mapped palaeosurface into narrow valleys carved on the next higher surfaces (Figures 9 to 13) is not entirely representative, because of they were eroded, partially by current fluvial networks. However, it is clear that the palaeosurfaces exert control on the streams, observed from the knick-points in longitudinal profiles.

The scarp that limits palaeosurface 2 is highlighted by a noticeable anomaly in the distribution of the isobase

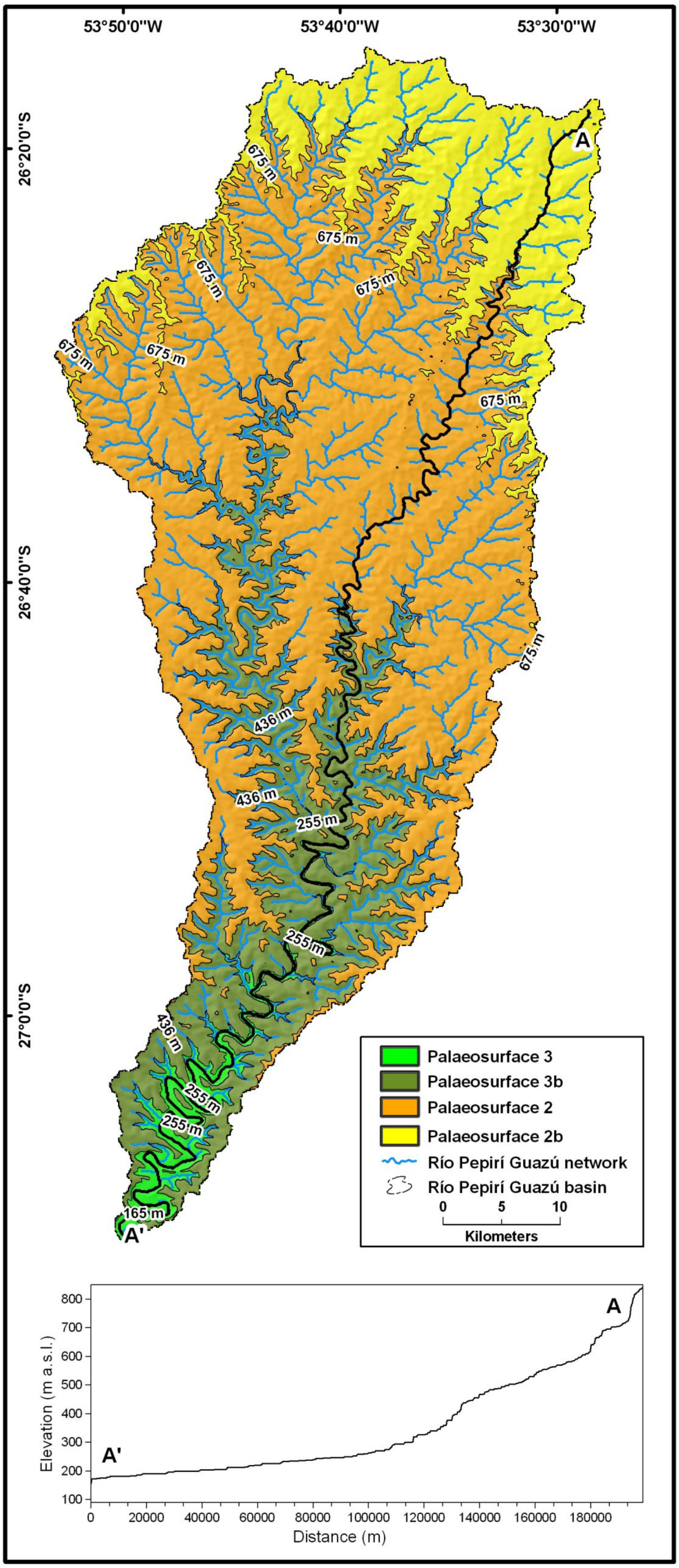

FIGURE 9. SRTM-DEM-based map of paleosurfaces in the Río Pepirí Guazú basin. The simulated hydrographic network is also represented. In the insert, the longitudinal profile extracted from the main collector of the basin is shown.

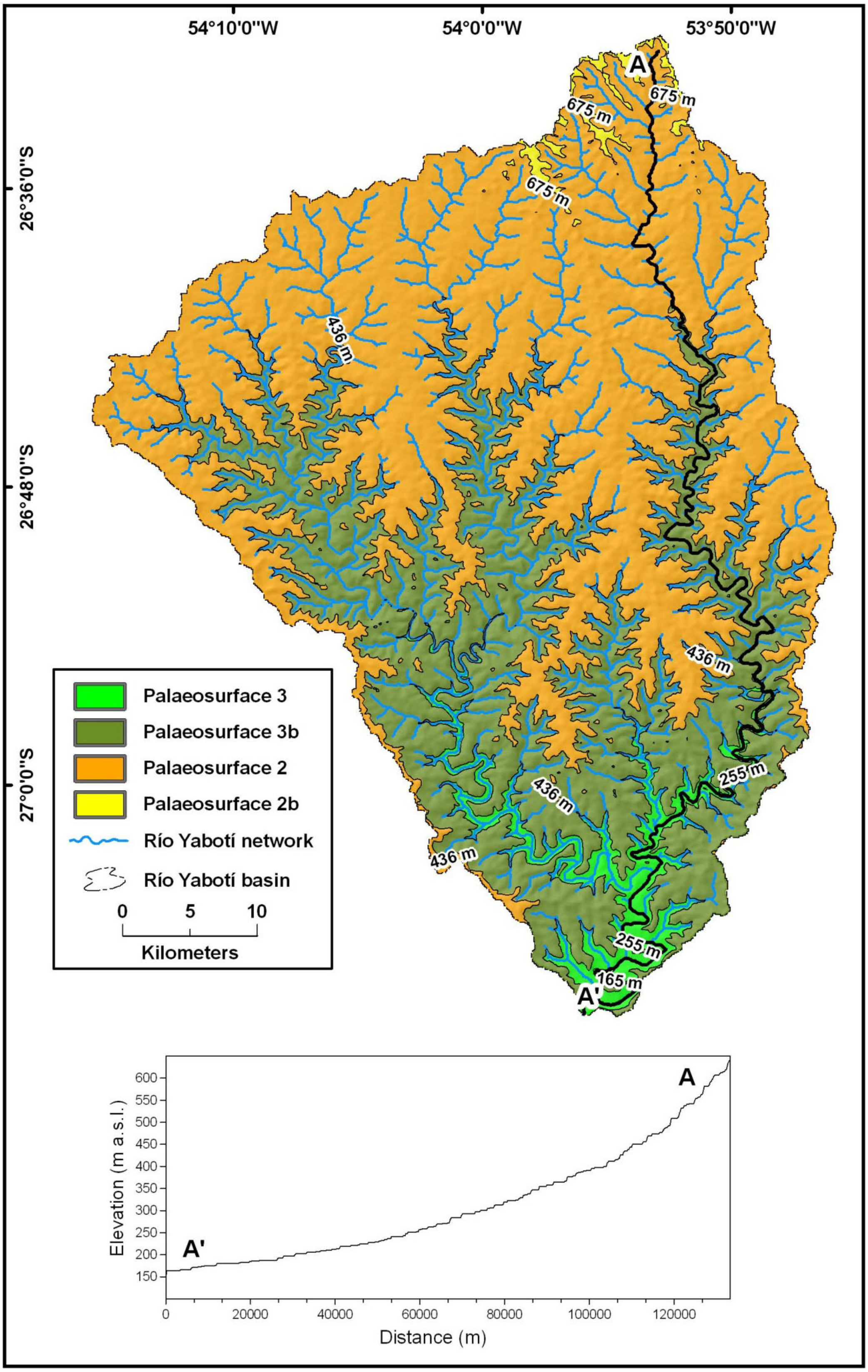

FIGURE 10. SRTM-DEM-based map of paleosurfaces in the Río Yabotí basin.

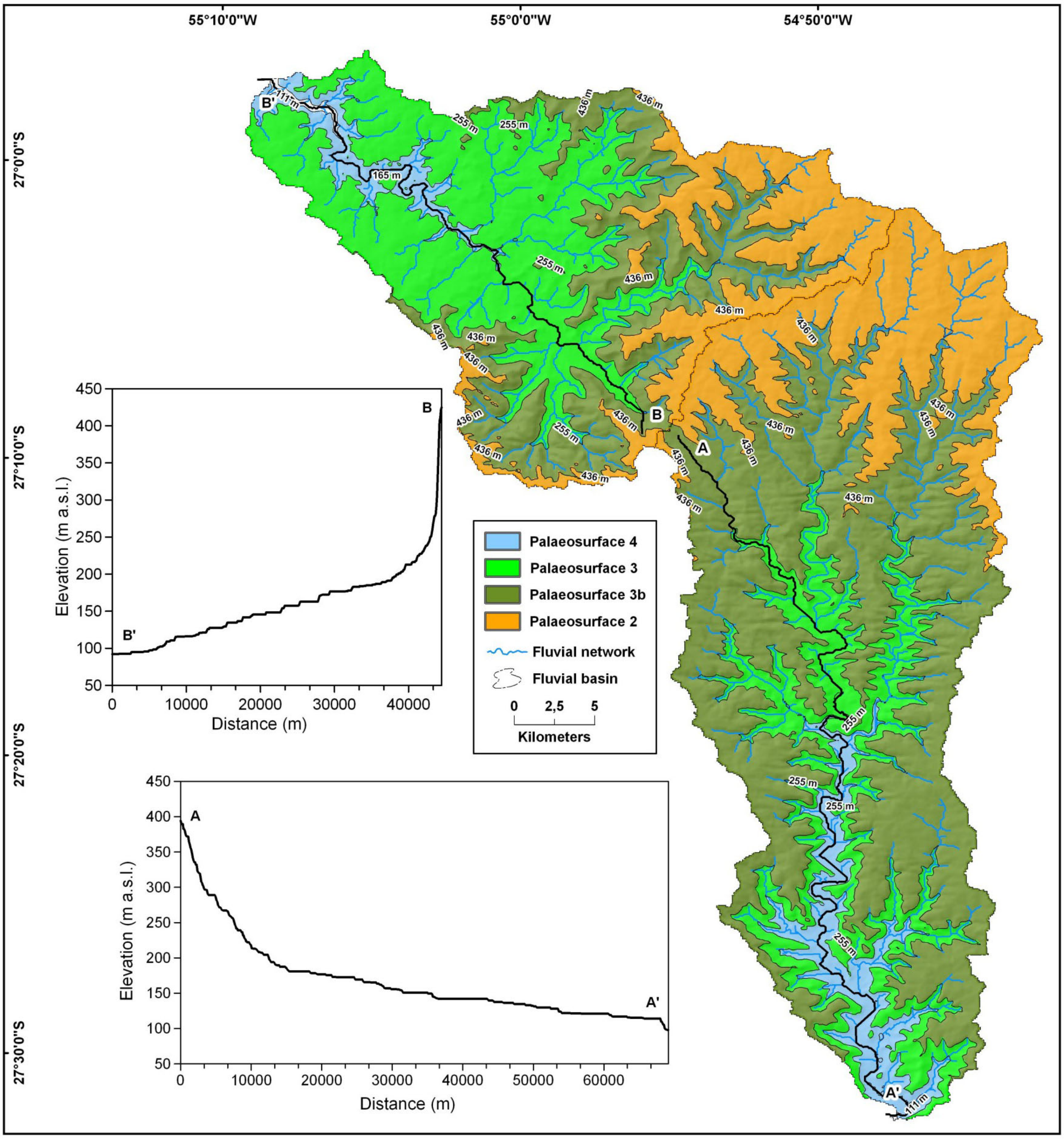

FIGURE 11. SRTM-DEM-based map of paleosurfaces in the Cuña Pirú (B-B´profile) and Acaraguá river basins (A-A´profile).

lines, elaborated from the intersection of contour lines with the 2nd and 3rd order stream channels belonging to the Río Cuña Pirú basin (Figure 14a). The strong control on the headwaters of this tributary basin is also observed in the longitudinal profile of the collector (Figure 11, profile B-B´). The isobase map constructed on the 1st order streams allows delimiting the area remaining unaffected by the current fluvial erosion (Figure 14 b), that correspond to the remnant of palaeosurface 2. Slopes that connect both levels of the landscape (palaeosurfaces 2 and 3) are sharp with frequent debris composed by boulders of high angularity, which suggests that the process of areal erosion was produced mainly by rock landslides.

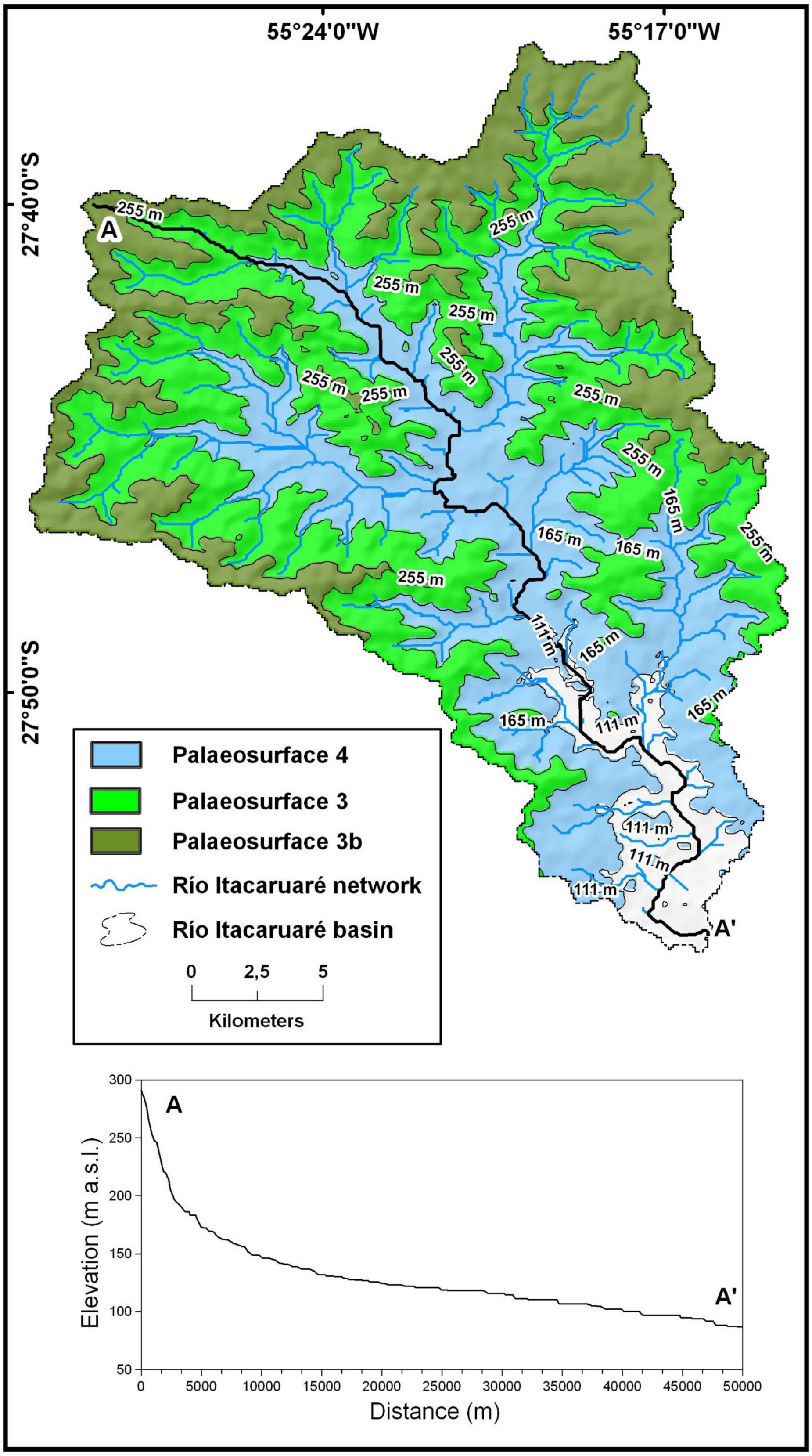

FIGURE 12. SRTM-DEM-based map of paleosurfaces in the Río Itacaruaré basin.

According to the obtained results, palaeosurfaces 1 and 1b in this work are equivalent to the King's *Sul-American Surface* (or *Pd3* of Bigarella et al., 1965). If the Upper Río Uruguay basin corresponded to the lower segment of such palaeosurface, a predicted base level value would be estimated around 840 m a.s.l. (Table 1). Both palaeosurfaces 1 and 1b are well represented in the Pelotas basin (Figure 13). The higher remnant surface of the area of Bernardo de Irigoyen (northeastern Argentina) was considered a "sensu lato" equivalent of King´s *Sul-American Surface* in morphological and stratigraphical sense by Iriondo and Kröhling (2008), but it is now reinterpreted as a different palaeosurface. It is characterized by palaeosurface 2b (676-883 m a.s.l.; Figure 7 and Table 1).

The King´s *Velhas Palaeosurface* (or *Pd2* of Bigarella et al., 1965*)* is correlated in this study with palaeosurface 2, which in Misiones province comprises the plane-top watershed between the Paraná and Uruguay basins, with a typical area near the town of Aristóbulo del Valle (436-676 m a.s.l.; Figure 7). A predicted base level value for this surface could be estimated around 400-425 m a.s.l. (Table 1). The lower surfaces 3 and 4 identified in this morphometric analysis correspond to the locally named *Apóstoles Surface,* which would be generated by the King´s *Paraguaçú cycle* (or Bigarella´s *Pd1*). The base level for these lower surfaces would be above 100 m a.s.l. (Table 1).

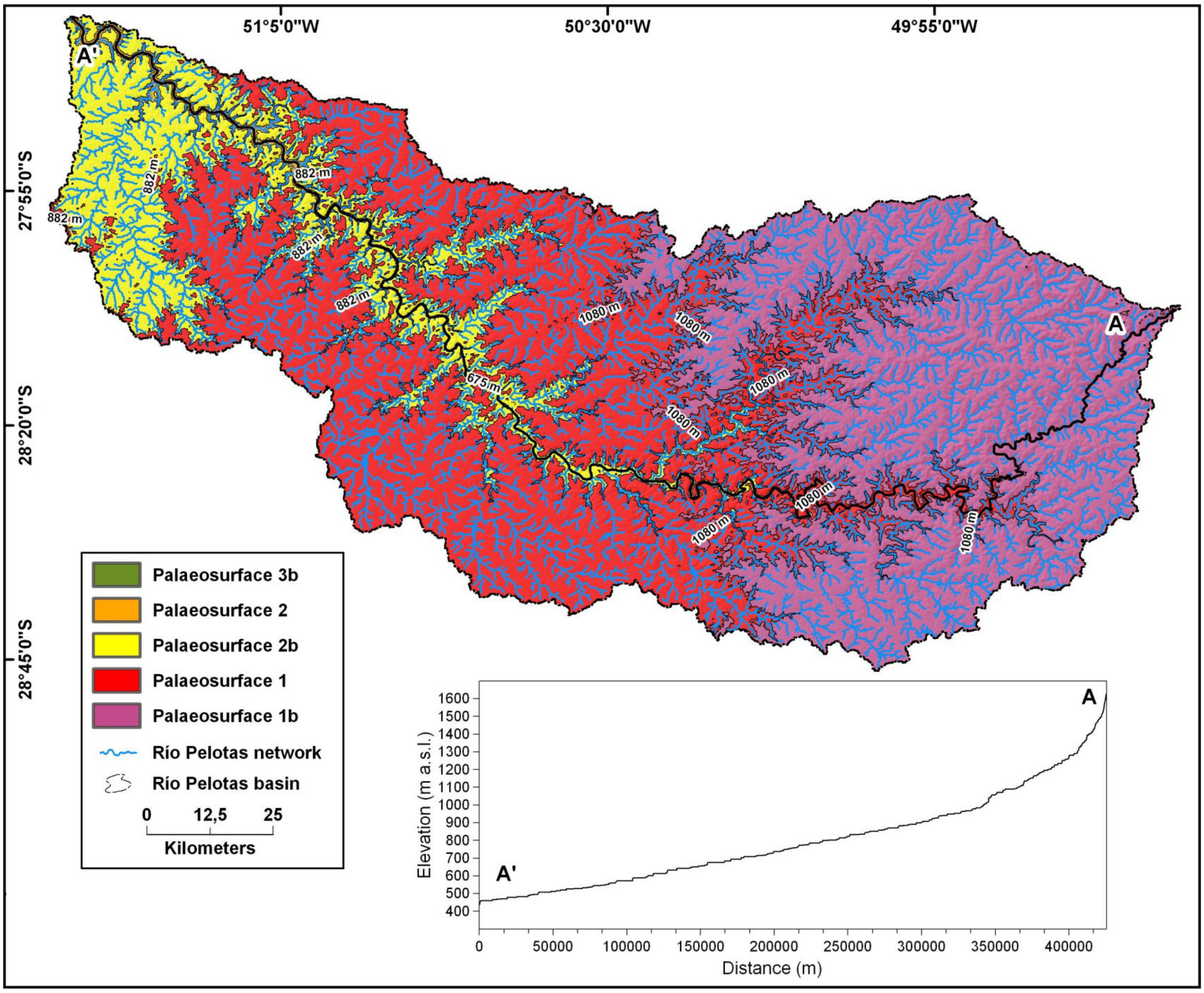

FIGURE 13. SRTM-DEM-based map of paleosurfaces in the Río Pelotas basin.

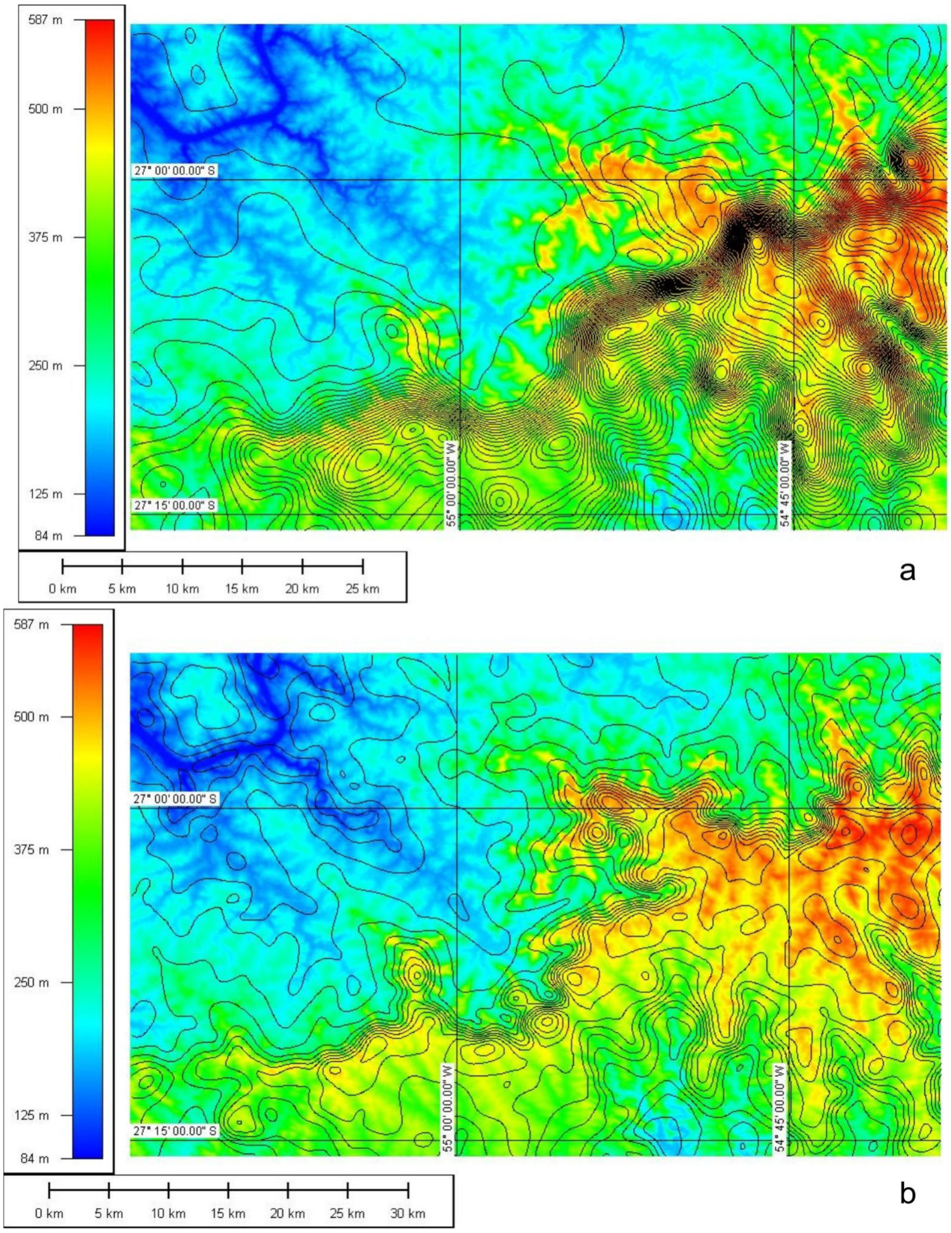

FIGURE 14. Isobase maps in the Aristóbulo del Valle area (Misiones - NE of Argentina).
a) Isobase map by interception of contour lines and 2nd and 3rd order streams.
b) Isobase map by interception of contour lines and 1st order streams. In these maps, it is possible to observe a noticeable anomaly in the distribution of isobase lines.

CONCLUSIONS

SRTM data constitute a good resource for morphometrical analysis for the large Cretaceous basaltic plateau of South America. Palaeosurface remnants of the Upper Río Uruguay basin preserve attributes that may be identified in digital elevation models. The generation of hypsometric curves in five representative tributary basins of the Uruguay basin and also in one small basin tributary of the Río Paraná permitted to identify, classify and map the main Cenozoic palaeosurfaces. Other morphometric parameters such as longitudinal profiles and isobase lines, complementary with field data, were utilized also to corroborate such surfaces.

The steeper longitudinal profile observed in a tributary of the Río Paraná (the Río Cuña Pirú), compared to the closest Río Uruguay tributary (Acaraguá), points out that erosion is more active on the Paraná system. The steeper sections, which show knick-points, may result from outcrops of the basalt and/or the active headward erosion by valley development and rock landslides. The presence of the palaeosurfaces also appears to exert control on these processes.

There is a good correlation between defined palaeosurfaces and well-known King´s *Paraguaçú cycle* (*Apóstoles Surface*), the *Velhas Palaeosurface* and the *Sul-American Palaeosurface*. However, the last one is restricted to the Río Pelotas area in southern Brazil, and it does not appear in the basaltic plateau of Misiones province (Argentina). Secondary palaeosurfaces were identified based on morphometric analyses.

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