Ancient Landscapes of Uruguay

Daniel Panario, Ofelia Gutiérrez, Leda Sánchez Bettucci, Elena Peel, Pedro Oyhantçabal, and Jorge Rabassa

Abstract In this chapter, based on the available geological information, a model for the genesis and evolution of the Uruguayan landscape is proposed. A structural framework of the landscape evolution is provided and the record of such evolution in the most representative geological units is considered. A brief summary of the Uruguayan geology and its location in the regional context is performed, from Precambrian to Cenozoic times.

From the analysis of the geological record, it may be observed that the climate was very arid during part of the Jurassic and the Early Cretaceous. Together with the lava flows of the Arapey Formation, the climate became less arid as the Gondwana continents were becoming apart from each other. However, the geological record suggests that semiarid climates were still prevailing. In the Middle Cretaceous, semiarid and wetter climates progressively alternated, until the Early Tertiary, when very wet and warm conditions were established, in coincidence with the "Palaeocene–Eocene Thermal Maximum (PETM)", followed by semiarid climates in the Oligocene, wetter conditions in the Miocene and semiarid again in the Pliocene, with alternating semiarid and humid conditions during the entire Quaternary.

D. Panario (✉) • O. Gutiérrez
UNCIEP, Instituto de Ecología y Ciencias Ambientales (IECA), Facultad de Ciencias,
Universidad de la República, Montevideo, Uruguay
e-mail: daniel.panario@gmail.com; panari@fcien.edu.uy; oguti@fcien.edu.uy

L. Sánchez Bettucci • E. Peel • P. Oyhantçabal
Departamento de Geología, Facultad de Ciencias, Universidad de la República,
Montevideo, Uruguay
e-mail: leda@fcien.edu.uy; elena@fcien.edu.uy; oyhantca@gmail.com

J. Rabassa
CADIC-CONICET, Ushuaia, Argentina

Universidad Nacional de Tierra del Fuego, Ushuaia, Argentina
e-mail: jrabassa@gmail.com

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Based on the palaeoclimatic evolution, the development of relief is discussed, considering the analysis of different morphostructural units in which the country is divided. Due to their size, shape and location (passive margin) of Uruguay, climate uniformity is assumed for each period throughout the entire territory. It is also assumed that the surfaces around elevations of 500 metres above sea level (m a.s.l.) correspond to relicts of probably pre-Cretaceous etchplains, strongly denudated, which are observed only in the surroundings of Aiguá area.

The landforms situated below the oldest surfaces, for instance, those below 320 m a.s.l. in the Eastern Hills Region (Sierras del Este), correspond to a new generation of geomorphological surfaces that may be considered of Cretaceous age, according to the information presently available. This surface may be correlated with the oldest surface developed on top of the lava flows of the Arapey Formation.

The extremely warm and wet climate of the Eocene prepared the conditions for the planation processes that covered most of the Uruguayan territory during the Oligocene, generating pediplains which were later reworked during the Late Cenozoic, up to the Quaternary, generating a landscape of smooth hills.

The morphogenetic potential of each morphostructural region determined the available energy of the resulting landscape, being this at a minimum in the Santa Lucía Basin, which continued to be under subsidence condition until the Tertiary, and almost nonexistent in the Laguna Merín Basin, where subsidence remains active until the Holocene.

Keywords Gondwana landscapes • Cenozoic landscapes • Uruguay • Paraná Basalt • Cratonic areas

Introduction

Uruguay lies on the West Atlantic Ocean coast of South America, between 30° and 35° South latitude and 53° and 58° West longitude (Fig. 1). It has a total land area of 176,215 km^2. The Uruguayan relief is quite reduced, between sea level and maximum elevation around 500 m a.s.l. (Fig. 2). Most of the territory is smoothly undulated, and it is developed within a range of 0–200 m a.s.l.

The climate of the region is temperate with an annual rainfall of 1,200 mm year^{-1} and a mean temperature of 18 °C. It is of the humid subtropical type (*Cfa* according to the classical Köppen climate classification). Seasons are properly well separated: spring is frequently humid, cool and windy; summers are warm; autumns are mild; and winters are chilly and uncomfortably damp. Bidegain and Caffera (1997) suggested the following climatic classifications: (1) mild climate, moderate and rainy (the cooler temperatures standing between −3 and 18 °C); (2) wet climate (rain is irregular, intermediate conditions between w and Köppen s types), "F type"; and (3) a temperature of the warmest month above 22 °C, "A type".

Fig. 1 Location map

Regional Geology

Precambrian Geology

Uruguay is part of the South American Platform and its geology consists of a Precambrian basement cropping out in the southern part and Palaeozoic to Mesozoic sediments and Mesozoic basaltic flows in the northern region, the latter being part of the Paraná Basin. Two main Mesozoic rift basins, related to the opening of the South Atlantic Ocean, are present in the southern portion (Santa Lucía Basin) and in the eastern portion (Laguna Merín Basin) of the country (Figs. 3, 4 and 5).

The Precambrian basement comprises nearly approximately 45 % of the country surface, and different approaches have been used within the last 30 years to define its main units. A first division was postulated by Ferrando and Fernández (1971), who considered two groups of ages defining two main domains, one of them of Palaeoproterozoic age (2.2–2.0 Ga) in the southwest and the other of Neoproterozoic age (900–550 Ma) in the East. Afterwards, Fragoso-Cesar (1980) defined the Dom Feliciano Mobile Belt (Neoproterozoic), located at the east of the Río de la Plata Craton (RPC).

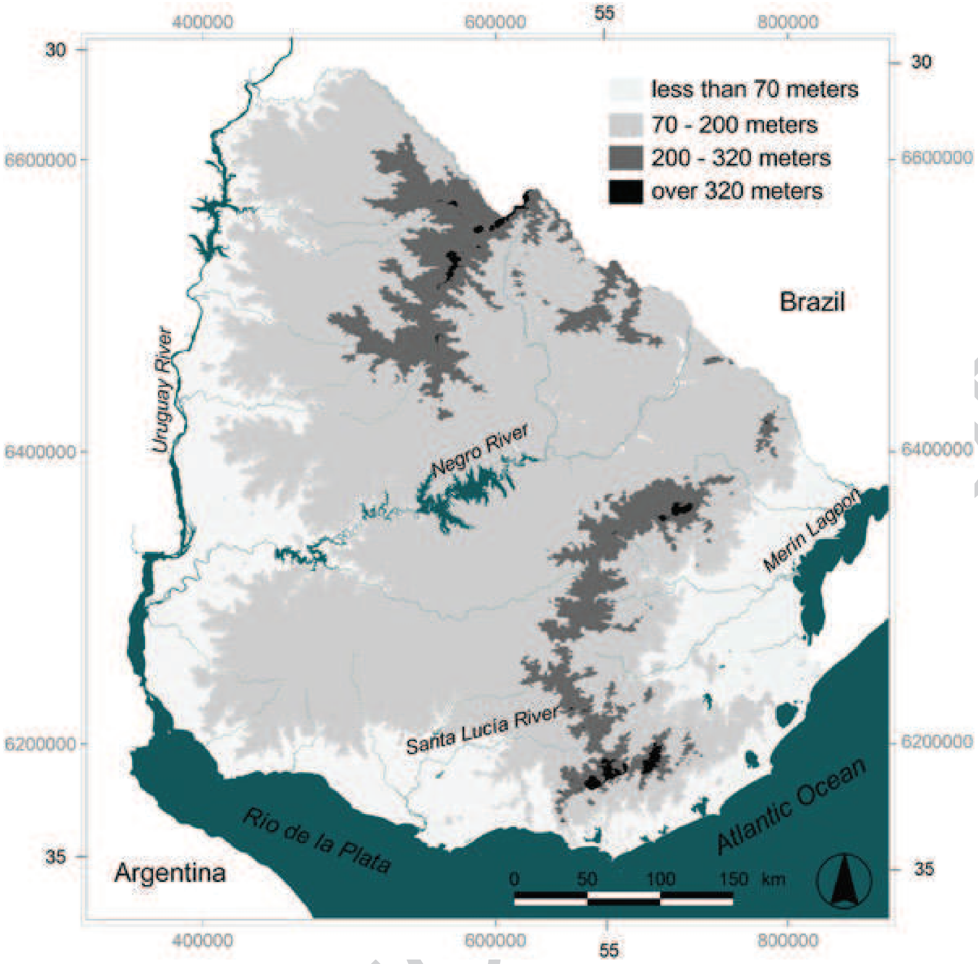

Fig. 2 Hypsographic map. Uruguay presents a landscape that occurs within a quite reduced altitudinal range, between sea level and maximum elevations around 500 m a.s.l. This hypsographic map has been prepared using 10 m contour lines in maps provided by the Servicio Geográfico Militar (SGM) of Uruguay

The Río de la Plata Craton (RPC) was originally defined by Almeida et al. (1973) including the older cratonic areas. Later, Bossi and Campal (1992) considered it as a build-up of two main terranes, the Piedra Alta Terrane (PAT) on the western side of the Sarandí del Yí Shear Zone (SYSZ) and the Nico Pérez Terrane (NPT) developed between the Sarandí del Yí and the Sierra Ballena Shear Zones (SBSZ) (see Fig. 5). Recently, Oyhantçabal et al. (2011) proposed the redefinition of the Río de la Plata Craton including only the juvenile Palaeoproterozoic rocks which were not tectonically reworked during the Neoproterozoic. According to this new definition, the Río de la Plata Craton (RPC) crops out only in the Piedra Alta Terrane of Uruguay (see Fig. 5) and in the Tandilia system in Argentina (Cingolani 2011). The Nico Pérez Terrane on the other hand includes Archaean and Palaeoproterozoic rocks, was strongly tectonically reworked during the Neoproterozoic and Brasiliano granitic intrusions are widespread; it should therefore be considered as an allochthonous basement unit, latter accreted to the Río de la Plata Craton (Oyhantçabal et al. 2011; Rapela et al. 2011).

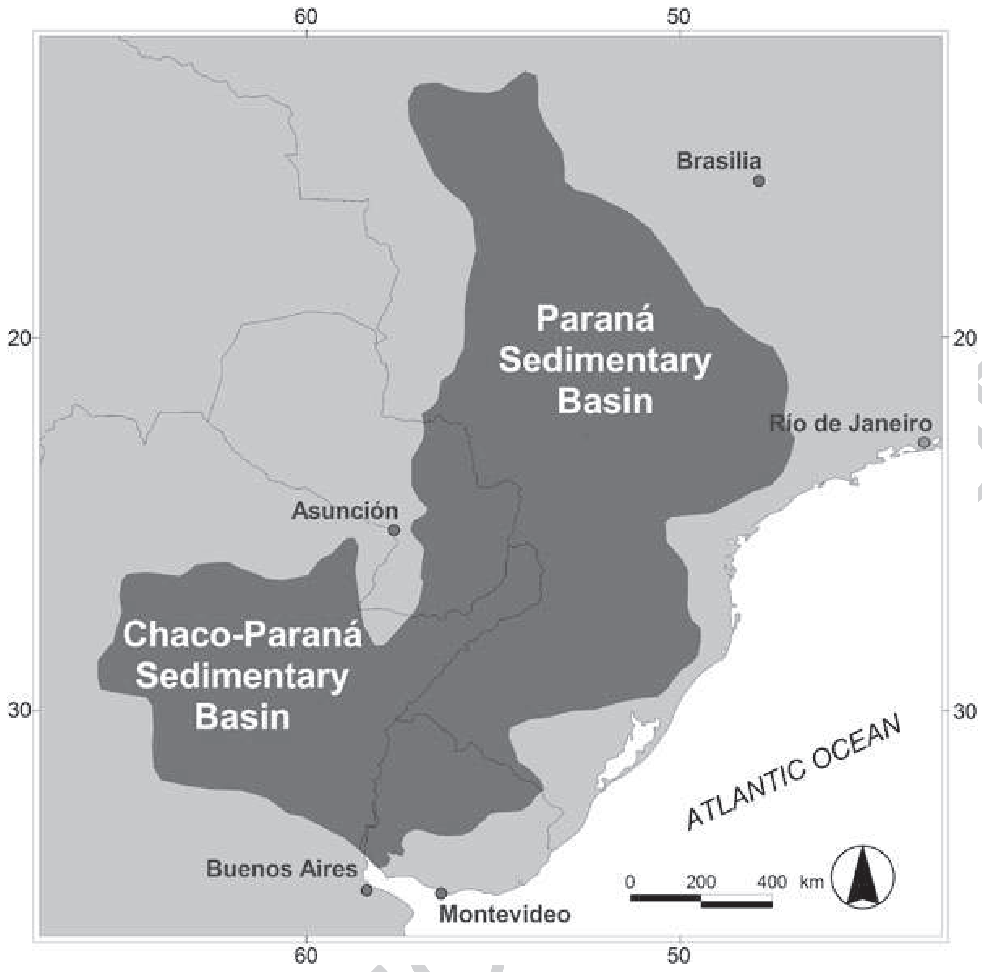

Fig. 3 Tectonic domains of Uruguay. Spatial distribution of the Paraná and the Chaco–Paraná sedimentary basins (Palaeozoic to Mesozoic) (Modified from Milani 1997)

The Dom Feliciano Belt (DFB) crops out in eastern Uruguay (see Fig. 5) and extends for more than 1,000 km along the Atlantic coast of Uruguay and southern Brazil. It was developed between ca. 750 and 550 Ma (Sánchez Bettucci et al. 2010a) and represents the Brasiliano/Pan-African orogenic cycle. It is genetically related to tectonic episodes that occurred during the convergence of the Río de la Plata, Congo and Kalahari cratons (Fig. 6) during Neoproterozoic times (Sánchez Bettucci et al. 2010a).

The basement of the Dom Feliciano Belt in the southern portion is named as the Campanero Unit (Sánchez Bettucci 1998; Sánchez Bettucci et al. 2010b) and comprises mainly orthogneisses with protolith age around 1.7 Ga (U/Pb SHRIMP in zircon; Mallmann et al. 2003). Similar ages were obtained by Sánchez Bettucci et al. (2004). In the easternmost part of the area, a pre-Brazilian Basement Inlier, the Cerro Olivo Complex (Masquelin 2002; Masquelin et al. 2012), consists of gneisses, migmatites and granulites of Neoproterozoic age.

The Dom Feliciano Belt on a regional scale is subdivided into three main tectonic units, from East to West (Basei et al. 2000): (a) Granite Belt, (b) Schist Belt and (c) Foreland Belt.

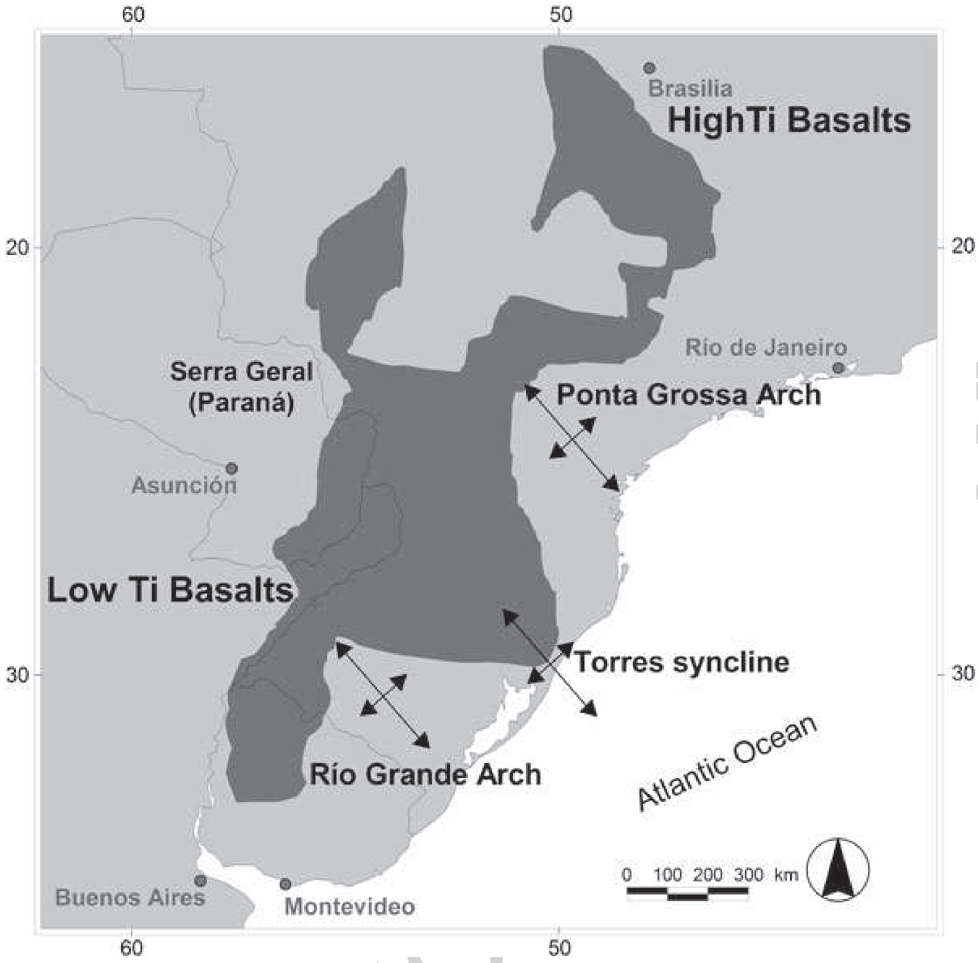

Fig. 4 Schematic map showing the geographic distribution of the Paraná igneous province displaying the distribution of high- and low-Ti areas. The main basement highs of the Basin (Ponta Grossa, Torres and Río Grande archs) are shown (Modified from Piccirillo and Melfi 1988)

The Granite Belt is represented by three large batholiths known as the Aiguá Batholith (Uruguay), Pelotas Batholith (Rio Grande do Sul State, Brazil) and Florianopolis Batholith (Santa Catarina State, Brazil). Ages between 630 and 550 Ma have been reported. These batholiths show calc-alkaline affinity.

The Schist Belt comprises pre-collisional Neoproterozoic meta-volcanic and sedimentary sequences showing metamorphism under greenschist to lower amphibolite facies. Three lithostratigraphic units are defined in this belt: the Lavalleja (Uruguay), Porongos (Rio Grande do Sul) and Brusque (Santa Catarina) groups of southern Brazil.

The Neoproterozoic Lavalleja Group is composed mainly of basic volcanics, schists, calc-schists and limestones, conforming three formations (Minas, Fuente del Puma and Zanja del Tigre; Sánchez Bettucci et al. 2001). Recently, the Zanja del Tigre Formation (Meso- to Neoproterozoic) integrated by limestones, quartzites, pelites, sandstones and minor BIF's ("Banded Iron Formation") and acid volcanic rocks, metamorphosed in greenschists to lower amphibolite facies

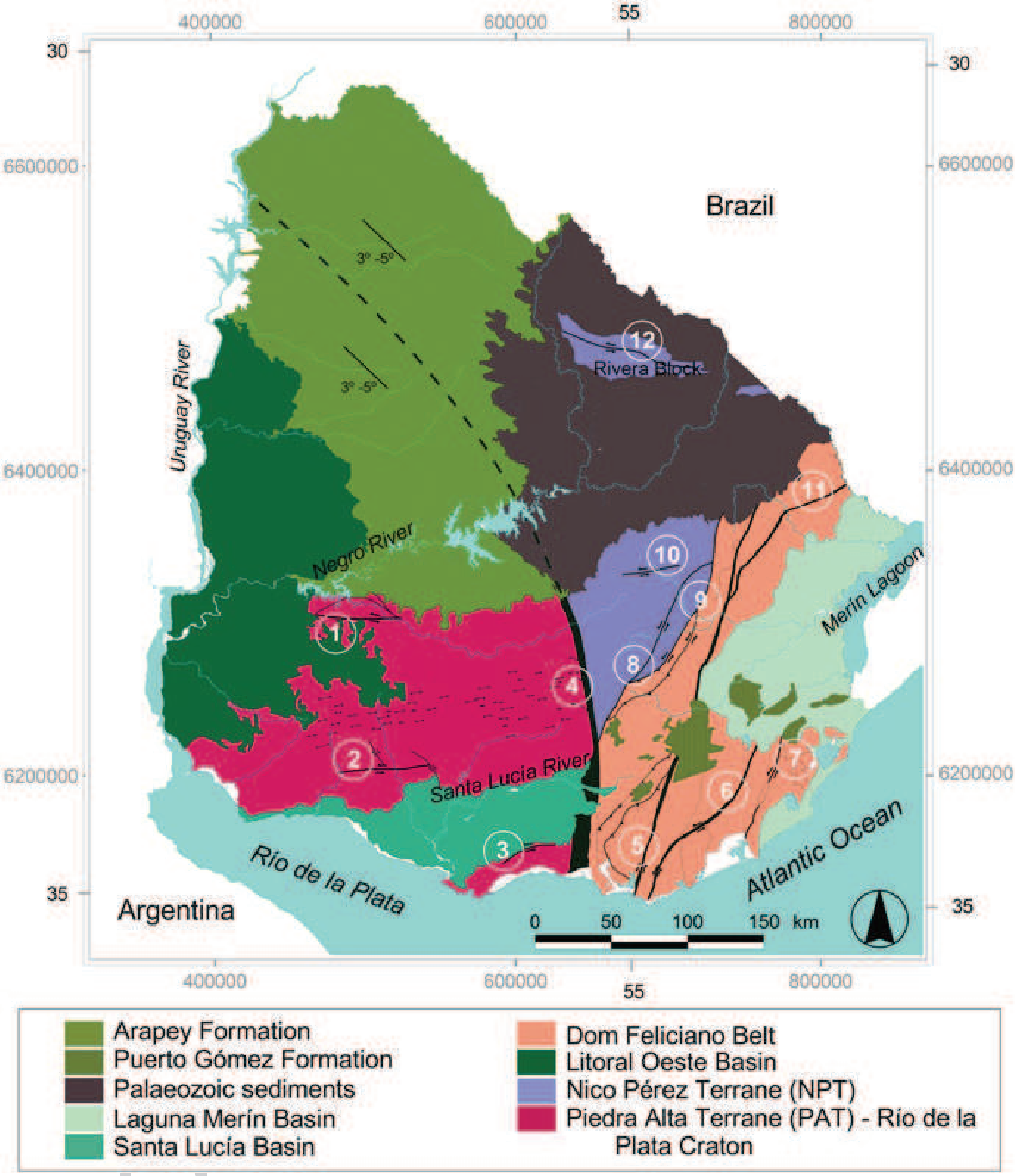

Fig. 5 Main geological units of Uruguay (Cenozoic cover is not shown): Precambrian terranes and shear zones, Palaeozoic sediments and Mesozoic basaltic flows and rift-related basins (Modified from Sánchez Bettucci et al. 2010b, after Preciozzi et al. 1985 and Bossi and Ferrando 2000). Shear zones: *1* Paso Lugo, *2* Cufré, *3* Mosquitos, *4* Sarandí del Yí, *5* Sierra Ballena, *6* Cordillera, *7* Rocha, *8* Cueva del Tigre, *9* Fraile Muerto-María Albina, *10* Tupambaé, *11* Cerro Amaro, *12* Rivera

(Sánchez Bettucci and Ramos 1999; Sánchez Bettucci et al. 2001, 2010a), is considered as a basement inlier of the Dom Feliciano Belt based on isotopic data (Oyhantçabal et al. 2009; Sánchez Bettucci et al. 2010a).

The Foreland Belt consists of several volcano-sedimentary and sedimentary successions located between the Schist Belt and the Palaeoproterozoic domains

Fig. 6 Approximate location of cratons older than 1.3 Ga in South America and Africa (https://commons.wikimedia.org/wiki/File:Cratons_West_Gondwana.svg)

of the Río de la Plata Craton (Basei et al. 2000). These basins include marine to molasse Ediacaran deposits of the Arroyo del Soldado (Gaucher 2000; Gaucher et al. 2003, 2004) and Maldonado Groups (Pecoits et al. 2004, 2008; Teixeira et al. 2004). These groups are affected by very low- to low-grade metamorphism and deformation.

The Sierra de Las Animas – Aiguá area – is considered the region of Uruguay where the relicts of Gondwana age palaeosurfaces are best preserved.

Overview of the Phanerozoic Geology of Uruguay

Palaeozoic Paraná Foreland Basin

The Palaeozoic Paraná Basin is located at the central southern region of South America. It is a foreland basin with sedimentary deposition ranging in age from Neo-Ordovician to Tertiary. This basin occupies about 1.7 million km^2 in Argentina,

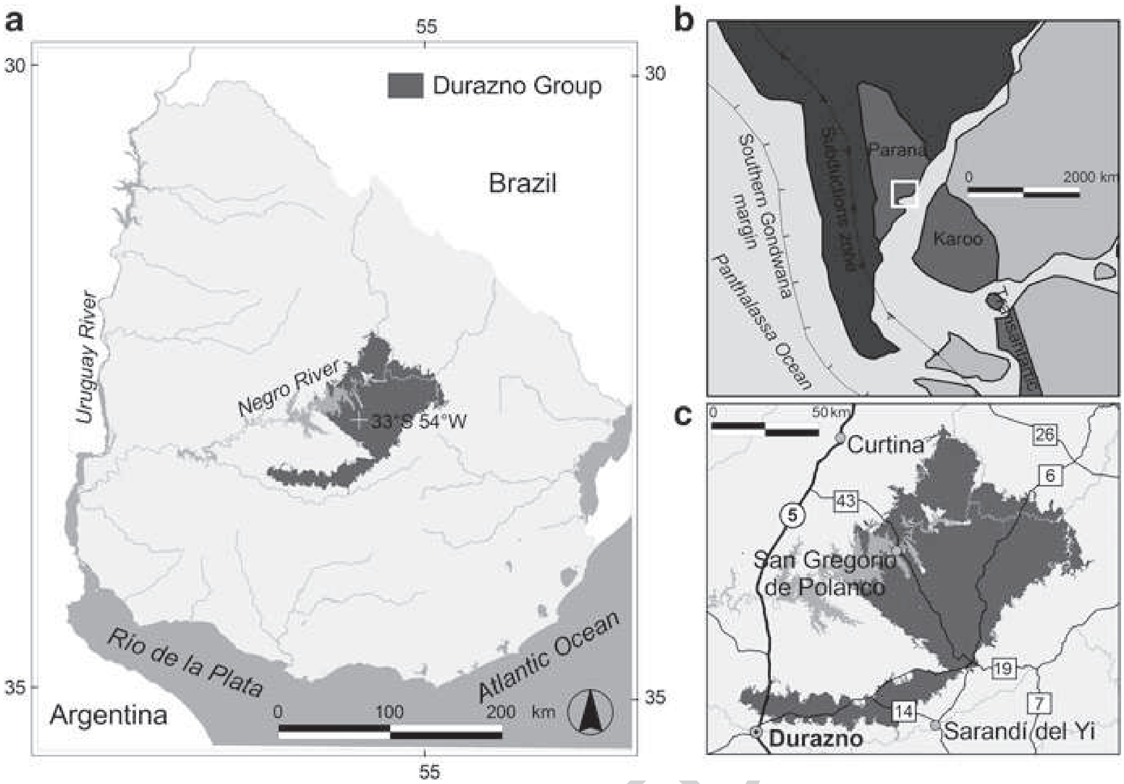

Fig. 7 (**a**) Regional distribution of Devonian sedimentary units in Uruguay (Durazno Group) which is more extensive than it had been established so far. Its surface has been inferred from their spectral response in satellite imagery (Landsat TM) and field observations (**b**) Palaeogeographic setting in the framework for the Western Gondwana (the present approximate location is indicated by a white square) (**c**) Details of the geographical location of the Durazno Group

Bolivia, Brazil, Paraguay and Uruguay. The basin has a NNE-SSW-trending elliptical form with two-thirds of its area covered by Mesozoic basaltic lavas. The stratigraphic record of this vast basin reaches 7,000 m in thickness in the central depositional centre, just under the Paraná River (Milani and Zalán 1999). Milani et al. (1998) suggested that the Paraná Basin comprises six stratigraphic mega-sequences delimited by interregional unconformities (Vail et al. 1977). The eastern border of the Paraná Basin corresponds to a crustal region deeply affected by the South Atlantic Ocean rifting (see Fig. 3). Consequently, the uplift and erosion have been responsible for the removal of large amounts of Palaeozoic sedimentary rocks. The western border of this basin is defined by the Asunción arch, a flexural bulge related to the loading of the Cenozoic Andean thrust belt nearby Argentina and Bolivia, whereas the northern and southern borders, these deposits on-lap the Precambrian basement (Milani and Zalán 1999). The arrangement of this basin has led some authors to postulate foreland basin deposits (Catuneanu 2004), together with the Karoo (South Africa), Beacon (Antarctic) and Bowen (Australia) basins.

The sedimentary record in Uruguay begins in the Lower Devonian to Lower Permian. The Devonian units constitute the Durazno Group (Veroslavsky et al. 2006) (Fig. 7) and the Carboniferous–Permian units form the Cerro Largo Group (de Santa Ana and Veroslavsky 2003; de Santa Ana et al. 2006a). The Durazno Group comprises the Cerrezuelo, Cordobés and La Paloma formations, and it represents an almost complete transgressive–regressive (T-R) cycle of marine and continental sediments. The sedimentary environments evolved from channelized braided rivers (the Cerrezuelo Formation) to clayey slope (the Cordobés Formation) and finally littoral plains (the La Paloma Formation). The start of the Neopalaeozoic sedimentation (de Santa Ana et al. 2006b) is marked by extensive glacial, glacial–marine or glacial-influenced sedimentary records. The Cerro Largo Group (de Santa Ana and Veroslavsky 2003; de Santa Ana et al. 2006a) is characterized by glaciogenic (Late Carboniferous–Early Permian), transitional, marine and finally fluvio-eolian (Late Permian) cycles. The most conspicuous levels are the glacial deposits that comprise diamictites and tillites. A compressional tectonic regime was recognized in seismic profiles and outcrops, and it is assigned to Permian–Triassic times (de Santa Ana and Veroslavsky 2003). This tectonic regime reactivated normal faults. On the other hand, Oleaga (2002) based on geophysical data suggested that the Precambrian basement is located at a depth of 3,500 m.

Mesozoic

The Atlantic Ocean Uruguayan margin, a portion of the eastern margin of the South American platform, corresponds to a passive or Atlantic-type margin. According to Turner et al. (1994), the thermal anomaly or Tristan da Cunha mantle plume was responsible for the opening of the South Atlantic Ocean and had its peak between 137 and 127 Ma. Thomaz-Filho et al. (2000) suggested that magmatic activity occurred in different stages during the break-up of South America and Africa (Cesero and Ponte 1997). The most important extensional event in Uruguay related to the break apart of Pangea took place in the mid-Triassic and is represented by Cretaceous magmatism related to continental rifting and is part of the Paraná–Etendeka magmatic province. The deformation is dominated by brittle faulting that affected all linked units and is characterized by normal faults, usually of short length and average East–West orientation dipping towards both the North and South. Also, there is a series of N 350° faults with westward to subvertical inclinations. Some brittle features are evidenced by gouge formation. The direction of preferential fault is N 75° to N 120° that generates hemi-graben-type basins filled by clastic deposits and alkaline and peralkaline magmatism.

Extensional Magmatism

The extensional magmatism was related to the continental rifting (Tristan da Cunha mantle plume) (e.g. O'Connor and Duncan 1990; Peate et al. 1990; Hawkesworth et al. 1992), and it is part of the Paraná–Etendeka magmatic province. The Paraná–Etendeka igneous province is one of the main flood volcanic provinces in the world covering an area of 1.2×10^6 km^2, with its magmatic activity peak at ca. 132 Ma

(Erlank et al. 1984; Bellieni et al. 1984; Renne et al. 1992, 1996a, b). The South American portion of this province (Paraná) contains an estimated acidic volcanic rock of 3 % of the total volume (Bellieni et al. 1984, 1986), whereas in the African portion (Etendeka), it is estimated in more than 5 % of the total volume. This difference of proportions would be related to the rift geometry asymmetry (Turner et al. 1994). The Paraná basalts were defined as aphyric tholeiitic basalts (Comin-Chiaramonti et al. 1988). Based on the criteria of separation in low TiO_2 (≈ 1) and high TiO_2 (>3) proposed by Bellieni et al. (1984), Fodor (1987), Cox (1988), Mantovani et al. (1985) and Turner and Hawkesworth (1995), among others, the existing data in Uruguay fall in the field of low TiO_2 (*sensu* Sánchez Bettucci 1998).

Unimodal Extensional Magmatism

The unimodal extensional magmatism is named in Uruguay as the Arapey Formation (Bossi 1966; see Fig. 5), and it is outcropping in the NW region of the country. The ages obtained for this formation are ca. 132 Ma (Creer et al. 1965; Umpierre 1965, in Bossi 1966; Stewart et al. 1996; Féraud et al. 1999). The ~134 Ma corresponds with main geodynamic changes in the Earth's history where large igneous provinces (LIPs) are developed (Renne et al. 1996a, b). Contemporaneously with these flood basalts, alkaline complexes were emplaced around the margin of the Paraná Basin. The Paraná Province displays characteristics of bimodality with a strong geographical correlation. The volcanic suite includes andesitic basalts to andesites. The volcanic rocks of Arapey Formation are emplaced above aeolian sandstones (Tacuarembó Formation, Jurassic–Cretaceous). A latest tectonic event determined that these basalts were tilted between 3° and 10° to the WSW. A major tectonic lineament (Sarandí del Yí Shear Zone) controlled not only the emplacement of basalts but also the further development of the Littoral Basin.

Bimodal Extensional Magmatism

The bimodal extensional magmatism is represented by the Puerto Gómez and Arequita formations and the San Miguel and Valle Chico complexes. These units in SE Uruguay are linked to aborted rifts (failed arms) associated with the opening of the South Atlantic Ocean.

The Arequita Formation is represented by acidic volcanic rocks including lava flows and pyroclastic rocks with rhyolitic to dacitic compositions. The high Zr concentrations indicate that these rocks show peralkaline affinity (Kirstein et al. 1997, 2000). The peralkaline rhyolites suggest an important late magmatic episode in the continental rifting event (Sánchez Bettucci 1998). The Puerto Gómez Formation is constituted by olivine and alkaline basalts (hawaiite), of strongly amygdaloid aspect, suggesting shallow submarine environments. Sánchez Bettucci (1998) suggested the occurrence of flows with pillow lavas.

The Valle Chico Complex (Muzio 2000; Lustrino et al. 2005) is composed of felsic plutonic rocks (quartz monzonites to syenites, quartz syenites and granites), volcanic rocks and dykes (quartz latites to trachytes and rhyolite). Lustrino et al. (2005) suggested chemical similarities between the Valle Chico Complex and the Arequita Formation. Lustrino et al. (2003) suggested that the existence of these mildly alkaline to transitional basic rocks is clear evidence that the Puerto Gómez and Arequita formations are atypical among the Paraná–Etendeka igneous province.

Litoral Oeste Intracratonic Basin

Intracratonic sag sedimentary basins occur in the middle of stable continental or cratonic blocks and are infrequently fault bounded, although strike-slip faulting can occur within them (Middleton 1989). The Litoral Oeste Basin of Uruguay occupies an area just over ca. 50,000 km^2 continuing westwards in the "Mesopotamia" region of Argentina. The basement of the basin in the southern portion is the Piedra Alta Terrane (Palaeoproterozoic), whereas in the North and Northeast, the basement is the Arapey Formation. The evolution of this basin apparently was controlled by thermo-tectonic subsidence (Goso and Perea 2004).

This basin is filled by Cretaceous and Cenozoic deposits. The Cretaceous units are the Guichón and Mercedes formations, both representing fluvial deposits (Goso and Perea 2004). Moreover, the Cenozoic deposits are represented by the Fray Bentos, Salto and Raigón Formations. The Fray Bentos Formation (Late Oligocene) comprises aeolian silts and scarce fluvial deposits developed in dry environments.

Rift Deposits (Santa Lucía and Laguna Merín Basins)

The Santa Lucía and Laguna Merín basins (see Fig. 5) are located in the South and East of Uruguay, respectively. Both basins present an elongated E-NE shape and are considered a failed rift formed during the Gondwana break-up (Sprechmann et al. 1981). They were controlled by the *Sa*nta *Lucía–Aigua–M*erín (*SaLAM*) tectonic alignment (see Rossello et al. 1999) related to the Paraná–Etendeka volcanic province (O'Connor and Duncan 1990). In the Santa Lucía rift, the Santa Rosa structural high (parallel to the basin borders) is located in the central region of the basin and divides it in two subbasins. The Cretaceous volcanic and sedimentary infilling is up to 2,500 m thick, whereas the Cenozoic sediments are only a few tens of metres thick (de Santa Ana et al. 1994). The Early Cretaceous sequence (the Migues Formation, 1,800 m thick; Jones 1956) represents the deepest levels of the basin, and it is composed of sandstones, siltstones and mudstones. The Migues Formation is overlain by siltstones and sandstones of the Oligocene Fray Bentos Formation.

The limestone sandstone deposits (the Mercedes Formation, Bossi et al. 1975, 1998) found in the Santa Lucía Basin were considered as part of the Upper

Cretaceous (Veroslavsky et al. 1997) and were formerly correlated to the "Calizas del Queguay" deposits that crop out in western Uruguay. Recent studies considered that these siltstones are the result of calcrete formation, post-depositional processes that occurred during the Tertiary (Goso and Perea 2004) or Early Pleistocene (Panario and Gutiérrez 1999). Different authors (Lambert 1940; Jones 1956; Goso 1965; Goso and Bossi 1966a, b; Gómez Rifas et al. 1981; Preciozzi et al. 1985; de Santa Ana et al. 1994; Peel et al. 1998) assigned a lacustrine origin to these deposits. Also, the Mercedes Formation records the most significant pedogenetic processes occurred in the Cenozoic times such as ferrification, silicification (silcrete formation) and calcretization.

The Laguna Merín Basin is filled primarily by volcanic rocks: basalts (the Puerto Gómez Formation), rhyolites, dacites, ignimbrites (the Arequita Formation) and to a lesser extent conglomerates and red sandstones (Veroslavsky 1999) and Quaternary loess and sands units.

Cenozoic

Towards the end of the Cretaceous, subsidence processes slowed down as the basins were filled and during the Cenozoic deposition and sedimentation were limited by uplift and erosion. The preserved sedimentary deposits are linked to successive transgressive and regressive eustatic cycles recorded at regional and global scale during the Cenozoic. Based on drilling information of the continental shelf, a detailed and fairly continuous record of marine sediments appears, corresponding to the Cretaceous–Tertiary boundary. Many successive variations in sea level were recognized during the rest of the Cenozoic (Ubilla et al. 2004).

The base of the Palaeogene is poorly represented. The scarcity of Palaeogene geological records is related to nondepositional processes that indicate climate variations at the beginning of the Palaeogene. Examples include the development of oxysol and ferricrete formation in the Eocene (Panario and Gutiérrez 1999) or in the Late Palaeocene–Eocene, and particularly on Cretaceous continental sediments (already mentioned above), the development of silcretes, fossiliferous pedogenetic calcretes, limestone and lacustrine deposits.

In the Oligocene, due to a basement reactivation linked to the Andean orogeny, alluvial and fluvial deposits, landslide processes and loess materials occurred. During the Late Miocene, there was a new marine transgression (Martínez 1989; Ubilla et al. 2004), and in the Pliocene–Pleistocene continental evolution, processes occurred, mainly developing extensive fluvial systems.

The Quaternary is characterized by the development of continental deposits on the coast of the Río de la Plata and the Atlantic Ocean. Associated with frequent oscillations of sea level, barrier islands, lake sedimentation, marsh and lagoon deposits occurred (Ubilla et al. 2004).

The Fray Bentos Formation (Bossi 1966) outcrops in western Uruguay in the Paraná Basin and to the South and East in the Santa Lucía and Laguna Merín basins. It lies unconformably on the Mercedes Formation and on the Precambrian basement.

Fig. 8 Details of the sedimentary structures of the Camacho Formation (Miocene), with sediments ranging from very fine to coarse sandstones, siltstones and mudstones with fossil marine bivalves among other groups

It is covered unconformably by the Camacho (Miocene) and Salto (Pliocene-Pleistocene) formations. The Fray Bentos Formation consists of fine sandstones, loess siltstones, mudstones, conglomerates and diamicton levels. It represents the first significant depositional episode during the Cenozoic (Goso 1965; Goso and Bossi 1966a; Veroslavsky and Martínez 1996) only preceded by the removal of oxisols and associated ferricretes and alterites off the main features as alluvial fans (Panario and Gutiérrez 1999). The thickness in outcrops is less than 15 m, but in the subsurface, it reaches 100 m (Bossi and Navarro 1991).

The Camacho Formation (Fig. 8) is composed of a succession of very fine to coarse sandstones, siltstones and mudstones (Martínez 1994; Ubilla et al. 2004). This unit outcrops along the coasts of the Colonia and San José departments, but it is also found in subsurface in San José, Maldonado and Rocha. The maximum outcropping thickness is about 15 m, whereas in the continental shelf, it reaches ca. 200 m (Gaviotín and Lobo drill holes: Stoackes et al. 1991; Ucha et al. 2004). It lies unconformably over the Precambrian basement or on the Fray Bentos Formation (Late Oligocene).

The Raigón Formation (Goso 1965) conformably overlies the Camacho Formation and it is uncomformably deposited over the Fray Bentos Formation and the Precambrian basement (Spoturno and Oyhantçabal 2004). The Raigón Formation is exposed at the coastal cliffs of the Río de la Plata with a maximum thickness of 30 m. This pile of sediments is of fluvial and transitional origin, and it is unconformably covered by the Libertad Formation, which developed in semiarid continental climatic conditions and has been assigned to the Pleistocene. This formation has been assigned to the Pliocene (Panario and Gutiérrez 1999), but, however, some authors like Perea and Martínez (2004) have considered as belonging to younger land-mammal ages (even Pliocene–Middle Pleistocene) those sediments formed following the re-transportation process of the Raigón Formation or otherwise to relate them with deposits of similar colour, grain-size characteristics and sedimentary environment of those corresponding to the genesis of such formation.

Andreis and Mazzoni (1967), following Francis and Mones (1966), named this unit as the San José Formation, dividing it into two sections: the bottom unit formed by clays, silts, sandy-silts and subordinate greenish-grey sands and the upper portion composed of medium to very coarse pink to yellow sandstones. According to Bossi and Navarro (1991), the Raigón Formation consists of green clay, medium-fine sand, coarse sands and conglomerate levels. Besides, Tófalo et al. (2006) indicated that these fluvial sediments can be divided into two sections predominantly sandy, separated by a regional discontinuity, pointing out to an episode of sedimentation reactivation.

The Salto Formation is attributed to the Late Pliocene and the Pleistocene, having also a fluvial origin. It is exposed in small outcrops near the Río Uruguay, and it was correlated with the Raigón Formation by Goso (1965) and Panario and Gutiérrez (1999). It also correlates with the Salto Chico and Ituzaingó formations in Argentina. According to Veroslavsky and Montaño (2004), it represents deposits of braided rivers distinguishing two depositional cycles. These deposits present lenticular geometry, are multi-episodic and have normal grading (Tófalo and Morrás 2009).

The Salto, Salto Chico and Ituzaingó formations are all clearly related to the Río de la Plata Basin, formed by the Paraná and Uruguay rivers, whose basins are only differentiated since their middle portions and whose sediments have continued to be deposited until today, according to Herbst (2000), which makes it difficult to establish the chronostratigraphic location of its deposits, which have been assigned both to the Pliocene and to the Pleistocene by different authors. Thus, the Salto Formation (Goso 1965; Panario and Gutiérrez 1999) and the Salto Chico Formation (Iriondo 1996) have been considered to be of Late Pliocene–Pleistocene age, as it is the case of the Ituzaingó Formation (Iriondo 1980).

The Libertad Formation (Early to Middle Pleistocene; Fig. 9) was defined by Goso (1965). This formation has a generalized distribution throughout the territory, but its greatest expression takes place in southwestern Uruguay. It has a thickness of about 20 m, lying unconformably over the Raigón Formation, several Cretaceous formations and both Palaeozoic rocks and the Precambrian Basement. It is also covered unconformably by Middle and Late Quaternary formations (Spoturno and Oyhantçabal 2004). According to Bossi and Ferrando (2000), it includes massive friable mudstones with scattered gravel and abundant calcium carbonate. According to Tófalo et al. (2006), it corresponds to loess deposits accumulated in semiarid regions of gentle slope undergoing significant pedogenetic processes.

Zárate (2003) suggested that this loess, mainly represented by a 1–2 m thick mantle, has similar composition to similar units of the Northern Pampas loess (Entre Ríos and Corrientes provinces of Argentina). Two main loess units have been identified, named Libertad I and Libertad II, of Early and Middle Pleistocene

Fig. 9 Loessic sediments may be observed in the cliff, showing a continuous process of soil formation, corresponding to the Libertad I Formation (Quaternary). The *dashed line* indicates the unconformity with the Late Pliocene Raigón Formation

age, respectively (Goso 1965). The Libertad I Formation is composed of poorly calcareous edaphized loess while the Libertad II Formation shows evidences of water reworking and pedogenetic modifications.

On the other hand, Sánchez Bettucci et al. (2007) presented preliminary magnetostratigraphic results of the Camacho, Raigón and Libertad formations (Neogene). Reverse polarity signal was found in the Camacho Formation, ascribed to the Gilbert magnetic zone. The sediments of the Raigón Formation have normal polarity interpreted as belonging to the Gauss magnetic zone. Finally, the Libertad I Formation shows reverse magnetic polarity, which is referred to the Matuyama magnetic zone. The palaeomagnetic pole obtained by these authors is located at 88.2° S lat., 189.7° W long, Dp 5° Dm 7.2° $N = 39$. The Libertad II Formation showed normal polarity, and it has been assigned to the Brunhes palaeomagnetic age, according to Sánchez San Martín (2010).

In Uruguay, neotectonic studies have not been performed, but some evidence of tectonic activity is known. Brazilian studies suggested that the Neotectonic period (Eocene–Oligocene) should be related to the episode at which the last major tectonic reorganization occurred. The Neotectonic period presents a possible correlation between events of the Andean orogeny (Bezerra et al. 2001, 2003; Bezerra and Vita-Finzi 2000). Hasui (1990) suggested that the maximum age of the neotectonic period in Brazil should be the Oligocene, which corresponds to the most recent extensional pulses of the South Atlantic Ocean extension. However, the depth at which Cenozoic units are located (at the west and east) suggests a steady continuous dominant subsidence since the Cenozoic mainly in the eastern part, whereas in the western region uplifting dominated. In this last region displacement direction and low-magnitude reverse faulting have been identified. In addition, the historical seismic data in Uruguay include low-intensity movements that certainly should have left their mark in the landscape.

Geomorphology of Uruguay

Landscape Modelling

The evolution of the Uruguayan landscape is the result of a variety of regional climates throughout its geological history. These climates had a strong influence upon the landscape modelling and modification of the pre-existing landforms. The sedimentary materials generated in the different periods and resulting landforms allow the inference of several palaeoenvironmental features. The time climate reconstruction based solely upon the observed landforms is only possible when those landforms have been preserved. Even though only at a relict level, those remnants are a clear expression of the dominant palaeoclimate.

These features are only possible under intense conditions or of long enough duration so as to imprint clear features of undoubted genesis which would provide a reliable interpretation.

Many landforms have certainly been eroded and erased from the surface: the oldest relict landforms are mainly represented by isolated elevations, generally thoroughly denudated. These relicts may be interpreted as either positional inselbergs, bornhardts, whereas others are considered as etchplains, which are the major landscape features.

Palaeoclimates

Palaeozoic

Some palaeoclimatic evidence may be established for this region since the Devonian. In this sense, from the Early Devonian to the Early Permian, several transgressive marine events have been identified. Continental deposits formed by braided rivers are also found, thus indicating alternating relatively arid conditions and presumably wetter climates. During the Early Permian, fluvio-aeolian deposits occurred as well, which are related to arid and semiarid conditions (Goso and Perea 2004). The wetter and warmer periods which would have taken place may be associated to the clayey facies, due to the landscape stability during the marine transgressive stages. There were also moraines and till deposits of Carboniferous–Permian age, which indicate the existence of higher relief, probably located further north.

Mesozoic

The cold and wet conditions of the Permian slowly changed to warmer and drier climates during the Late Permian and the Triassic. The climate conditions during most of the Jurassic were clearly those of a large desert, as it is shown by the sandstones of the Tacuarembó Formation, known as the Botucatú Formation in Brazil, mostly composed of rubified aeolian sands, which were then active dune fields. This formation also presents lagoonal environment facies of less extreme conditions (Bossi 1966).

The arid conditions were maintained during the Early Cretaceous, as it is proven by the existence of silicified barkhan dunes and sand sheets (inter-trap sandstones) coming from the north, interbedded with the Paraná volcanic province basalts.

Later on, the climate seemed to have evolved towards more semiarid conditions, related to the opening of the South Atlantic Ocean, exposed also by rubified fluvial sandstones (the Guichón and Migues formations). The semiarid conditions allowed the discontinuous development of incipient soils (Goso and Perea 2004) which persist until the end of the Cretaceous, but presumably under a temperate climate according to the sedimentology data pertaining to the Mercedes Formation. These circumstances suggest that the conditions needed for the genesis of planation surfaces were relatively continuous from some time in the Jurassic to the end of the Cretaceous if previous humid condition prevailed.

Cenozoic

The dominant climatic conditions during the Palaeocene are still somewhat unclear, since the geological record has not enough continuity. Deep drilling data coming from the submarine shelf will be undoubtedly very useful in this interpretation. The origin and development of the most extensive geomorphological features of Uruguay may be tracked back to Eocene (Panario and Gutiérrez 1999) or Late Palaeocene times. A widespread Cenozoic planation of the Uruguayan landscape was possible under the warm and humid Eocene climate, with deep weathering accompanied by oxysol development and ferricrete formation. Eocene ferricretes have developed over Cretaceous and Precambrian rocks in Uruguay and on basaltic rocks in the provinces of Corrientes and Misiones in Argentina. Ferricretes appear also as isolated boulders in Jurassic sandstones (the Tacuarembó Formation; Caorsi and Goñi 1958).

Oligocene erosion of the Eocene soils under generally arid and semiarid conditions resulted in the deposition of alluvial fans of plintite cobbles (Ford 1988), which pass upwards through a decimetre transition zone into the loess-dominated

Fray Bentos Formation. These erosion processes were facilitated by the intense Eocene weathering yielding extensive planation surfaces in metamorphic, igneous and sedimentary domains (Table 1).

During the Miocene, the geological record (Camacho Formation) indicates a marine transgression, whose mollusc fauna and the presumed associated continental fauna would indicate warm and wet climate conditions.

Based on palaeontological data, this unit was considered by Rodrigues et al. (2008) as deposited in subtropical marine provinces, ranging from intertidal to middle-shelf setting.

The Pliocene erosion, again under generally arid conditions, resulted in the formation of coarse braided river deposits known as the Raigón Formation (Goso 1965), alluvial fans (Malvín Formation; Antón and Prost 1974) and probably the Salto Formation related with the Uruguay River as well as other fluvial sediments in southwestern Uruguay, comparable to the Ituzaingó Formation as defined by De Alba (1953), Herbst (1971) and Herbst et al. (1976) in Argentina (see Krohling and Iriondo 1998; Brea and Zucol 2011).

The Structural Framework

The landscape evolution in Uruguay presents different characteristics basically due to the structural framework and mainly because of the size of its territory, which suggests that climatic conditions were relatively uniform for the entire surface of the country for each studied period. The main morphostructural regions are characterized by tectonic events and within each region, for the variety of rock types involved, which provide the landscape with their peculiar characteristics (Panario 1988).

The following eight main structural features present in almost the entire extent of the country clearly transitional zones, of 17–20 km in width, with the exception of the western margin of the Eastern Hills Region (Sierras del Este) and the Río Uruguay (the boundary with Argentina), which does not allow the boundary definition at the cartographic resolution of this scale. In the present graphical representation, the boundaries were determined by changes in the spectral response of the Landsat images at the chosen scale.

Landscape Characteristics of the Different Morphostructural Regions

North Eastern Sedimentary Basin

The Gondwanic Sedimentary Basin was stable in terms of sediment accumulation since times long before those that modelled the landscape during the Cenozoic, which allowed the process expression according to the resistance of the pre-existing

Table 1 Cenozoic units of Uruguay (Modified from Panario and Gutiérrez 1999, and Ubilla et al. 2004)

Era	System/period	Epoch	Tectono-sedimentary processes		
Cenozoic	**Quaternary**	Holocene	Fluctuations in sea level, local tectonic reactivations	Fluvial terraces – coastal sand dunes *Villa Soriano Formation*	11,700 year B.P. to present
		Pleistocene	Fluctuations in sea level, local tectonic reactivations	*Dolores-Sopas*	2,588 to 11,700 year
				Chuy Formation	
				Libertad Formation, Bellaco unit[a]	
	Neogene	Pliocene	Fluctuations in sea level, local tectonic reactivations	*Salto Formation – Raigón Formation*	5,332 to 2,588 Ma
		Miocene	Marine ingression. Development of Río de la Plata Basin	*Camacho Formation*	23.03 to 5,332 Ma
			Uplift, minor faulting, erosion (Miocene unconformity)		
	Palaeogene	Oligocene	Tectonic reactivation, formation of small basins	*Fray Bentos Formation*	33.9 to 23.03 Ma
		Eocene	Condition of general stability	*Ferricretes: del Palacio Paleosols* (Oxisols)	55.8 to 33.9 Ma
		Palaeocene	Condition of general stability	*Calizas del Queguay*[b]	65.5 to 55.8 Ma
				Gaviotín Formation	

[a] It corresponds to a soil unit of the 1:1,000,000 scale soil map of Uruguay (Dirección de Suelos y Fertilizantes 1976), but still not stratigraphically formally defined

[b] Both the calcrete and silicification formation processes may be attributed to several episodes during the Cenozoic; thus, the assignment of these formations to a certain age may later on be modified

materials. The absence of later accumulation processes of certain relevance suggests that the morphogenetic potential of the region has not been modified during the Quaternary, when the main incision of the landscape took place presumably, and, therefore, it is composed of strong slopes and large hills. According to Panario (1988), a large portion of the main drainage lines are born in remnants of the basaltic "cuesta" front as described in the Sierra de Ríos, thus suggesting that the role of the uplift of the Rivera Crystalline Island (Fig. 9) in the basin modelling the relief was of a secondary significance.

Basaltic "Cuesta"

The main structural events in the region are the tilting of the Arapey basaltic flows (of Cretaceous age), which provides the region with a dominant "cuesta" structure which is facing eastwards (see Fig. 10). These flows covered sedimentary rocks of the previously mentioned basin.

The characteristic of these lava flows is a dominance of horizontal structures and the strong resistance of such fresh rocks to fluvial incision, which have favoured in this region the preservation of planar landforms, which has motivated doubts about the morphoclimatic origin of these landforms. Nevertheless, when a lower resistance to weathering is available, large ranges and hills with nonplanar upper surfaces are found. Several higher hills, such as Cerro Travieso, have lost their planar upper surface. In those regions in which the basaltic flows have a certain inclination, they occur at the surface with relatively parallel boundaries, which in general is interpreted as of erosive origin. With the exception of the alterite accumulation zones, the soils in this area are very thin (Fig. 11) which has favoured a slope retreat of the concave type, characteristic of the dominance of erosion processes under semiarid conditions (Fig. 12). Some of the accumulation surfaces, such as accumulation glacis ("glacis d'accumulation"), are slightly dissected, generating smooth hills at the divides, as in Recta de Cunha.

Litoral Oeste Sedimentary Basin

This unit is composed of thick packages of Cretaceous sandstones and Tertiary sediments with very thin Quaternary cover (see Fig. 10). This sedimentary basin is also related to the Cretaceous tectonics, possibly accordingly to the tilting of the basaltic cuesta.

As in the previous unit, this basin received only small sediment supply during the Quaternary, and, therefore, the drainage lines became more entrenched here than in the southern and southwestern tectonic basins. The frequent existence of layers of varied hardness within the accumulated sediments, usually formed by boulder pavements, was the result of scarp recession during previous epochs, of which very little evidence still remains, such as Cerro del Clavel, or small elevations of the ferricretes named as the Asencio Sandstones, or sub-horizontal calcareous duricrusts

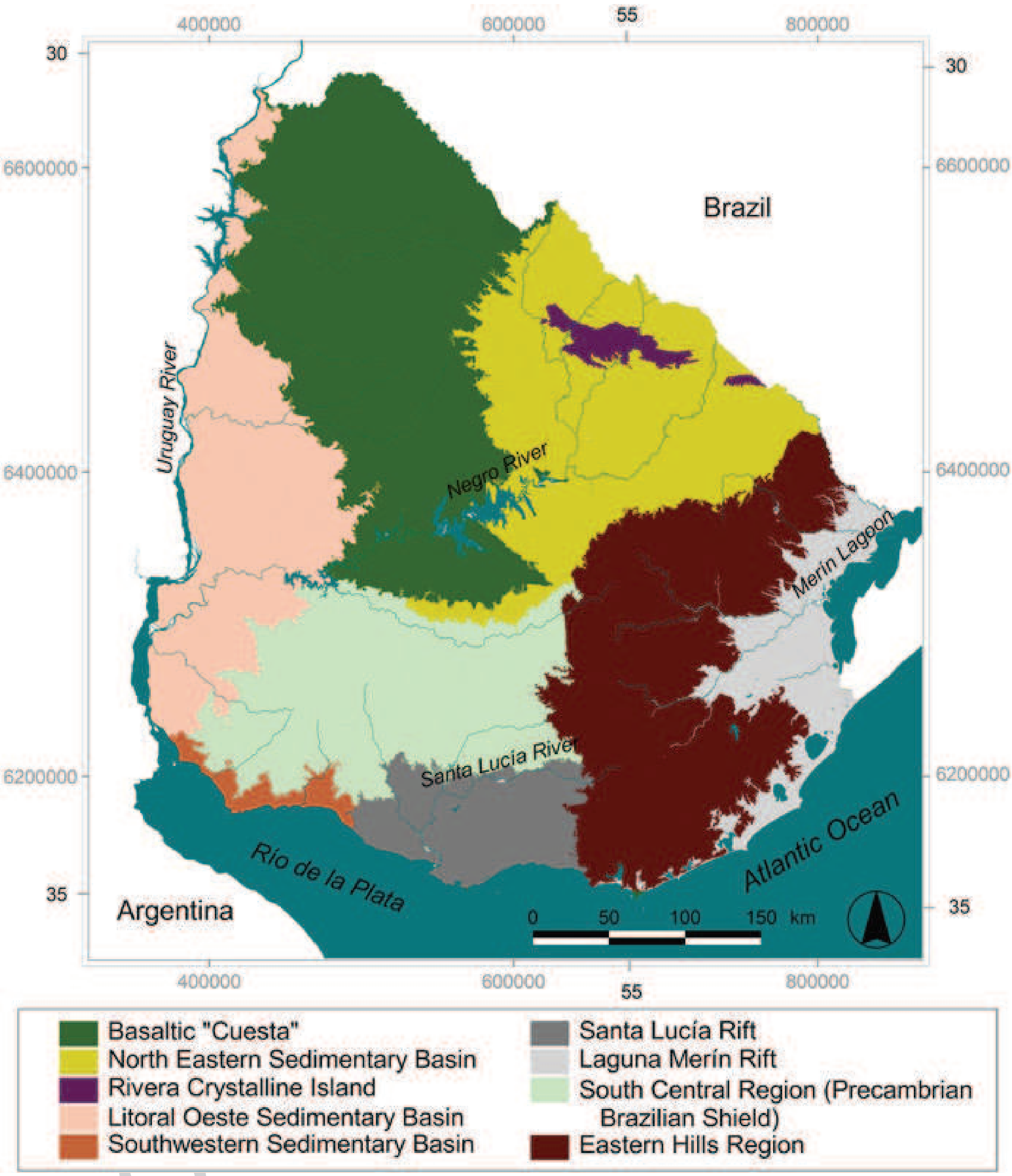

Fig. 10 Structural framework of Uruguay. The boundaries of the units have been depicted following CONEAT (1979) cartography and the topography generated from the 10 m contour lines in maps provided by the Servicio Geográfico Militar (SGM) of Uruguay, satellite imagery (Landsat TM), photointerpretation of aerial photograph (1:40,000) and field observation

with rugged borders, when preserving a surface of sufficient extension and generate hilly interbasin divides, such as those in the Camino de la Cuchilla, Department of Río Negro. When this surface is smaller, tabular hills are present, and when the scarp recession allowed the generation of a landscape at a lower level, smooth hilly valleys occur, generally without much area expression, as those existing in the Department of Río Negro (Mellizos), the Sánchez Grande and Sánchez Chico River basin, and Quebracho, at the Department of Paysandú.

Fig. 11 Very flat landscape with superficial soils in the basaltic zone of northern Uruguay, formed from an erosion glacis

Fig. 12 Scarp retreat with recessional concave profile characteristic of the basaltic zone of northern Uruguay

Southwestern Sedimentary Basin

Towards the southwest, another sedimentary basin of smaller significance is found (see Fig. 10), based on its territorial extent as well as for the thickness of its sedimentary accumulations, mainly very thick Tertiary and Quaternary deposits.

This region has acted as a sediment reception basin until recent times, late Middle Quaternary. The present dissection of the landscape does not agree with its morphogenetic potential or with the fragility of the composing materials, what suggests that it could have been affected by tectonic uplift until very recent times. This hypothesis is supported by: (i) the existence of paleo-coastlines and coastal lagoons that are clearly in-filled by sediments even at elevations above present sea level, (ii) the occurrence of marine units such as the Camacho Fm., several meters above their corresponding stratigraphic units in Argentina (the Paraná Formation) and, at different levels in Uruguay (Antón and Goso 1974), (iii) the existence of creeks that still have entrenching capabilities in unconsolidated materials, and (iv) Quaternary marine deposits that occur at higher levels than those found in the rest of the country. This uplifting process is perhaps continued irregularly eastwards, at least along a narrow coastal fringe until the Merín Rift.

Santa Lucía Rift

Southwards, the basin of Santa Lucía is found (see Fig. 10), more likely one of the two most important of the Cretaceous basins within the continental portion of the country, from the point of view of the Cretaceous, Tertiary and Quaternary sediments included in it. Subsidence and sedimentation were very active in the Santa Lucía Tectonic Basin until the Early Quaternary. This means it had no morphogenetic potential in this period and that after it, such potential was very reduced, which determined a landscape composed mainly by smooth hills of gentle slopes, with the exception of those found at the margins of the basin and the Santa Rosa Basement high (Rosello et al. 2000).

Laguna Merín Rift

Eastwards, another rift with similar age for the beginning of the event and size is located (see Fig. 10); this basin, however, presents Tertiary and Cretaceous sediments in its continental side as the oldest materials. Eastern ranges and the Laguna Merín Tectonic Basin, a system of hills and low ranges is located, which are composed of crystalline rocks with a thin Quaternary cover, whose genesis could be related to the tectonic events that formed the cited basin. Studies on the Uruguayan continental shelf in the region have shown that this rift has materials whose age also dates back to Cretaceous (Rosello et al. 2000) their geomorphological characteristics, which has allowed the interpretation that it has been active until present times with organic sediments in its most depressed areas. The capture of part of the Cebollatí River Basin during the Holocene (Bracco et al. 2012) is a clear demonstration of their recent activity, compared with the Santa Lucía rift, as well as other smaller basins located in between, such as those of Valle Fuente, Valle Aiguá, that were remodelled during the Pleistocene.

The nature of the sediments, their diagenetic evolution and the resistance of the crystalline and consolidated materials to weathering and the morphogenetic potential of each of these regions are the conditions that are responsible for their geomorphological profile.

The landscape of this region is practically flat due to its almost null morphogenetic potential. The deposition of the Pleistocene and Holocene sediments in it is largely developed under the shape of stepped sedimentary terraces, which allows the identification of at least four levels of plains separated by breaks in slope, which vary from a few centimetres to a few metres.

South Central Region (Precambrian Brazilian Shield)

The Southern Central Region is occupied by rocks belonging to the Brazilian Shield (see Fig. 10) which have kept under conditions relatively stable at least during Cretaceous times. These relatively stable conditions, as well as the characteristics of the morphoclimatic systems dominating the area since those times, have provided the landscape with a "senile" aspect, which determined that Chebataroff (1955) described it as a "crystalline peneplain", in accordance with the genetic interpretations of those times. At present it is defined as dissected and reworking plains.

The arid and semiarid periods that occurred with short interruptions during most of the Tertiary and the Quaternary must have modelled the palaeolandscape into erosional plains with a few local smooth elevations, characteristic of planation on crystalline rocks. During the early Quaternary, this area received a sedimentary cover of alterites coming from the hilly areas, these materials being still preserved on the main interfluvial divides. After the formation of this pediment, it was strongly dissected, a process favoured by deep weathering processes generated during the Eocene (Panario and Gutiérrez 1999) and earlier. This dissection produced an undulating relief, interrupted by smooth hills at the interfluvial divides at the areas with thicker Quaternary accumulation.

Eastern Hills Region

This region is composed by a complex of folded emerged structures and other uplifted features as Dom Feliciano Belt, of which the oldest one is undoubtedly the Carapé Massif which corresponds to the main water divide in the region (see Fig. 10), due to the fact that the drainage lines which have their sources in the region are cross-cutting other features, including highly deformed granites and quartzites as the Sierra de la Ballena and Sierra de las Cañas chains.

This unit represents the landscape with higher potential energy. Notwithstanding, the uppermost portion of the Sierras shows rather flat top surfaces, which correspond to very old planation (etchplains) processes developed probably during the Cretaceous or even older, with others at lower elevation which may have been formed during the Middle Tertiary. This group of elevations shows a clear SW-NE orientation and they would have acted as a mountainous region of the southernmost Brazilian Shield from which the glacis were carved, providing most of the infilling sedimentary materials of the Santa Lucía and Laguna Merín rift.

Within this area, certain areas of tectonic down-warping are found which generated smooth hilly valleys, such as Valle Fuentes and Valle Aiguá.

Palaeosurfaces

Gondwana Palaeosurfaces

The uppermost palaeosurface on the Granite Batholiths (see "Precambrian Geology") is located on granite exposures with two "treppen" in the sense of Penck (1953). The second surface is located on deeply weathered granite. These surfaces could be of the same age or, alternatively, of quite close ages, with little time difference in between their formations.

There are obvious dating problems concerning the palaeosurfaces, and the correlation with Southern Brazil has not been established yet.

The existence of a volcanic explosions in this region with an $^{40}Ar/^{39}Ar$ age of ∼130 to 128 Ma (Cernuschi Rodilosso 2011), the lack of evidence of it on the ancient surfaces, suggests that these surfaces are planation surfaces, probably etchplains, which suffered later on intensive denudation, presumably since the Oligocene until part of the Pleistocene, but for this, it is necessary to assume a denudation rate of 5–10 m per million years, only possible under extremely stable condition.

The first palaeosurface is located approximately between 320 and 500 m a.s.l., whereas the second palaeosurface is found between 280 and 320 m a.s.l.

The elevation difference between them is very small, but this would not be too rare in a tectonically very stable, as it happens in the Tandilia and Ventania ranges of the Buenos Aires province, Argentina (Demoulin et al. 2005; Rabassa et al. 2005, 2010, 2014).

The Cerro Campanero, in the Department of Lavalleja, shows a perfect example of weathering front remnants, on which corestones have been left after removal of the weathered materials. These corestones are a common feature in the granitic batholiths (e.g. Carapé region) (Fig. 13) and are part of dismantled tors, and some of them may have also reached the state of rocking stones during their evolution. Looking northwest in Fig. 14, the clear flatness of the supposed Gondwana palaeosurface is exposed forming the horizon, with very little local relief, as mentioned before.

Fig. 13 Examples of (**a**) tors and (**b**) corestones which may be observed on granitic rocks at the summits of the hills of Sierras de Carapé

In the northern part of the country, the inselbergs modelled on basalts of the Arapey Formation prove that they were developed after the eruption of these rocks (Early Cretaceous). At a lower altitude compared with these relict features, but in accordance with them, degraded surfaces assigned to arid climates have been described and named as "Charqueada" (Antón 1975). This name has been given to this surface due to their occurrence in a site in the Department of Artigas where these features are found, extending to the Eastern and Northeastern hills. It is presently considered that this surface may be subdivided in two units, separated by an entrenchment. It is herein proposed the preliminary denomination of "Charqueada I" for the highest, supposed oldest, extensive surface and "Charqueada II" for the younger (lower) unit. The scarce preserved soils in the uppermost surface are of the mineral, reddish type, which indicate very strong weathering produced under very warm climatic conditions and, at least, seasonally very humid environments. Most of these soils occur in such positions that indicate colluvial processes along associated slopes and valleys. However, it should be taken into account that these

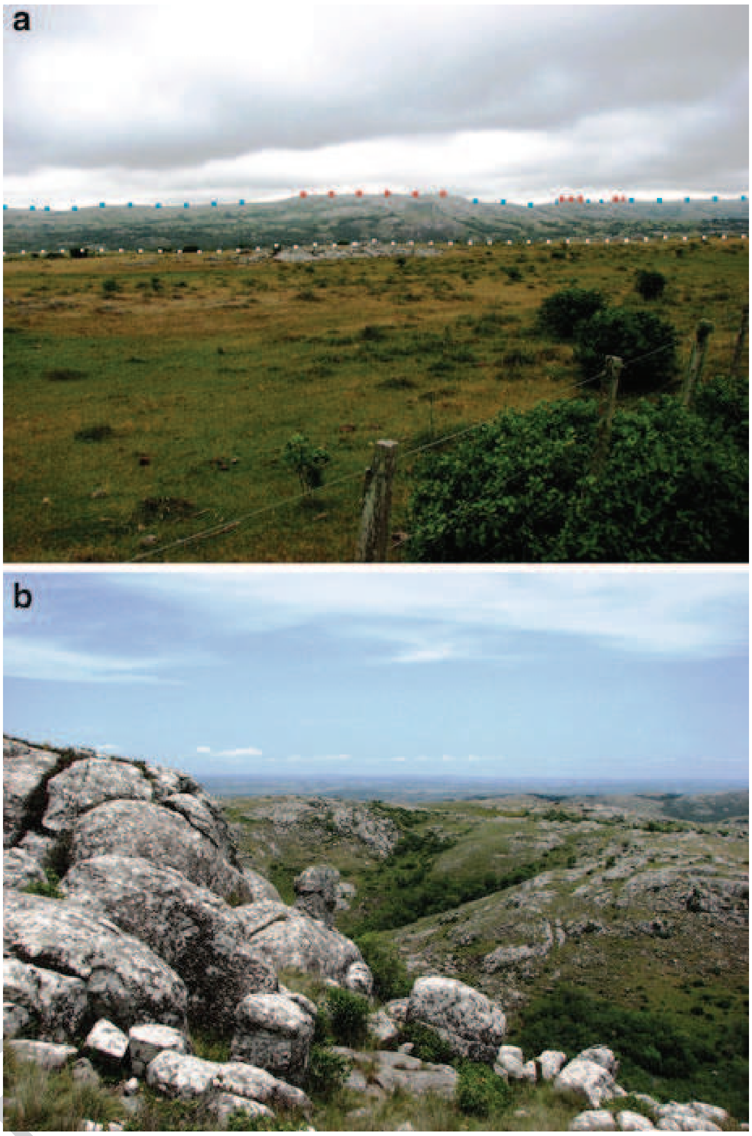

Fig. 14 (**a**) the *dashed line* depicts the change in landscape surface. Relicts of two palaeosurfaces are found above, indicated by a *bluish line* (*the lower one*) and a *reddish line* (*the higher one*). The small relief in between them suggests that these two surfaces were essentially coeval or separated by a very short time span. (**b**) Panoramic view from the uppermost topographic surface, in which the two lower surface levels may be observed

soils are perhaps the result of superposition of several red alteration (lateritic) processes. In the second palaeosurface, which occurs at a lower level, the soils are better developed, although formed by a brownish material, same times more or less lixiviated mollisols. These palaeosurfaces are clearly exposed when the summits of the regional ranges are linked in a graph, such as the Eastern, Aiguá and Yerbal Sierras.

However, tectonic action has deformed these landscapes in a great manner, due to their antiquity. Thus, overlying sediments are not always preserved, making very difficult the correlation of the surface relicts. Younger relocation and transport of the sediments make even more questionable their identification and correlation. Precisely, the entrenchment and development of a new surface does not freeze the evolution of the older one, but it may accelerate it instead, although under varying conditions with respect to the original ones, frequently removing sediments from the upper zones to the lower landforms. The humid periods responsible for the entrenchment that separates the Charqueada I and II surfaces, and other surfaces of the region (Masoller), could have been also responsible for the aforementioned red alterite formation during de Eocene. These surfaces, when they suffered the action of alternated periods of wet and dry climates, originated most of the landscape of the Eastern Hills Region, which had been previously uplifted by tectonic processes. When the valley incision did not affect the upper surface, highland ranges were formed (Sombroek 1969). Contrarily when the valley incision affects the upper surface, typical "sierras" (steep hills) landscape is developed.

Cenozoic Palaeosurfaces

Separated from the old surfaces by an entrenchment, perhaps favoured by the Eocene alteration process, another surface of similar genesis (arid morphogenesis) occurs, which was named as the Masoller surface by Antón (1975). Erosion and accumulation glacis that formed it are found in many localities, as it may be observed in the geomorphological map by Antón (1975). According to Panario and Gutiérrez (1999), this surface may be assigned to a more intense planation process that developed during periods of semiarid climate in the Tertiary (perhaps, the Oligocene), simultaneously with the conglomerates, limestones and aeolian deposits of the Fray Bentos Formation. This process continued during the Pliocene, when fluvial deposits also of semiarid conditions were formed, such as conglomerates and sandstones of the Salto and Raigón formations.

The deposits of the Salto and Ituzaingó formations have been defined as of subtropical climate by several authors (Iriondo 1980; Jalfin 1988; Herbst 2000). However, it should be taken into consideration that the Río de la Plata Basin extends over a wide latitudinal band and it reaches much lower latitudes at its mouth. Therefore, even if the provenance of the materials may be from tropical or subtropical areas, the conditions in the depositional areas could have been very different.

The Salto and Raigón formations present a higher variability of their sedimentary materials which indicates environmental rhythmicity. During their genesis, periods with sufficient aridity developed so as to transport and deposit coarse materials and other wetter periods in which the transport and deposition of the finer sediments took place, thus favouring the formation of large glacis. The deposition of very fine (clayey) materials seems to correspond to lacustrine environments, characteristics of these climatic conditions when closed depressions are available (Raigón Formation). The fact that aeolian silts were herein incorporated suggests that there were some periods in which, even though locally, a certain plant cover developed. Towards the later portion of this period and in coincidence perhaps with the earlier major glaciations, the deposition of the Libertad I Formation took place, most likely under semiarid conditions. From a genetic point of view, the Libertad Formation was formed during several Pleistocene glacial periods, without clear internal unconformities, perhaps with the exception of the events known as Libertad I and Libertad II, which points towards a loess unit with continuous soil formation, as it has been noted by Blasi et al. (2001) under similar conditions in the Argentine Pampas.

Between the Salto and Raigón formations and the Libertad Formation does not exist any entrenchment which may indicate the necessary conditions for landscape dissection. The Libertad I Formation is generally composed of finer materials than the Raigón Formation. This would imply that a loss of competence of the transportation agents would have taken place, due to a loss of morphogenetic potential or climatic changes in the region; the latter interpretation would be preferred. Apparently, the deposition of the final portion of the Libertad Formation would have taken place under somewhat more humid conditions, whose more evident relicts are the clayey deposits occurring under seasonally confined, shallow waters where vegetation and/or evaporation would be responsible for their deposition or later weathering of finer sediments into montmorillonite clays. The smaller amount of illite in relation with smectites would indicate a warmer climate than during the deposition of the Libertad sediments.

The deposition of clays and fine materials requires very special conditions which are related to lakes, ponds or marshes with dense vegetation. The latter case would be the one better adapted to the conditions in this country, perhaps reconstructing ancient drainage basins. After the deposition, due to the difficulties to erode the clayey sediments when climate changed, drainage channels tended to entrench the margins of the swampy areas but not their deposits. In the long term, a process of relief inversion took place, with the clayey deposits in the uppermost areas. Considering the crystalline zone, the Risso and La Carolina units of the 1:1,000,000 scale soil map of Uruguay (Dirección de Suelos y Fertilizantes 1976) may be considered, together since they are zones with vertisols and calcium–montmorillonite-dominated soils. A palaeobasin may be reconstructed which, starting at the Eastern Ranges, would extend southwestwards until approximately the present mouth of the Uruguay River (Panario and Gutiérrez 1999). The dry period in which the Libertad I Formation deposition took place would be associated to the glacial periods at the beginning of the Pleistocene, as low sea levels would be related to glaciation and dry climates. The increase of the morphogenetic potential implied by lowering sea level is compensated in dry areas by the loss of erosion potential of the streams, due to loss of yield and detrital load. The entrenchment under these conditions would have taken place during wetter periods at the end of the glaciations, before sea level rises. The subsequent climatic alternating periods modelled the thus formed surfaces, originating most of the present smooth hills like the Cuchilla Grande. Some relict surfaces are found even in the neighbourhood of the city of Montevideo (the La Tabla Range, among others), connected to position inselbergs such as El Cerrito de la Victoria. The higher energy of the hilly landscape may be attributed to successive periods of entrenchment affecting the same drainage lines previously established, which forced frequent changes in slope inclination in the landscape. In those places where the landforms are due to a varying rock resistance, larger high plains were preserved, such as Cuaró, Recta de Cunha and Masoller. After the formation of these surfaces, marine transgressions took place, since then, alternating wetter–drier, warmer–colder climates related to glacial–interglacial periods represent the dominant conditions during the rest of the Pleistocene and the early Holocene.

Final Remarks

The existence of pre-Cenozoic palaeosurface relicts has been largely discussed from a neo-Darwinian and classic thermodynamics point of view, still perceived in modern geomorphology. Although the absolute ages of the older surfaces are difficult to establish at our present state of the art, some conclusions may be obtained:

1. For the first time, the nature, characteristics and distribution of Gondwana landscapes in Uruguay has been presented within the framework of the long-term landscape evolution of this country.
2. The different stratigraphic units found in the various morphostructural regions of Uruguay have been presented, and their relationship with the occurrence and distribution of landscapes and landforms has been discussed and analyzed.
3. Several features emerged from such analysis. The Cretaceous lava flows of the northern portion of the country show clear evidence of tilting.
4. In the topographically higher area, the existence of palaeosurface relicts with recessional scarps of the knick-point type may be observed, carved on the basaltic flows of the upper section, thus the younger ones.
5. The topographically lower area of the tilted Cretaceous lava flows is covered by fluvial deposits pertaining to a Middle Cretaceous sedimentary basin, clearly genetically separated by the scarp.
6. Part of the sediments present here is related to the denudation processes that originated the relicts. Thus, it may be clearly assumed the existence of at least extensive surfaces of Late Cretaceous age.
7. In those place were the Cretaceous lavas are overlying the northwest margins of the Dom Feliciano Belt, they are found at elevations around 200 m a.s.l., whereas the maximum elevations of this structure and its corresponding palaeosurface may reach 500 m a.s.l., which could be interpreted as an Early Cretaceous or even a pre-Cretaceous age for these surfaces, in which corestones, tors and other landforms indicating pre-existing deep alteration mantles over highly quartzose, granitic rocks are found.
8. The existence of Carboniferous–Permian glacial sediments of the mountain glaciation type suggests that very high mountain summits were already present in those times. On the other hand, the occurrence of Eocene ferricrete clasts in the matrix of Oligocene fine-grained aeolian deposits and the distribution of surfaces framed by iron mantles at elevations corresponding to the general landscape planation during an Oligocene semiarid period are also according with the extensive planation of the emerged landscape.
9. Absolute dating and/or clear correlation among the palaeosurfaces of the South American passive margin with surfaces genetically and geographically related, located in other parts of South America and Southern Africa, will be undoubtedly needed to establish a reliable genetic chronosequence.
10. The study of the provenance of Cretaceous and pre-Cretaceous sediments would also be a significant input in the future to understand the timing of

the development and denudation of these ancient landscapes. The cratonic areas of Uruguay were affected by deep chemical weathering during perhaps millions of years in the Late Mesozoic and the Early Palaeogene. An enormous cover of saprolite, perhaps many hundreds of metres thick, was removed by subaerial denudation during the Tertiary. These weathering products are mostly lying today in the surrounding ocean basins. The sedimentary sequences of these marine basins will inform us about the characteristics and thickness of the weathered materials, but understanding the ancient weathering processes and their products will enable us to interpret the provenance, nature and age of the sediments infilling those basins. Needless to say, regional studies on the geomorphology of the cratonic areas of Uruguay should be paired to the investigation of the marine basins of the South Atlantic Ocean.

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