Gondwana Paleosurfaces in the State of Rio Grande do Sul, Southern Brazil

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Abstract Several papers in Brazil have identified the importance of the planation surfaces in the evolution of the landscape, particularly those referring to the Gondwana Surface and the "Sul-Americana" Surface. These works were especially common between the 1950s and 1970s. Starting with the 1980s, such contributions became much scarcer. More recently, several, more appropriate dating techniques stimulated again the publication of papers related with these themes. This study has the aim of reviewing the knowledge about the paleosurfaces of the state of Rio Grande do Sul. The investigation discusses the summit surfaces named by Ab'Sáber as the Vacaria Surface and the Caçapava do Sul Surface. The Vacaria Surface is carved into Mesozoic effusive rocks, whereas the Caçapava do Sul Surface has a much more complex evolution, basically eroded on Precambrian rocks. Contrarily to other areas of Brazil, the surface carved in the oldest rocks is located at intermediate elevations. The Vacaria Surface evolved during the Late Cretaceous and the Paleogene, whereas the Caçapava do Sul Surface has an even older development, typically corresponding in this area to the Gondwana Surface, with some particular characteristics which are unique in regional terms, as remnants of Triassic sedimentary rocks on top and evidence of lateritic profiles, which today occur only in the lowest parts of these sections, but which had influence on the development of some landforms until today.

Keywords Gondwana • Brazil • Rio Grande do Sul • Passive margin geomorphology • Planation surfaces

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Introduction

Planation surfaces are topographic surfaces that cut across rock types of different nature and age (Godard et al. 2001). The Gondwana paleolandscapes are related to long-term landscape evolution of planation surfaces that were developed over many millions of years, under very warm and wet climatic conditions and with tectonic stability as typical passive margins (Rabassa 2010, 2014; Ollier 2014a, b). These surfaces in South America were developed at least until the Early Cretaceous, when the rifting processes started the destruction of Gondwanaland and the Southern Atlantic Ocean was formed.

Several works have identified these surfaces in Brazil, as part of the relief, particularly the Gondwana Surface and the "Sul-Americana" (i.e., South American) Surface (Moraes Rêgo 1932; De Martonne 1943; Freitas 1951; Ab'Sáber 1955a, b; King 1956; Barbosa 1965; Dorr 1969; Braun 1970; Bigarella 2007), among many other papers by these authors and other scientists). A synthesis of several proposals which covers the entire Brazilian territory is presented in Table 1, showing a certain analytical complexity when a diversity of interpretations according to the different authors is observed.

Particularly in Southern Brazil, Brasil (1986) indicated that it is a region which presents a polycyclic relief characteristic that brings as a consequence the difficulties of identification, correlation, and genetic determination of several areas, what also adds to the polygenetic character of the larger planation surfaces, the result of superposition of morphoclimatic systems. Concerning this situation, Ab'Sáber (1969) noted that even when these surfaces are widely represented and with well-defined geographic distribution and topographic position in the state of Rio Grande do Sul, the southernmost of Brazilian states (Fig. 1), the high degree of preservation of these landforms occurring in the states of Goiás, Mato Grosso, or Bahia is not observed here.

In Rio Grande do Sul, Ab'Sáber (1969) indicated that the paleosurface scenario is much more complex, since higher surfaces occur in the area of the huge Paraná Basin, which may be older than the highest summits of the Uruguay-Rio Grande do Sul shield.

In the state of Rio Grande do Sul, the areas with higher altimetry correspond to two, very characteristic summit surfaces. On one side, the highest surface is found with altimetry normally higher than 1,000 m above sea level (m a.s.l.), on rocks of the Serra Geral Formation (rhyolite and basaltic flows with ages between 110 and 160 Ma), located at the northeastern sector of the state (a surface that extends into the State of Santa Catarina) and another summit surface, with lower altimetry (around 450 m a.s.l.), carved onto crystalline basement rocks, with a much longer and more complex evolutionary history than the first one, found in the central-southeastern portion of the state of Rio Grande do Sul (a surface that continues into Uruguay).

The central objective of this chapter is to present a revision of the knowledge of these paleosurfaces, with the aim of organizing the information about the summit

surfaces of the state of Rio Grande do Sul, and to show data belonging to field studies in the area. In this chapter, the two summit surfaces indicated by Ab'Sáber (1969) will be discussed: (a) the Vacaria Surface, which presents portions with elevations of 1,000 (m a.s.l.) on the volcanic flows of the Serra Geral Formation (which would correspond to the surfaces of the top of the "Planalto" – that is, high plain – dos Campos Gerais, as stated by Dantas et al. 2010), and (b) the Caçapava do Sul Surface, with altimetry between 450 and 460 m a.s.l. and which cuts across the rocks of the Sul-Rio-Grandense Shield (Ab'Sáber 1969) (being the equivalent to the uppermost surface of the Planalto Sul-Rio-Grandense, according to Dantas et al. 2010). Brasil (1986) has worked as if these two surfaces were correlated, whereas in this chapter, they will be treated separately because they are associated with different materials and are located at very different topographic levels. Nevertheless, it should be noted that the question of their correlation is not considered here.

Summit Paleosurfaces of Rio Grande do Sul

In altitude terms, the state of Rio Grande do Sul presents its highest summits in the northeastern portion of the state (Fig. 2), at the border with the State of Santa Catarina, commonly with elevations higher than 1,000 m a.s.l., reaching up to 1,800 m a.s.l. in some places of Santa Catarina itself. In this sector, the altitudes diminish towards the west and southwest. The Planalto Sul-Rio-Grandense extends further southwards with lower altimetry, slightly higher than 400 m a.s.l. In a clear way, these high plains are separated by the valley of Rio Jacuí, where lower elevations are observed, together with the tributaries of the Rio Uruguai that divide the state territory in a west–east direction.

In climatic terms, the state of Rio Grande do Sul has a humid subtropical climatic régime, with cold winters in the southern part and along the higher surfaces of the high plains resulting in moderate chemical weathering, due to the dominating relatively low temperatures (Dantas et al. 2010). In the higher portions of the landscape, it is common to have transitory snow cover during the winter.

According to Dantas et al. (2010), four major geomorphological dominions are observed in the state of Rio Grande do Sul: (1) the coastal plains, composed of marine, eolian, and fluviolacustrine deposits of Quaternary age; (2) the Planaltos Alçados (i.e., "uplifted plains"), developed upon the volcanic and volcano-sedimentary sequences of Mesozoic age of the Paraná Basin; (3) the inter-plain depressions, which have evolved on the Paleozoic and Mesozoic sedimentary sequences of the Paraná Basin; and (4) the high plains and the Serras Baixas (i.e., "low hills"), modeled upon the crystalline basement rocks of Precambrian age of the Sul-Rio-Grandense Shield. This classification is similar to that developed by Suertegaray and Fujimoto (2004), who proposed a synthetic scheme about the evolution of the morphogenesis of Rio Grande do Sul. Basically, these authors outlined three morpho-structures that characterize the landscape of the state of Rio Grande do Sul: (1) the Rio de La Plata Craton and the Dom Feliciano Belt,

Table 1 Synthesis of the different interpretations concerning the Brazilian paleosurfaces (Ponçano and Almeida 1993; Leonardi et al. 2011.)

Period		Epoch	Moraes Rêgo (1932)	De Martonne (1943)	Freitas (1951)	King (1956)
Cenozoic	Quaternary	Holocene	Uplift		Quaternary Cycle	Paraguaçu Cycle
		Pleistocene				
	Tertiary Neogene	Pliocene	Peneplanation	Neogenic Surface	Level A peneplain or Tertiary peneplain	Velhas Cycle
		Miocene	Uplift			
	Paleogene	Oligocene		Cristas Médias Surface		Uplift
		Eocene	Peneplanation post-Cretacic			
		Paleocene				Sul-Americana Surface
Mesozoic	Cretaceous	Late		Campos Surface	Level B peneplain or Cretacic peneplain	
		Middle				Post-Gondwana Surface
		Early				
	Jurassic	Late				Gondwana Surface
		Middle				
		Early				
	Triassic	Late				Surface aggradation under desert regime
		Middle				
		Early				
Paleozoic	Permian	Late				
		Early				
	Carboniferous	Late		Pré-Permian Surface		
		Early				
	Devonian	Late				
		Middle				
		Early				
	Silurian	Late				
		Early				
	Ordovician	Late				
		Middle				
		Early				
	Cambrian	Late				
		Middle				
		Early				

which correspond to Precambrian igneous and metamorphic rocks belonging to the Uruguayan-Sul-Rio-Grandense high plain; (2) the Paraná sedimentary basin, characterized by Paleozoic and Mesozoic sedimentary rocks,corresponding to the so-called Peripheric Depression, the Planalto Meridional and the Cuesta de Haedo. (3) the Pelotas sedimentary basin constituted by Cenozoic sedimentary rocks, corresponding to the coastal plains and lowlands. The basic geomorphological units, based upon Dantas et al. (2010), are shown in Fig. 3.

The two geomorphological units discussed here are the Planalto dos Campos Gerais, whose summits would correspond to the Vacaria Surface (according to

Table 1 (continued)

Ab'Sáber (1962) and Bigarella (2007)	Almeida (1964)	Barbosa (1965)	Braun (1970)	Bigarella (2007)	Valadão (2009)
Jundiaí Surface		Cycle XII – Paraguaçu of King	Velhas Cycle		Sul-Americana II Surface
Neogene Surface	Several surfaces along the valleys	Pediplan X – Velhas Surface of King	Sul-Americano Cycle	Pd_1	Sul-Americana I Surface
		Pediplan VIII – Sul-Americana Surface		Pd_2	Uplift
Cristas Médias Surface	Faulting				Sul-Americana Surface
	Japi Surface			Pd_3	
Altos Campos Surface					
		Pediplan VII – Superfície Culminante (Pós-Gondwana)			
		Pediplano V (?) – Superfície Gondwana Surface of King and Campos Surface of Martonne	Post-Gondwana Cycle		
			Gondwana Cycle		
	Itagua Surface				
	Itapeva Surface				

Ab'Sáber 1969), and the Planalto Sul-Rio-Grandense, where the highest points would belong to the Caçapava do Sul Surface (Ab'Sáber 1969). The Planalto dos Campos Gerais would correspond to the highest portion of the "Planalto das Araucárias" (IBGE 1995; Dantas et al. 2010). It is composed of volcanic flows pertaining to the Serra Geral Formation (Cretaceous). According to Dantas et al. (2010), its elevations vary from 600 to 1,300 m a.s.l., with a smooth inclination to the west. In these areas, freezing is common and snow is not rare in the highest points.

The Planalto Sul-Rio-Grandense is located in the south-southeast sector of the state of Rio Grande do Sul, composed of Precambrian igneous and metamorphic

Fig. 1 Location of the study area

rocks. This area is characterized by the Rio de la Plata Craton and the Dom Feliciano Belt. This belt corresponds to an ancient collision area between two continents and these rocks correspond today to the cratons of Rio de la Plata (state of Rio Grande do Sul and Uruguay) and Kalahari (Southern Africa) (Fig. 4). The rocks corresponding to the Rio de la Plata Craton and the Dom Feliciano Belt became the source of the Paleozoic sedimentation that took place within the Intercratonic Depression of Paraná (Paraná Basin). These sediments are basically of continental nature and are essentially periclinal structures, diminishing mainly towards the west, that is, towards the Paraná and Lower Uruguay river basins (Suertegaray and Fujimoto 2004). In those times, in geomorphological terms, the area of Rio Grande do Sul comprised two units, the Planalto Sul-Rio-Grandense, which was undergoing erosion, and a large sedimentary plain corresponding to the Paraná sedimentary basin.

The present configuration of the relief of Rio Grande do Sul has its origin in the breakup of Gondwanaland, which in this area is characterized by the opening of the South Atlantic Ocean that started around 132 Ma (Suertegaray and Fujimoto 2004). Since then, the geomorphological scenario became much more complex, with the occurrence of the rhyolite and basaltic flows and the formation of faults which generated elevated and depressed regions. Between the Middle Jurassic and

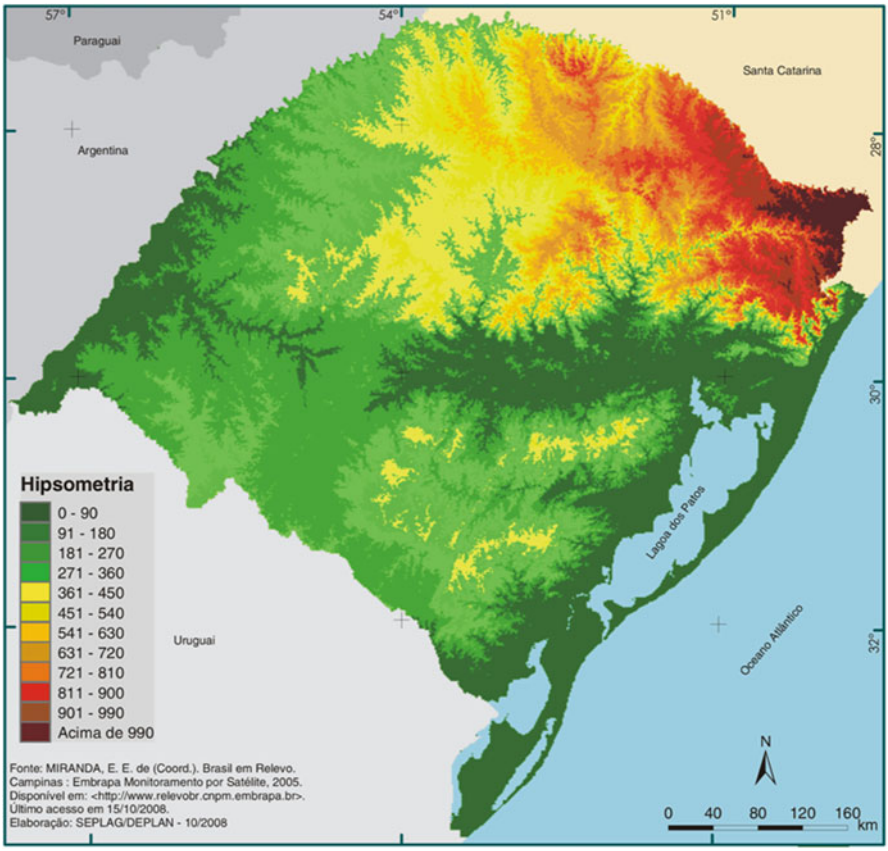

Fig. 2 Hypsometric map of the state of Rio Grande do Sul

the Middle Cretaceous, the fragmentation of Gondwanaland forced a series of fault lines and reactivation that defined the main compartments of the present regional landscape.

The opening of the South Atlantic Ocean created a new direction for the erosion of the Planalto Sul-Rio-Grandense, where a new surface was formed to the east, associated with the creation of a depressed area which the ocean would occupy later on. The reactivation of fault alignments followed by uplifting and down-warping promoted the reorganization of the drainage, which initiated the erosion processes that would generate the Periphery Depression of Rio Grande do Sul. Thus, towards the Late Cretaceous, a strong erosion phase became installed in the area, ending with a subsequent dynamics with dominance of depositional processes (Suertegaray and Fujimoto 2004). The area of the Planalto Sul-Rio-Grandense passed this phase with intense vertical erosion, forming the Rio Camaquã valley, which drains eastwards cutting the Planalto Sul-Rio-Grandense in two portions, north and south.

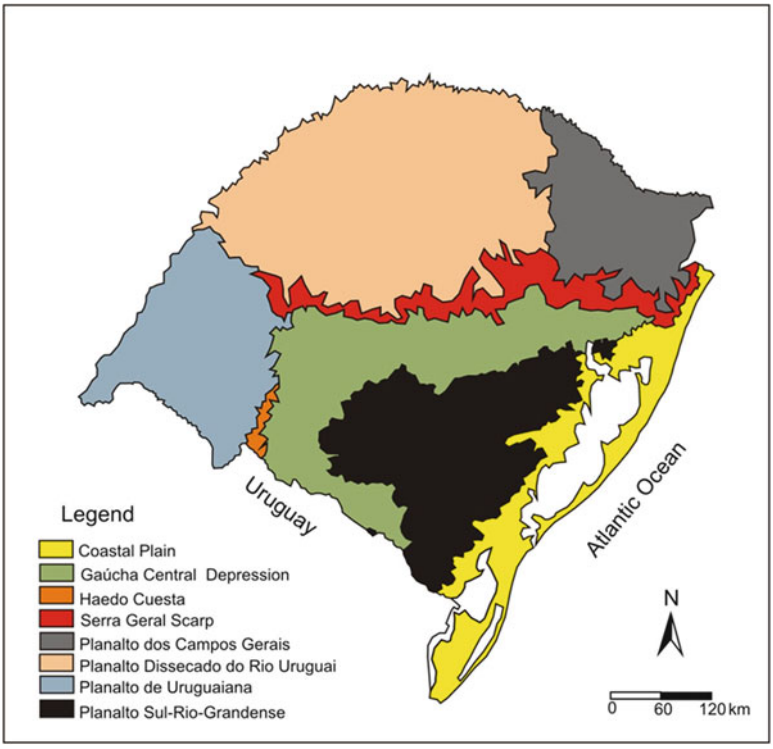

Fig. 3 Geomorphological units of the state of Rio Grande do Sul (Dantas et al. 2010)

According to Ab'Sáber (1949), towards the end of the Cretaceous, the area would have been a vast lowlands extending across planated remains of the crystalline nuclei and basaltic plains, with drier climate and endorheic drainage. In the Tertiary, the climate would have been more humid and the uplifting of the area would have promoted the establishment of exorheic drainage, forcing marginal denudation.

The Vacaria Surface

The Vacaria Surface corresponds to the highest portions in the entire state of Rio Grande do Sul (Fig. 3), with altimetry between 950 and 1,100 m a.s.l., smoothly sloping towards the west, south, and southeast, preserving the same landscape pattern until altitudes of 750–800 m a.s.l. are reached, when this high plain is abruptly interrupted by high scarps (Ab'Sáber 1969).

In the eastern portion of the area the highest elevations (close to 1,200 m a.s.l.) occur, and in the State of Santa Catarina several isolated points are even higher, as it is the case of the Morro da Igreja, with 1,822 m a.s.l. (Brasil 1986).

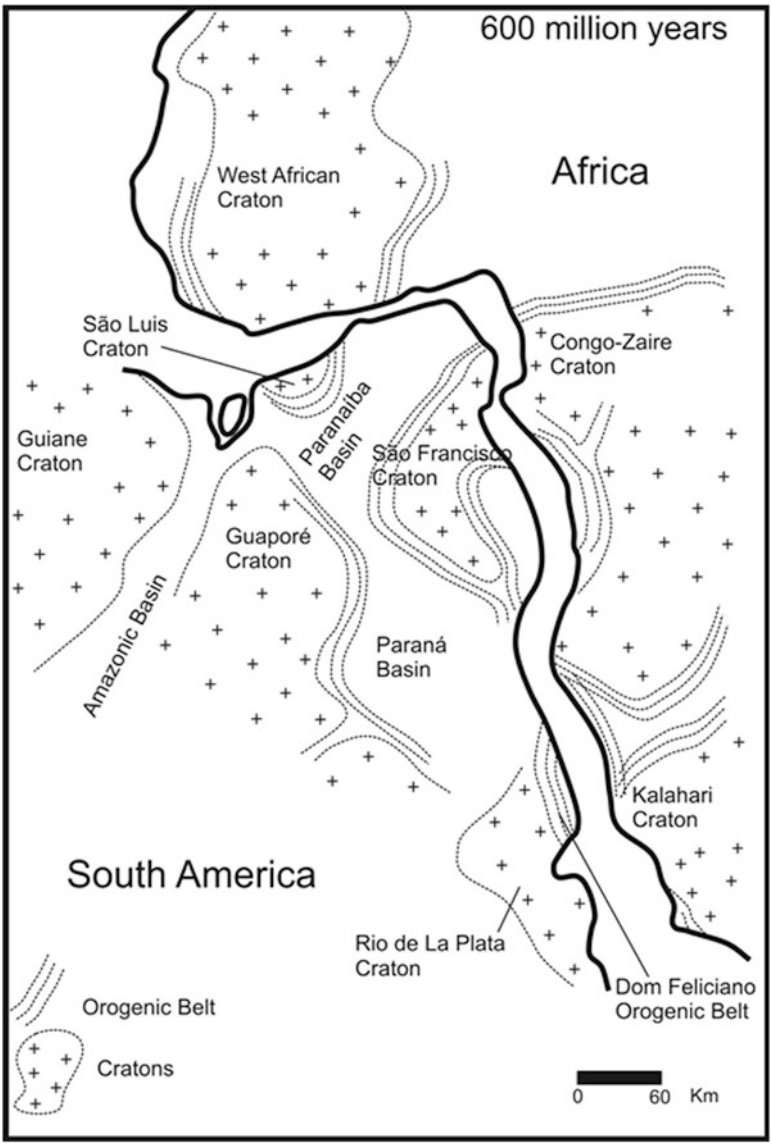

Fig. 4 Position of the Rio de la Plata and Kalahari cratons and the Dom Feliciano Belt, approximately ca. 600 Ma (Salgado-Laboriau 1994)

According to Brasil (1986), this surface is well preserved and it was formed by pediplanation processes, truncating rocks with little or no weathering. The evolution of the relief in this area indicates the existence of different phases of recurrent erosion processes, with the persistency of a well-preserved planation surface, interfingering with areas where erosion was able to elongate the valleys and create

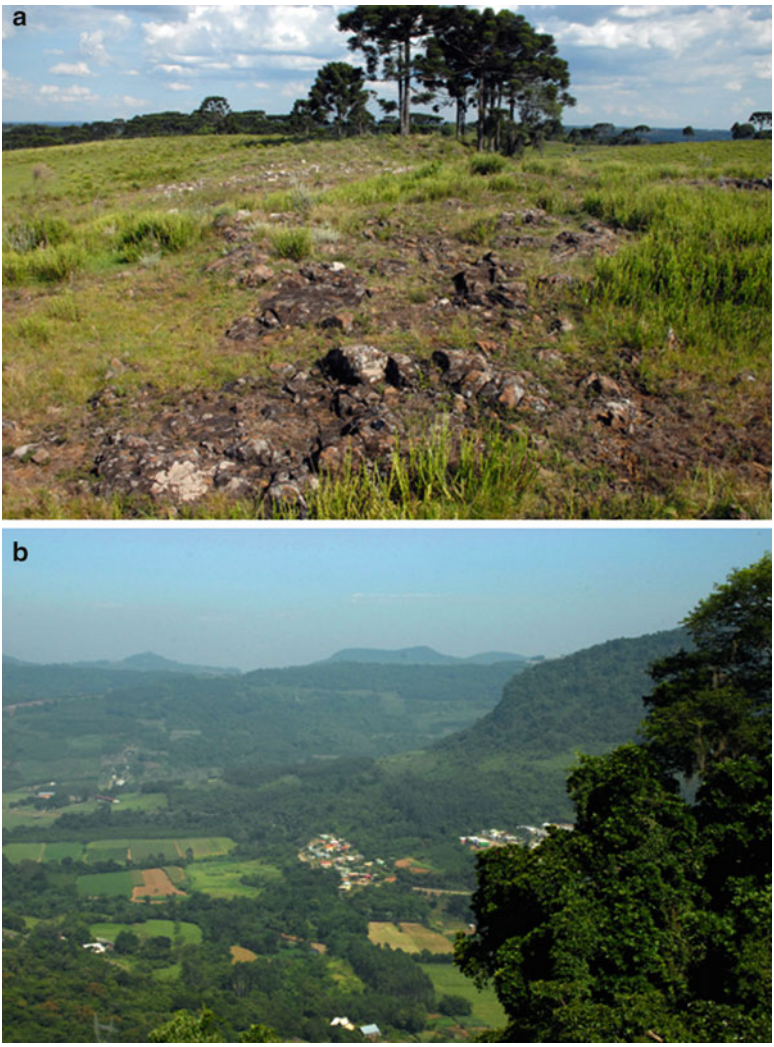

Fig. 5 Surface elaborated on rhyodacites at the top of the Planalto dos Campos Gerais (Vacaria Surface) (**a**) and at its scarps (**b**), with the summit surface around elevations of 850 m a.s.l.

topographic thresholds with scarps of minor relief. In some areas, erosion succeeded in extensively expanding the valleys, leaving remnants of the old surface. The latter ones correspond to large areas with isolated hills, separated by broad valleys with flat bottoms. These hills usually preserve flat summits and breaking of inclination along the slopes (Brasil 1986; see Fig. 5).

This surface would correspond, in a broad sense, to the geomorphological region named as "Planalto das Araucárias" (or that of the Campos Gerais, according to Dantas et al. 2010), with extension to the State of Santa Catarina,

presenting homogeneous geomorphological characteristics, with the higher parts corresponding to broad planation surfaces which sometimes end in scarps with more than 500 m of local relief (Brasil 1986).

Brasil (1986) indicated that this surface is developed on top of rocks belonging to the Serra Geral Formation. Its upper part consists of acid lava flows, such as rhyolites, rhyodacites, and felsic gabbros. In the basal portions of the Serra Geral Formation, in this area, basic rocks occur. The Vacaria Surface has been mainly developed on the acid rocks of the Serra Geral Formation, but locally it has evolved on more basic rocks where relief is flatter. According to Ab'Sáber (1969), the remnants of that surface at elevations close to 800 m a.s.l. show an inclination from north to south and from north-northeast to south-southwest, indicating the impact of a modern deformation on the ancient planation surface. For this author, this surface would correspond to an important period of exorheic pediplanation, postdating the lava flows, and most likely of Cretaceous age.

Ab'Sáber (1969) believed that this summit surface would have been affected by pediplanation at the time when the different sectors of the present Brazilian states of Rio Grande do Sul, Santa Catarina, and Paraná of the southern high plains served as watersheds of the Cretaceous deposits in the northern portion of the craton (states of São Paulo, Mato Grosso, southwest of Goiás and the Triângulo Mineiro) and of the southern sector (Uruguay and southwestern portion of Rio Grande do Sul) of the Paraná sedimentary basin.

According to Ab'Sáber (1969), this surface would have been very well preserved, because for a long time the drainage was scarcely incised. But fast epirogenetic uplifting movements in the Paleogene and the Neogene generated strong incision of the stream channels, whereas the water divides of the high plains would have been preserved. In spite of the canyon deepening, the summit areas in between them remained quite flat and untouched by stream erosion.

Suertegaray (2010) noted, with information based in more recent mapping projects (DNPM 1989), that there is a larger diversification of the rock types related to this surface, not only basalts as it was believed before. More specifically reddish porphyritic rhyodacites occur on the Vacaria Surface. This acid volcanic rock is much more resistant than basalt to weathering and erosion. Ab'Sáber (1969) noted that in this area the soils were quite thin which could be associated, on one hand, to the lower temperatures that occur in this area (Dantas et al. 2010) and also to the resistant rock. In spite of their shallow nature, the soils of the region are intensively used for agricultural purposes (Fig. 6).

In this surface, the fluvial channels are strongly incised following structural alignments (Brasil 1986) (Fig. 7).

Caçapava do Sul Surface

The area of crystalline basement in Rio Grande do Sul is the so-called Planalto Sul-Rio-Grandense, which extends for over 46,000 km^2, bounded to the north and west by the Gaúcha Periphery Depression, to the east by the Inner Coastal Plain and to the

Fig. 6 Vacaria Surface with relatively thin soils, normally Cambisols and Neosols (**a**) and a relatively flat topography being used for soya crops in the neighborhood of the city of Vacaria (**b**)

south by the Uruguayan territory where it continues. The area of higher elevations (above 400 m a.s.l.) belongs to the better preserved portion of the Caçapava do Sul Surface, with a total extent of 15,070 km^2 (Brasil 1986). Normally, the contact of this high plain takes place smoothly without large topographic irregularities, as happens with the coastal plain (Fig. 8).

The complexity of the Precambrian lithology of the area is reflected in the variety of the landforms. The area is intensely and deeply dissected, especially following the SW-NE and NW-SE directions. Similarly to this area, other less incised landscapes

Fig. 7 A deep canyon eroded in the Vacaria Surface

Fig. 8 Planalto Sul-Rio Grandense (at the background), with a substratum of granite in contact with the Coastal Plain, which locally presents altitudes lower than 10 m a.s.l.

occur, in summit positions, corresponding to pediplain surfaces (Brasil 1986). This better preserved surface located in summit positions was named the Caçapava do Sul Surface by Ab'Sáber (1969); Brasil (1986) named it as the "Planaltos Residuais" ("residual high plains") of Canguçu and Caçapava do Sul, because these higher high plains are dissected by the valley of the Rio Camaquã (Figs. 9 and 10).

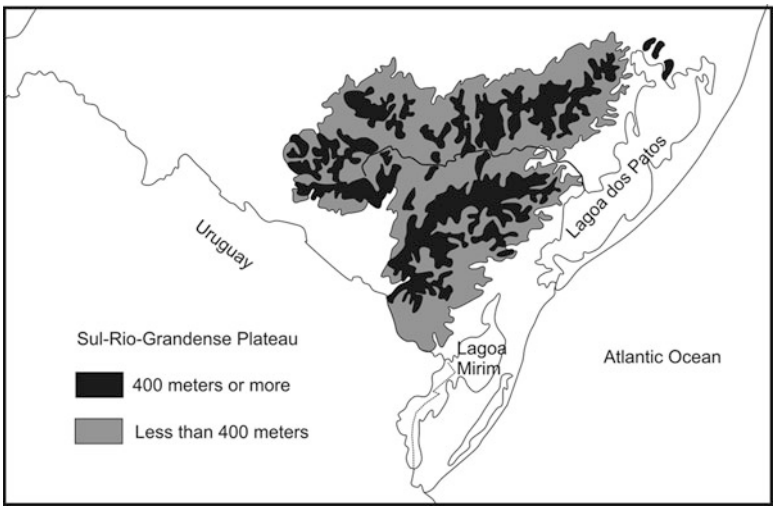

Fig. 9 The Planalto Sul-Rio-Grandense and the Rio Camaquã. The *darker colors* correspond to elevations above 400 m a.s.l. and the *lighter* ones represent the lower elevations

Fig. 10 Summit surface (*A*) near 420 m a.s.l., with the southern portion at the foreground (Canguçu) and the northern portion of the Planalto Sul-Rio Grandense (Caçapava do Sul) at the background; (*B*): the valley of the Rio Camaquã, with elevations lower than 200 m a.s.l.

Brasil (1986) noted that residual portions with elevations above 400 m a.s.l. were surrounded by another surface with altitudes lower than 400 m a.s.l., both eroded on the crystalline basement rocks. The better dissected and with lower elevation portions of the Uruguayan-Sul-Rio-Grandense Shield appear in between

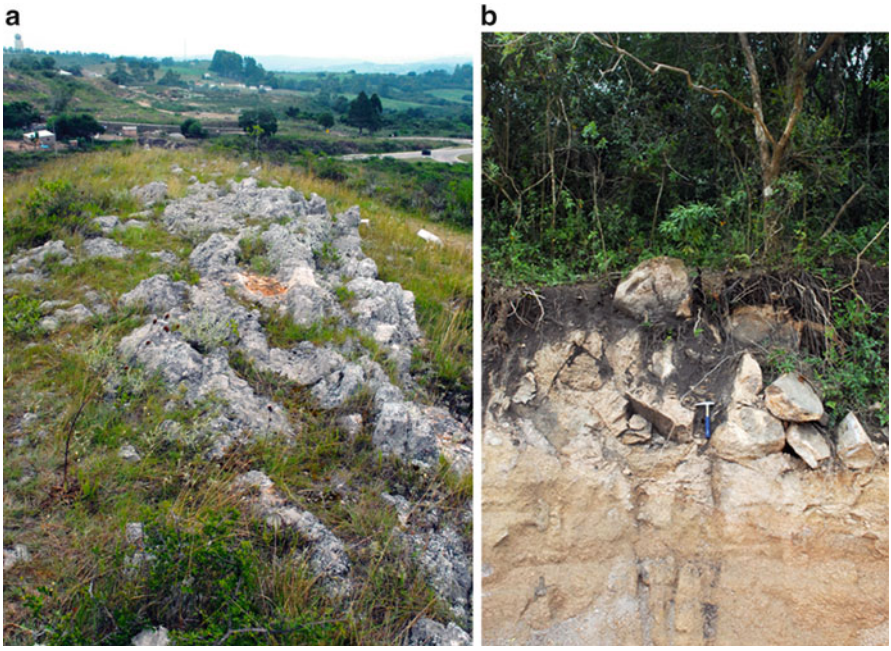

Fig. 11 The Canguçu region. Top of the surface at 463 m a.s.l., with outcropping granites (**a**), associated with Neosols forming tors (**b**)

100 and 200 m a.s.l. These eroded areas of the relief are intensively dissected in the Precambrian rocks, and they have steep slopes where ridges, inselbergs, and inclined rocky plains are found (Brasil 1986).

Brasil (1986) indicated that the areas with higher elevations of the Uruguayan-Sul-Rio-Grandense (Planalto Sul-Rio-Grandense) are only slightly dissected in portions of the area, being formed by hills with flat tops that are remnants of the ancient pediplanation surface. Hermann and Rosa (1990) noted that the most densely dissected portions are those between the contour lines of 100 and 200 m a.s.l.

The less dissected areas or those with flat summits are characterized by thin superficial formations or exposed bedrock in the form of rocky outcrops and detrital pavements (Hermann and Rosa 1990) (Fig. 11).

In spite of their modest elevation (450–460 m a.s.l.), this is one of the summit surfaces most characteristic of the country, corresponding to a surface that levels the central portion of the Uruguayan-Sul-Rio-Grandense Shield, indicating a high degree of perfection in the ancient planation processes. This surface is present in both the territories of Rio Grande do Sul and Uruguay, with no residual landforms in any point of its entire extent. It cuts indiscriminately across all sorts of structures and lithological types (Ab'Sáber 1969).

Ab'Sáber (1969) indicated that, in its original extent, it would have been a vast pediplain, plunging towards the west, south, and southwest, although it also slopes

Fig. 12 (**a**, **b**) Tors positioned at the slopes of the uppermost surface

towards the northeast and the east. The eastern portion of the region is strongly affected by the Atlantic (passive margin) tectonics. Suertegaray (2010) stated that this inclination towards the east of the summit surface of the Uruguayan-Sul-Rio-Grandense Shield is directly related to the opening of the Atlantic Ocean (Middle Jurassic to Cretaceous), when a reactivation of the faulting zones parallel to the present coast of the state of Rio Grande do Sul took place, sloping the surface eastwards, in the same manner as block down-warping affected the Paraná Basaltic high plain.

It is worth noting that it is quite rare to observe tors in the higher portions of this surface, although these are very common in the lateral slopes of the highest portions (Fig. 12). These blocks are rather abundant in several areas, particularly in those on granites.

Fig. 13 Images of the Santa Tecla Formation (silicified sediments of the Early Tertiary) in the area of Caçapava do Sul, positioned next to the crystalline rocks of the Planalto Sul-Rio-Grandense, being thus associated with them (Photos by Constantino Brião de Oliveira).

Ab'Sáber (1969) indicated that, contrarily to what happens in the Vacaria Surface (which does not have correlative deposits in its surroundings), the Caçapava do Sul Surface shows its relationship with the deposits of the Santa Tecla Formation, which would be quite important for its geomorphological characterization. When Ab'Sáber described this association, the Santa Tecla Formation was considered to be Cretaceous in age, but it is considered today as of a probably Early Tertiary age (Kaul 1990) (Fig. 13).

Ab'Sáber (1969) believed that at the time of formation of the summit surface of the Uruguayan-Sul-Rio-Grandense Shield, in its northern portion, the surface of the rhyolite and basaltic plain was above the Caçapava do Sul Surface. The space where the Gaúcha Peripheral Depression is today would have a much larger volume of Gondwana deposits, which would have surrounded laterally or partially covered the axis of the shield. In such times, the Vacaria Surface would have evolved affected a much larger amount of geological formations and structures. With renewed Cretaceous uplift and deformation, there was also a renewal of the planation processes, which exhumed various buried areas of the shield and created vast pediplains across the summits. The planation of the Caçapava do Sul Surface would have conquered geographical areas which previously belonged to the Vacaria Surface. This author believed that the carving of this surface would correspond to the end of the Cretaceous sedimentation in Uruguay and the state of Rio Grande do Sul.

After the elaboration of this surface, Ab'Sáber (1969) noted that uplift of this area forced intense vertical erosion, in both in the central area of the massif and its surroundings, forming broad surfaces in between the high plains. Several of those inter-"planalto" surfaces, younger than the Caçapava do Sul Surface, were well preserved due to the silicification and ferrugination processes on the sandstones of the Rio Bonito Formation.

The down-wasted surface, which Ab'Sáber (1969) discussed, underwent a relatively intense process of lateritic profile formation. This profile affected in an undifferentiated manner crystalline basement rocks and also Triassic sedimentary rocks of the Santa Maria Formation (Figs. 14 and 15). The base of these lateritic profiles is preserved exclusively on the lower surfaces, below 300 m a.s.l. Most likely, this profile covered the entire high plain during the Early Tertiary but was later partly eroded.

Also in this largely down-wasted portion, little, shallow depressions are very common, which have been formed directly on the crystalline basement (Fig. 16). In these areas, the soils are very shallow, indicating that they are not related to recent karst processes. These small depressions may be related to the most depressed portions of the weathering front, at the contact between the weathering profile and the fresh bedrock (Jorge Rabassa, personal communication, 2012). At these elevations, lateritic accumulations also occur, as was identified by Ladeira and Santos (2006). These are the remains of former, extensive lateritic profiles which were formed in a distant past, and in most places, the entire lateritic profile has been eliminated. The present soils are very thin, some of them evolving on top of the remnants of Tertiary lateritic profiles.

Geomorphological Evolution: From the Permian to the Paleogene

During the Paleozoic and the Mesozoic, the South American Platform was affected by uplifting and subsidence processes which were fundamental in the sedimentation and configuration of the Paraná Basin (Almeida 1964, 1981). In this period, three

Fig. 14 (**a**) Eroded lateritic profile on gneiss, at 110 m a.s.l.; (**b**) Detailed view

well-defined, tectono-sedimentary cycles have been recorded, which marked periods of deposition or erosion (Soares et al. 1978) that were very important in the long-term sculpting of the center-south portion of Brazil. In Fig. 17, it is possible to observe a proposed evolutionary scheme for the Southern Brazil surfaces, from the Paleozoic onwards.

In the studied area, Devonian sediments are absent, being the surface elaborated only on the crystalline basement materials. By the Late Permian, deposition processes started concerning the materials corresponding to the present Planalto Sul-Rio-Grandense as source area of the sediments, generating deposits of this age

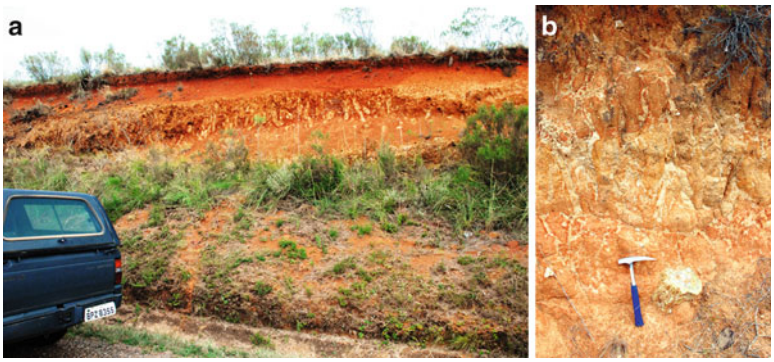

Fig. 15 (**a**) Profile of lateritic weathering affecting the Triassic sediments of the Santa Maria Formation, within the valley of the Rio Camaquã, in the inner portion of the Planalto Sul-Rio-Grandense; (**b**) Detailed view

towards the west, northwest, and southeast of the shield. Eastwards, these materials do not occur because the Atlantic Ocean was not yet open. These deposits have a well-defined, marine character (Kaul 1990).

In the Late Triassic, continental deposits of the Santa Maria Formation occurred, which in the state of Rio Grande do Sul cover the crystalline basement, a fact confirmed by the presence of terrestrial deposits of this formation, with fossilized tree trunks in the interior of the Planalto Sul-Rio-Grandense, especially in its western portion. In the Late Jurassic eolian deposits are associated with the Botucatú Formation. The source area for these sediments should be positioned farther away towards the east, where the crystalline basement was still outcropping. These areas are positioned today in Africa and in the submarine platform of the Southern Atlantic Ocean.

At the end of the Jurassic and in the Early Cretaceous, the rifting processes started that would lead towards the genesis of the Atlantic Ocean. In this process, volcanic activity took place that generated vast areas with lava flows belonging to the Serra Geral Formation. Ab'Sáber (1969) did not rule out the possibility that these flows would have covered even the crystalline basement area of the present Planalto Sul-Rio-Grandense, since these rocks were not observed during field studies. According to Brasil (1986), on the contrary, in the Late Jurassic, with the beginning of the Gondwana breakup processes, the area of the Planalto Sul-Rio-Grandense was undergoing erosion processes, whereas the rest of the areas were receiving continental sedimentation. In that moment, fissure volcanism was in-filling the Paraná Basin. Synchronically to these deposits, subsidence processes were taking place which allowed a significant piling-up of volcanic rocks. Thicker deposits occurred within the syncline, whereas they were thinner in the borders. At this time the Pelotas Basin started to form.

From this time erosion of the basement took a new direction, going in an eastward direction towards the Pelotas Basin. During the Cretaceous, the Triassic and Jurassic deposits on top of the basement were almost totally eroded, remaining only at just

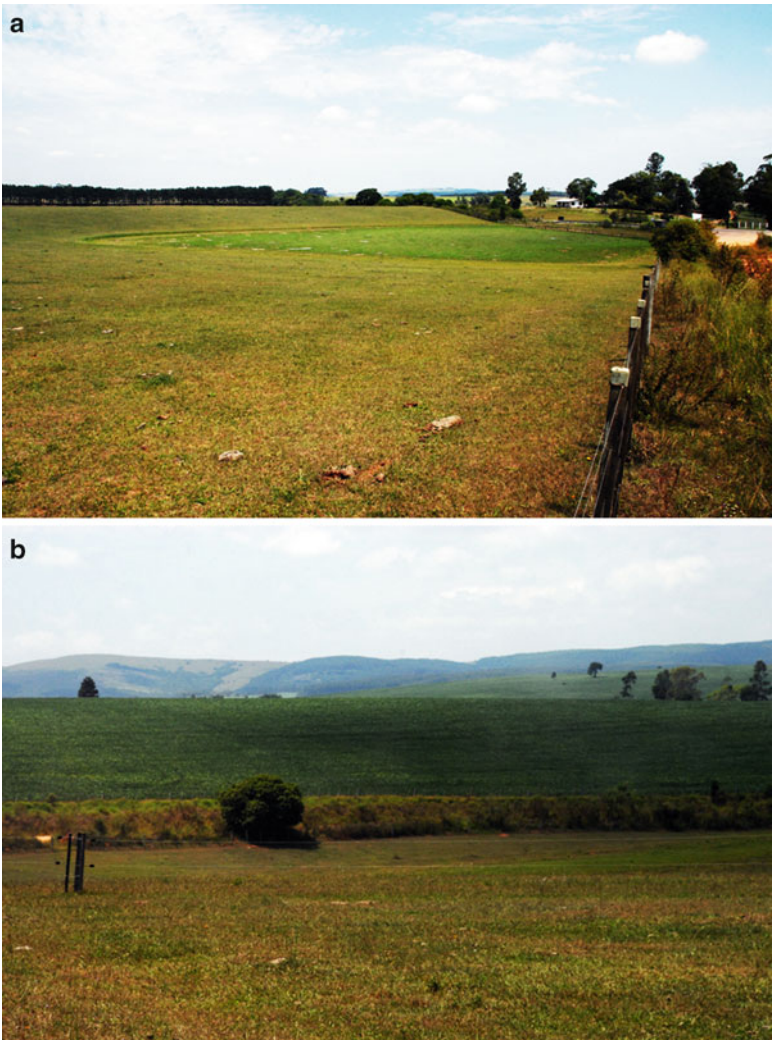

Fig. 16 (**a**) Depressions in a landscape of smooth slopes; (**b**) A depression in the foreground, below elevations of 300 m a.s.l.; in the background, the higher surface of the Planalto Sul-Rio-Grandense

a few specific points. Thus, during the Cretaceous the Planalto Sul-Rio-Grandense became again an important positive area provider of sediments for the surroundings; therefore, it had been exhumed during this period.

During the Early Tertiary, the area of the Planalto Sul-Rio-Grandense was still a source area for the continental deposits of the Santa Tecla and Tupanciretã formations, and it continued to be the source area for the coastal and marine deposits of the eastern face, with the Rio Camaquã cutting the entire basement in an eastward direction.

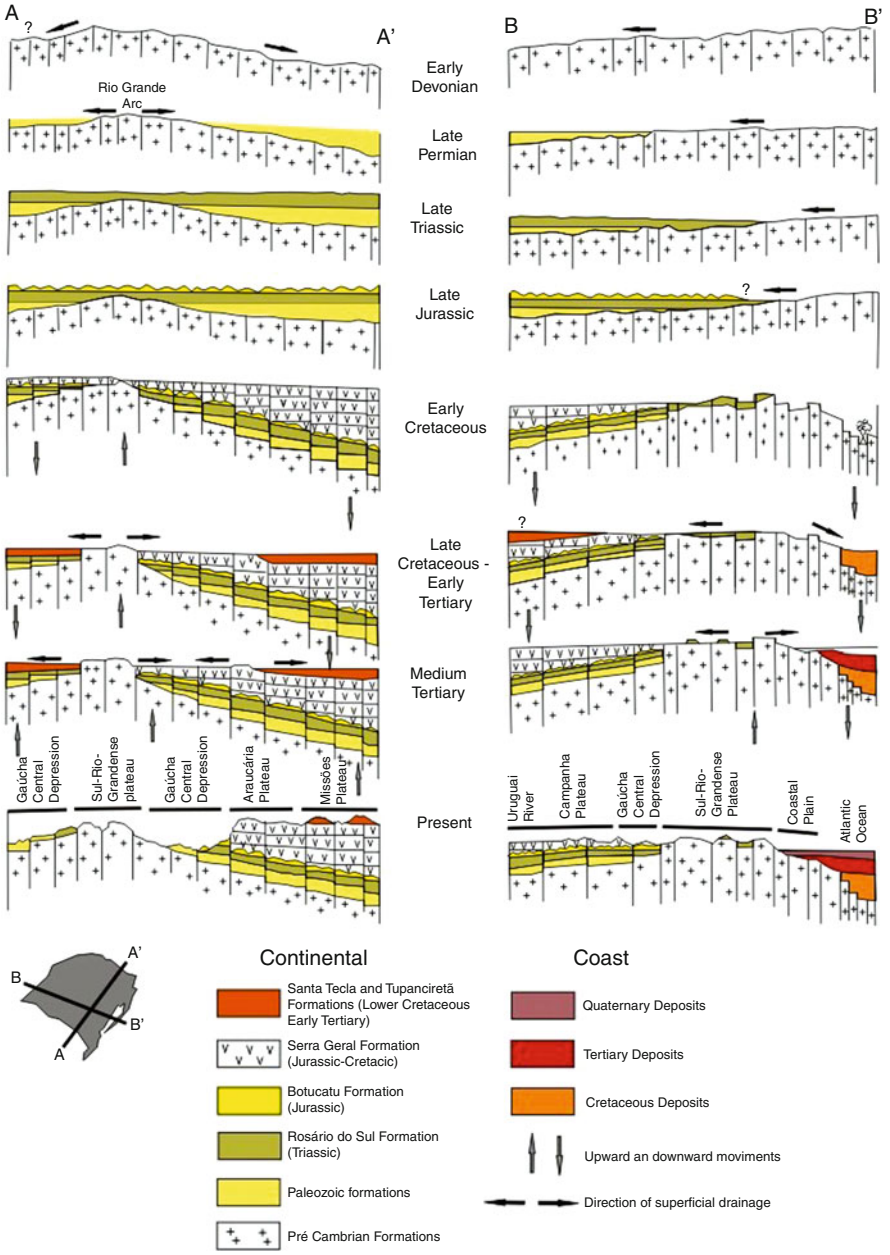

Fig. 17 Schematic profiles of the morpho-structural evolution (Brazil 1986)

By the Early Tertiary, the present geomorphological configuration of the state of Rio Grande do Sul was established, with its different units. It is likely that in the Early Tertiary the lateritic weathering profiles were developed, affecting very clearly the Planalto Sul-Rio-Grandense. Presently, all these profiles have been truncated, indicating erosion action after this period.

The tectono-magmatic events stopped during the pre-Aptian times in the Cretaceous, starting then a long period of quietness that lasted until the Late Cretaceous. In this period, the Pelotas Basin was receiving sediments of a tafrogenic sequence, and in the hinterland, a polygenetic erosion surface was developing, whose evolution continued even into the Paleogene. In the interior, both in the north and the south of the Rio Grande Arc, correlative sediments were deposited which corresponded to the Santa Tecla and Tupanciretã formations (Brasil 1986).

During the Late Cretaceous the pediplanation surface in the Planalto Sul-Rio-Grandense was affected by tectonic reactivation and alkaline magmatic processes (Brasil 1986).

According to Brasil (1986), during the Paleogene more humid and cooler conditions dominated, following the uplift of the Andean Cordillera to the west and the presence of the large oceanic mass of the Atlantic. Then, an exorheic drainage network was established on a surface without large topographic irregularities, being almost horizontal. The slow uplifting that affected the area allowed the superimposition of the drainage. This action, associated to the impact of alternating aggressive climates allowed the occurrence of down-cutting phases with moments of lateral degradation and intense erosion of the slopes, which provoked the removal of the capping of effusive rocks and the Gondwana deposits in the periphery of the Planalto Sul-Rio-Grandense, initiating an extensive peripheral denudation.

Following Brasil (1986), the endorheic conditions that evolved in the Paleogene allowed the elaboration of the Caçapava-Vacaria Surfaces. The highest topographic levels correspond to evolutionary conditions in an endorheic system, which was modified when the exorheic conditions were established.

As stated by Brasil (1986), the Vacaria and Caçapava Surfaces followed a similar evolutionary pathway, and therefore, they would be part of the same surface. The surface would have had a polygenetic evolution, according to the occurrence of successive erosion phases and the climatic variations dominating during their formation, which would have taken place from the Cretaceous until the Oligocene.

Final Remarks

The paleosurfaces of the state of Rio Grande do Sul deserve a more dedicated analysis, with mapping and research in greater detail. These surfaces are characterized by specific conditions that help in interpretation and are more complex than other areas of Brazil. The understanding of these surfaces includes situations in which two sets of lithology with totally different ages were deeply involved and closely associated.

From one side, the surface named by Ab'Sáber (1969) as the Caçapava do Sul Surface cuts through a varied lithology and served as a source area for the Paleozoic sedimentary units. At some moment of the Early Mesozoic, this surface was covered by sediments (and perhaps also by lava flows related to the opening of the South Atlantic Ocean). In the Late Cretaceous, this surface was exhumed (the present Planalto Sul-Rio-Grandense) and became the source area for the sediments of the Late Cretaceous and the Tertiary, a process that still continues today. Likewise, the exhumation was not able to fully eliminate the Triassic sediments found today in the hinterland of the Planalto, a strong indication of this ancient covering.

It would be of great importance if joint research projects between Uruguayan and Brazilian geomorphologists could be developed for the observation and correlation of the Gondwana Surfaces in the territory of these two adjacent countries.

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