GONDWANA PALEOSURFACES IN ARGENTINA: AN INTRODUCTION

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ABSTRACT – Gondwana paleosurfaces in Argentina were already identified by Juan Keidel and Walther Penck at the beginnings of the 20th century, as well as by other geologists and naturalists of the different European schools that worked in this country. These studies were continued at a very good level in Brazil, thanks to the work of Lester C. King, later on intensively followed by João José Bigarella. However, these concepts gradually disappeared from the Argentine geological scene, dominated by the influence of American geomorphologists, and particularly William Thornbury, who doubted about the existence of such ancient landforms, when one of the main paradigms of the time was that "practically there is no landscape older than the Pleistocene". These landforms are the result of deep chemical weathering and/or pedimentation processes, developed in very stable tectonic and climatic environments, mostly under hyper-tropical climates, extremely wet, extremely arid or seasonally changing. The Gondwana paleosurfaces or their fragmented remnants have been recognized in Argentina, from north to south, in the basaltic hills of the province of Misiones, the Sierras Pampeanas of the provinces of Catamarca, La Rioja and San Juan, the Sierras Chicas, Sierras Grandes and Sierra Norte of Córdoba province, the Sierras de San Luis, the Sierra Pintada or San Rafael Block of Mendoza province, the Sierras de Tandil, Sierra de la Ventana and the Pampa Interserrana of Buenos Aires province, the Sierras de Lihuel Calel of the province of La Pampa, the Somuncurá or Northern Patagonian Massif in the provinces of Río Negro and Chubut, the Deseado Massif of Santa Cruz province, and the Malvinas/Falklands archipelago. In other regions of Argentina, these surfaces have been down-warped in tectonic basins and are covered by sedimentary and/or volcanic units of various ages. The age for the Gondwana paleosurfaces have been estimated in between the middle Jurassic and the Paleogene. The Gondwana paleosurfaces were uplifted, fragmented, denudated and isolated during the middle to late Tertiary due to the Andean orogeny, and they have remained as mute testimony of the past above extensive pediplains and piedmont deposits, while climate and environments changed to more arid and cooler, approaching the present conditions.
Keywords: Gondwana, paleosurfaces, Argentina, Mesozoic, planation surfaces, etchplains, pediplains.

RESUMEN – *J. Rabassa, C. Carignano, M. Cioccale - Gondwana paleosuperficies en Argentina: una introducción.* Las paleosuperficies Gondwánicas en Argentina fueron identificadas por Juan Keidel y Walther Penck ya en los comienzos del siglo 20, como así también por otros geólogos y naturalistas, procedentes de las diferentes escuelas europeas, que trabajaron en este país. Estos estudios fueron continuados en un gran nivel académico en Brasil, gracias a los trabajos de Lester C. King, más tarde desarrollados intensamente por João José Bigarella, entre otros. Sin embargo, estos conceptos desaparecieron gradualmente de la escena geológica argentina, la cual fue paulatinamente dominada por la influencia de los geomorfólogos norteamericanos, y particularmente, William Thornbury, quien dudaba profundamente acerca de la existencia de geoformas tan antiguas, cuando uno de los principales paradigmas de su tiempo era que "prácticamente no hay paisaje más antiguo que el Pleistoceno". Las geoformas que se discuten en este trabajo son esencialmente el resultado de procesos de meteorización química profunda y/o procesos de pedimentación, desarrollada en ambientes tectónicos y climáticos muy estables, bajo climas que hemos denominado "hiper-tropicales", extremadamente húmedos, extremadamente áridos, o estacionalmente muy variables. Las paleosuperficies Gondwánicas o, en la mayoría de los casos, sus remanentes fragmentarios, han sido reconocidas en Argentina, de norte a sur, en las colinas basálticas de la provincia de Misiones, las Sierras Pampeanas de las provincias de Catamarca, La Rioja y San Juan, las Sierras Chicas, Sierras Grandes y Sierra Norte de la provincia de Córdoba, las Sierras de San Luis, la Sierra Pintada o Bloque de San Rafael en la provincia de Mendoza, las Sierras de Tandil, la Sierra de la Ventana y la Pampa Interserrana

de la provincia de Buenos Aires, las Sierras de Lihuel Calel de la provincia de La Pampa, el Macizo de Somuncurá o Macizo Norpatagónico en las provincias de Río Negro y Chubut, el Macizo del Deseado en la provincia de Santa Cruz, y las colinas de las Islas Malvinas. En otras regiones de Argentina, estas superficies han sido arrastradas al fondo de cuencas tectónicas y sepultadas por sedimentos marinos y continentales y/o unidades volcánicas en distintos momentos del Cenozoico. La edad en que las paleosuperficies Gondwánicas se generaron ha sido estimada entre el Jurásico medio y el Paleógeno. Las paleosuperficies Gondwánicas fueron elevadas tectónicamente, fragmentadas, denudadas y aisladas durante el Terciario medio y tardío por la Orogenia Andina, y ellas han permanecido en el paisaje como mudo testimonio del pasado, por encima de extensas pediplanicies y depósitos pedemontanos, a medida que los climas y los ecosistemas cambiaban hacia ambientes más áridos y fríos, hasta alcanzar las condiciones presentes.

Palabras clave: Gondwana, paleosuperficies, Argentina, Mesozoico, superficies de planación, planicies grabadas, pediplanicies.

INTRODUCTION

Gondwana paleosurfaces were originally defined by Fairbridge (1968) as an "ancestral landscape" composed of "series of once-planed remnants" that "record traces of older planation" episodes, during the "late Mesozoic (locally Jurassic or Cretaceous)". This has been called the "Gondwana cyclic land surface" in the continents of the southern hemisphere, occurring extensively in Australia, Southern Africa and the cratonic areas of South America. Remnants of these surfaces are found also in India, the Arabian Peninsula and it is assumed they have been preserved in Eastern Antarctica, underneath the Antarctic ice sheet which covers that region with an average thickness of 3,000 meters. These paleolandscapes were generated when the former Gondwana super-continent was still in place and similar tectonic conditions in its drifted fragments have allowed their preservation. These are very old, Mesozoic landscapes and most of them were never covered later by marine sediments and they have been exposed at the surface since their genesis.

The Mesozoic paleoclimates and tectonic conditions in Gondwanaland allowed the formation of paleolandscape systems in all portions of the ancient super-continent. In South America, these surfaces have been studied in Brazil, Uruguay, the Guyana Massif and Argentina. These geomorphological systems were generated when the former Gondwana super-continent was still in place and similar tectonic conditions in its drifted fragments have allowed their preservation. The nature and genesis of these paleolandscapes have been thoroughly discussed by Rabassa (2010, this volume).

The Gondwana paleolandscapes were discussed in Argentina by Alfredo Stelzner (1885), Luis Brackebush (1879, 1880, 1891), Guillermo Bodenbender (1905), Giuseppe Rovereto (1911), who analyzed the possible Cretaceous age of the summit surfaces of the Sierras de Córdoba, J. Walther (1912), who was the first one in mentioning the existence of sub-tropical climate landforms in the Sierra de Tandil, Oscar Schmieder (1921), who identified inselbergs and rumpffläche and Juan Keidel (1916, 1922) who described paleosurfaces in Sierra de la Ventana. Finally, it should be noted that Edgardo Rolleri (1975) and Marcelo Yrigoyen (1975) proposed the idea of the Buenos Aires Positive morpho-structure and its ancient surfaces.

In modern times, the first contributions devoted to Gondwanic paleolandscapes are those of Rabassa et al. (1995, 1996, 1997, 1998), Zárate et al. (1995, 1998), Pereyra & Ferrer (1995), Pereyra (1996), Carignano et al. (1999) and Carignano & Cioccale (1997, 1998).

GONDWANA PALEOLANDSCAPES IN ARGENTINA

In Argentina, Gondwana Paleolandscapes are recognized in all exposed cratonic areas (see Carignano et al., 1999; Figure 1). Although the possibility that landforms of this nature, genesis and age may be present in other morpho-structural units, they have been observed in the (a) the basaltic hills of the Province of Misiones, (b) the Sierras Pampeanas of Córdoba, San Luis, La Rioja, San Juan and Catamarca, (c) the Central Buenos Aires Positive area, including the Sierras Septentrionales (Tandilia), the Sierras Australes (Ventania) and the Pampa Interserrana, (d) the San Rafael or Sierra Pintada Block in Mendoza, (e) the Sierras de Lihuel Calel in La Pampa, (f) the Northern Patagonian Massif, (g) the Deseado Massif and (h) the Malvinas-Falklands Islands. The nature and characteristics of the Gondwana paleolandscapes in the aforementioned areas are described and briefly discussed in this paper.

BASALTIC HILLS OF THE PROVINCE OF MISIONES

The province of Misiones, in the northeastern end of Argentina (Figure 2), is presently under wet tropical climate. These conditions may have persisted throughout the Tertiary, maintaining this region under environmental conditions quite similar to those that existed during the Late Mesozoic. The entire region was covered by a huge basaltic plateau, the Paraná
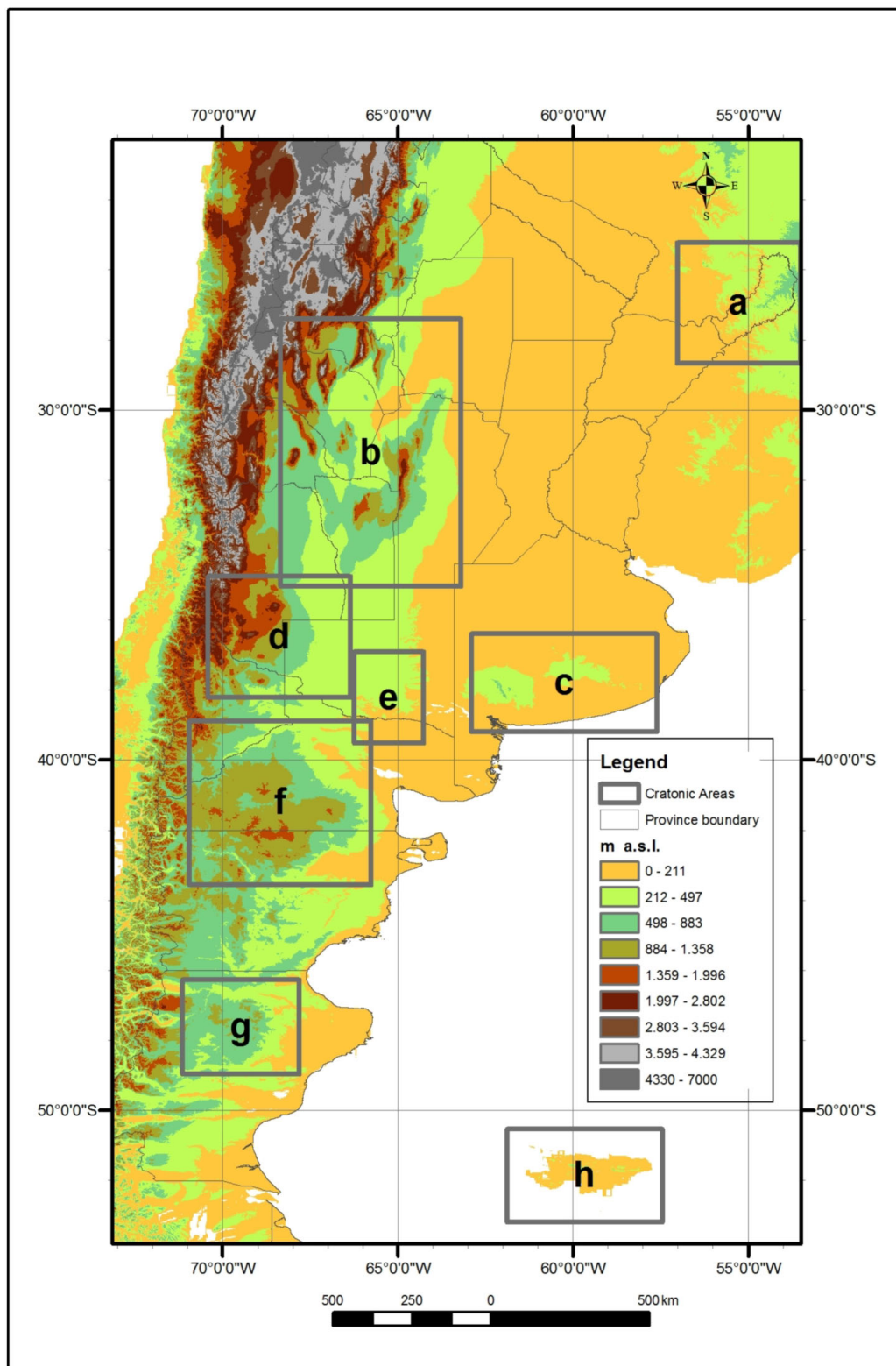
FIGURE 1. Map of Argentina, showing the area in which significant extensions of Gondwana Paleosurfaces are present. All ancient surfaces rise at least above 300-500 m a.l.s. These paleosurfaces reach their highest locations in the western Pampean Ranges. (**a**) the basaltic hills of the Province of Misiones, (**b**) the Sierras Pampeanas of Córdoba, San Luis, La Rioja, San Juan and Catamarca, (**c**) the Central Buenos Aires Positive area, including the Sierras Septentrionales (Tandilia), the Sierras Australes (Ventania) and the Pampa Interserrana, (**d**) the San Rafael or Sierra Pintada Block in Mendoza, (**e**) the Sierras de Lihuel Calel in La Pampa, (**f**) the Northern Patagonian Massif, (**g**) the Deseado Massif and (h) the Malvinas-Falklands Islands.

Plateau. These volcanic eruptions produced more than 1.5 million km^3 during less than 1 million years, starting at 133 ± 1 Ma, closely after the Jurassic-Cretaceous boundary (Renne et al., 1992), and immediately before the rifting of Gondwana and the opening of the South Atlantic. These volcanic units were never covered afterwards by continental deposits in Misiones province, and therefore, they started a period of long-term landscape evolution under tropical climate which was probably sustained during most of the Tertiary. However, these same units were covered by Tertiary continental and marine sediments in the Chaco-Paraná Basin, provinces of Entre Ríos and Corrientes, Uruguay and western Brazil. Little is known about the paleolandscape of Misiones, where most authors have considered the summit surfaces as just structural surfaces of the basaltic flows. However, Brazilian geomorphologists have identified the "planalto de Vacaria" or Vacaria Surface (Ab'Sáber, 1969), a summit surface developed on the Early Cretaceous basalts, between 950 and 1100 m a.s.l. The Vacaria surface is deeply cut by stream canyons, adapted to modern fractures and joints. This surface extends into Argentina and Uruguay, as the landscape slopes towards the S and the SW. The age of the surface is considered to be Late Cretaceous or Paleogene.
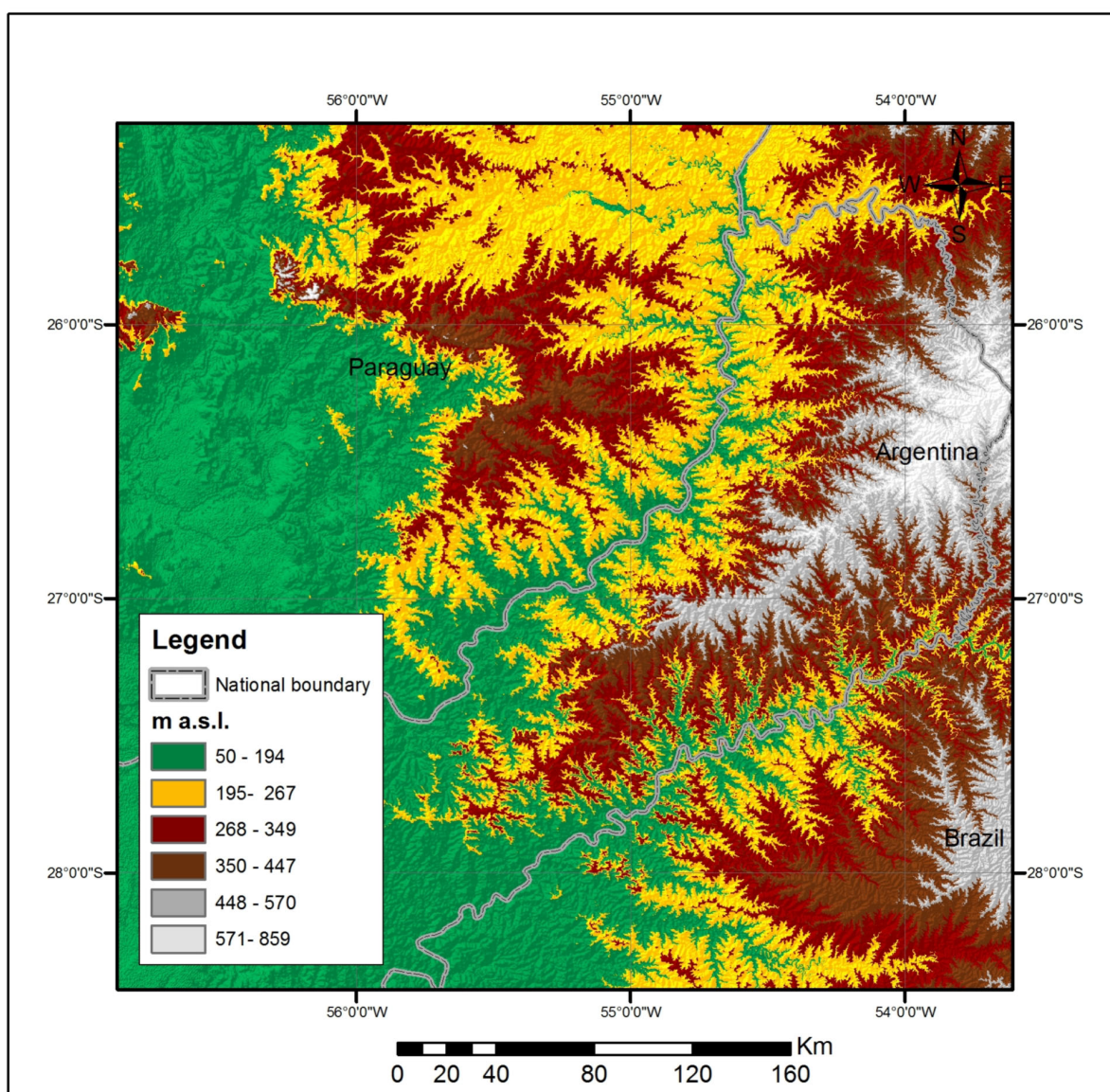

FIGURE 2. Basaltic hills of the Province of Misiones. Hypsographical map. This region is located southwest of the Paraná Plateau, presenting altitudes between 200 y 860 m a.s.l.

Sierras Pampeanas of Córdoba, San Luis, La Rioja, San Juan and Catamarca

The Sierras Pampeanas or Pampean Ranges (Figures 3, 4) are characterized because they keep extensive planation surfaces at or near their summits, which have usually been considered as a single unit and named as a "peneplain" or erosion surfaces, with assigned ages ranging between the Paleozoic and the end of the Mesozoic, and which would have been exhumated during the Tertiary orogeny. These concepts were strongly challenged by Carignano et al. (1999), who proposed that there is not a single surface, and that the existing surfaces are chronologically and genetically different, and they have remained exposed to the atmosphere since the time of their formation (Carignano & Cioccale, 2008).
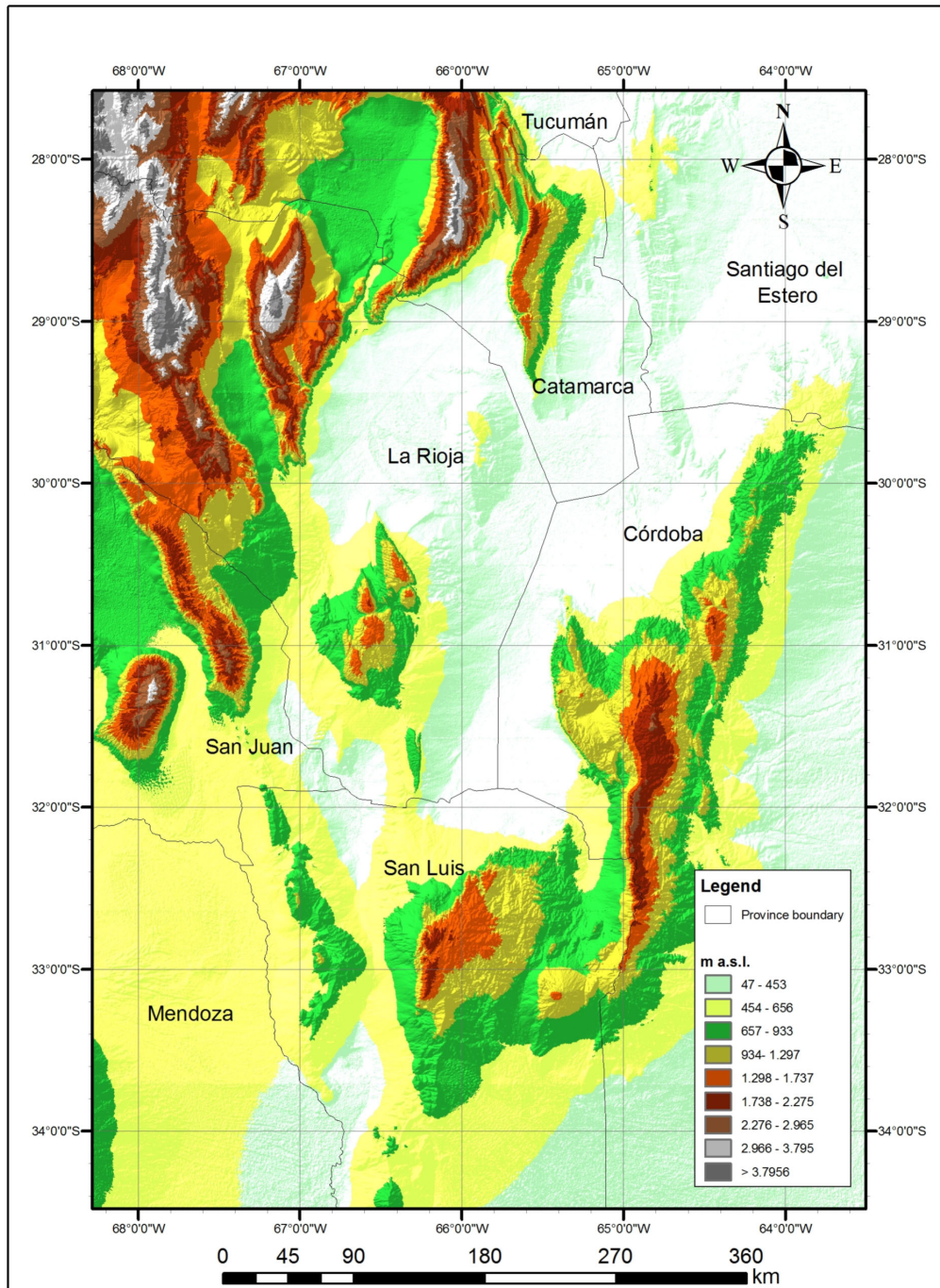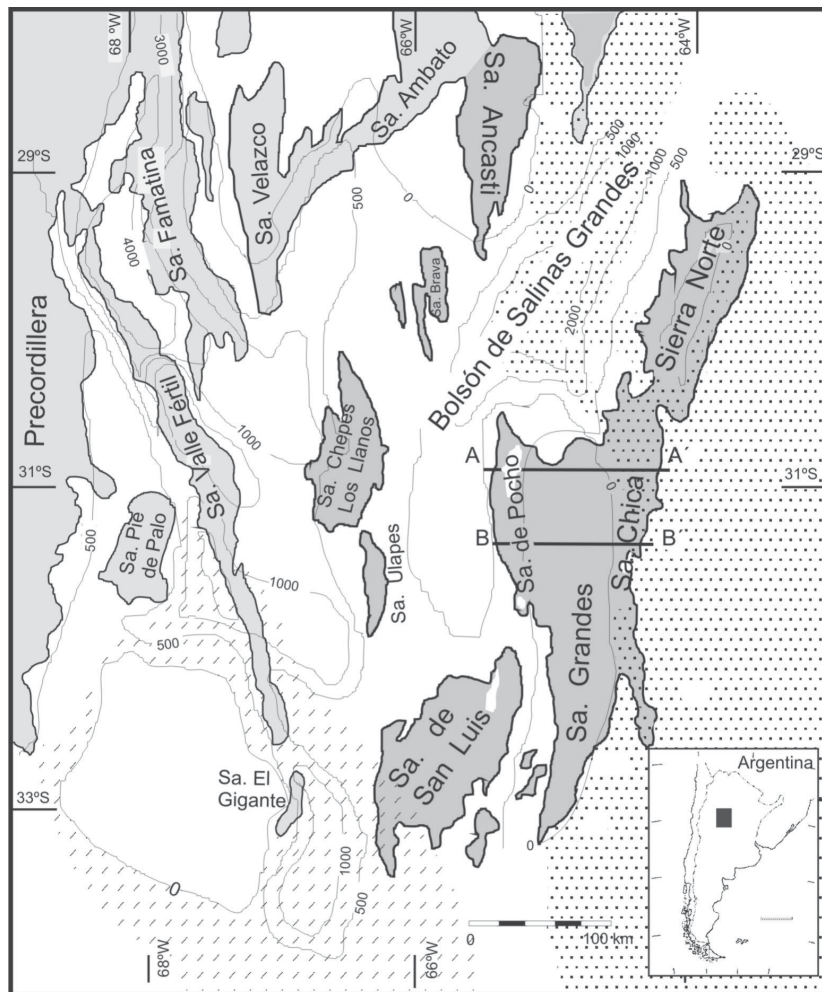

FIGURE 3. Sierras Pampeanas of Córdoba, San Luis, La Rioja, San Juan and Catamarca. Hypsographic map. They are divided into two main regions, the northwestern mountains reaching heights above 3500 m a.s.l. and the eastern mountains, showing heights below 3000 m a.s.l.
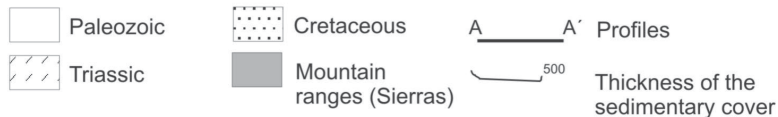
FIGURE 4. Geographical distribution of Sierras Pampeanas, with local names for each of the ranges. Modified from Carignano et al. (1999).

The ideas about the geomorphological development of the Sierras Pampeanas started with Stelzner (1885), Brackebusch (1879, 1880, 1891) and Bodenbender (1890, 1905, 1907, 1911) who prepared the first stratigraphic schemes of the Sierras Pampeanas and noted the clear coincidence in the elevation of the mountain summits, which they sometimes called "altiplains". When Bodenbender (1905, 1911) suggested that the uplifting of the Sierras Pampeanas took place due to the Andean movements during the Tertiary, he settled the bases for the interpretation and regional correlation that was characterized, mainly, by the extension to these areas of observations done somewhere else in the Andean Cordillera. This was a significant precedent that has conditioned even up to

today the geomorphological interpretation of the Sierras Pampeanas. Rovereto (1911) did the first purely geomorphological studies in Argentina, dedicating a chapter to the Sierras de Córdoba, defined by him with an outstanding vision as "a gigantic residual mass of a Paleozoic mountain". This author, also, considered that what he called the "semiplains" of the sierras corresponded to four different erosion surfaces which he named as "peneplains". Though he never mentioned it, the influence of William Davis' concepts was obvious. The three first surfaces would have been developed during the Paleozoic and the fourth during the Mesozoic, of pre-Cretaceous age. Rovereto (1911) recognized in the Sierras de Córdoba, a superposition of the Andean and Brazilian-Uruguayan structural styles and he

observed for the first time that the historical geology of these sierras was almost identical to that of SW Brazil. In this sense, he was the first in assigning Cretaceous age to the sedimentary sequences that outcrop east of the Sierras de Córdoba but, because he was clearly ignored by his colleagues, the idea of a Permo-Triassic age for these beds was sustained until the 70's, when thanks to radiometric dating, their Cretaceous age was confirmed.

Rovereto's (1911) observations and deductions were practically ignored in his time due to the usual criteria of extending the basics of Andean geology to these central regions. Gerth (1914, 1927), Rassmuss (1916), Beder (1916) and Rimann (1926) recognized only one erosion surface in different areas of the Sierras Pampeanas, which had been formed between the Late Paleozoic and the Cretaceous, with a general agreement in a Permo-Carboniferous age. Gerth (1914) proposed also that such erosion surface would have been exhumed.

The following purely geomorphological investigation for this region was done by Schmieder (1921) who, under the influence of other German geologists, confirmed the hypothesis of one single, dismembered Paleozoic surface, uplifted by the Andean movements. In spite of that, this author described in detail the remnants of the surface, noting the presence of "inselbergs" in the highest remnant, the Pampa de Achala. In this work, the first geomorphological map of the region, together with cross sections, was presented, in which the remnants of the surface were represented according to their position and characteristics. The mapped units are in a very clear agreement with those of Rovereto (1911). Schmieder (1921) indicated that he was referring to the erosion surface in the sense of *Rumpffläche* of the German geologists. This term has no genetic meaning (Gross, 1948) but, in the Spanish version that word was replaced by "peneplain", though with the note that it was not equivalent to the genetic term in the sense of Davis (1899, 1909). This serious mistake, probably due to the lack of a proper Spanish term and under the influence of the American literature, set conditions to the future interpretation of the papers authored by the German geologists and derived in problems in the present knowledge of the Sierras Pampeanas geomorphology.

In 1924, W. Penck published his theory on the geomorphological evolution and modelling of the Earth landscape, which in fact was firstly conceived in Argentina (Gross, 1948), when he conducted reconnaissance work in Northwestern Sierras Pampeanas (Penck, 1914, 1920). From his observations in that area and the Sierras de Córdoba, Penck (1924) postulated the existence of four erosion surfaces, generated by a complex geometrical mechanism of slope retreat, each one with its own characteristics and different ages, clearly rejecting the idea of one single planation surface. All of Penck's conclusions are funded in a very careful geomorphological reconstruction, sustained in a strict stratigraphic and structural control.

The first quarter of the 20th century was characterized by the development of important geological and geomorphological theories, as the hypothesis on the connection between the Sierras Pampeanas, the Sierras of Buenos Aires province, the Brazilian-Uruguayan Massif and South Africa (Frenguelli, 1921), originated in the works of Bodenbender (1895, 1911), Walther (1912) and Keidel (1916, 1922), later confirmed by Du Toit & Reed (1927). Contrarily, in following years, the absence of new geomorphological ideas is surprising and, moreover, a clear recession in the geomorphological investigations took place, drifting away from those brilliant epochs of the precedent decades. Thus, the general belief that there was only one erosion surface, named as "peneplain", without a clear genetic concept to support it, as a consequence of the mixture of the local literature (based on the work of the German geologists) and the wide global domination of the Davisian concepts. A clear example of this situation is observed in the work of Schlagintweit (1954), who preferred to avoid the term "peneplain" to refer instead to what he called a "coherent original semiplain", which he observed in the Sierras de Córdoba, recognized as "monadnocks" the hills rising over the general level of the plain, cited the contribution by Gross (1948) and recommended the analysis of Lester C. King's (1953) paper.

Thus, a sort of academic chaos was generated on the genetic and chronological interpretation of the surfaces which remains still today, as shown by papers in which some authors considered the surface as a "pediment" (González Díaz, 1974) and, later, closely supporting the Davisian concepts, the erosion surfaces were interpreted as isolated portions of one, single regional "peneplain" of Paleozoic-Tertiary age, developed during one extended cycle of fluvial erosion (González Díaz, 1981). Others, such as Sayago (1983, 1986), considered the "primeval plain" as a "peneplain" formed by physical weathering and sheet runoff under semiarid climate, however without ruling out, at a same time, a possible origin by deep chemical weathering under tropical or subtropical climate.

Jordan et al. (1989) estimated by thermochronometry the age of the "basement peneplain" of the Sierras Pampeanas, that is the major planation surface found at the summit of these ranges. Their results show that the surface is not a Paleozoic, neither an Early Mesozoic exhumed "peneplain" and that by Triassic times the

rocks now exposed in the planation surface were at 2-4 km down the existing surface at that time. Note that these authors are using the term "peneplain" as any regional surface of low relief created by erosion. This study also revealed that the so-called single "peneplain" is in fact a complex of many different planation surfaces, of varied age and origin, some of which were formed in times as apart as 300-400 million years, but none of them is Late Cenozoic in age. Therefore, their denudation took place long before the Late Cenozoic, i.e., Miocene and after. There are not significant sedimentary units of Jurassic age in the Sierras Pampeanas, and non-marine Cretaceous sedimentary and volcanic rocks are very scarce, mostly limited to the eastern extreme and in some of the western Triassic depocenters. Therefore, it is clear that the Sierras Pampeanas have been a positive element of the landscape as a whole since the Triassic, and locally, perhaps even from the Permian or even before. These authors have established that the denudation rate in the Sierras Pampeanas during the Mesozoic and Cenozoic was very slow, between 0.012 and 0.026 km/myr, though still much faster than in the Australian craton. The available data suggested that there are some of the planation surfaces which are in fact exhumed Early Paleozoic surfaces, whereas most of the surfaces were indeed formed by deep weathering after the Middle Triassic and continuing denudation until the Neogene. The most important results of this study are that the so-called "basement peneplain" is in fact a diachronous group of erosion surfaces, separated in time by 300-400 Myr, and that the younger unit was formed later than the Middle Triassic.

In recent years, thanks to the collaboration with South African colleagues, it has become clear the need of returning to the ideas of Lester C. King (1950, 1956, 1963, 1967) on the evolution of landscape as a conceptual framework, following the methodology in the work of Partridge & Maud (1987) on the study of equivalent erosion surfaces in Southern Africa.

The Sierra Norte and Sierra de Ambargasta (30º 40'-26º 30' S; 65º 25'-63º 15' W) has an elongated shape in a N-S direction, with an extension of over 65,000 km², and a maximum altitude of 1,140 m a.s.l. (Carignano & Cioccale, 2008). These ranges are very useful to understand the genesis of these paleolandscapes. They are composed by Precambrian-Early Paleozoic crystalline basement and though they were affected also by the Andean orogeny, they do not show the characteristic asymmetrical profile of the other Pampean ranges. The Sierra Norte is characterized by a slightly convex upwards shape, in which several extensive planation surfaces are found as stepped levels with planed summits, with incised shallow valleys. These sub-horizontal surfaces may be easily reconstructed. Four major surfaces are found at approximately 900-800, 750-600, 650-550, and 500-350 m a.s.l., distributed in a concentric way around the ranges and progressive decreasing age. The uppermost level is cutting Late Paleozoic sedimentary rocks, whereas the 2nd surface is covered by Cretaceous breccias and alluvial fan conglomerates, and the 3rd one by Cretaceous conglomerates and sandstones. Finally, the 4th planation surface is covered by Miocene marine sediments, a transgressive facies from the Atlantic Ocean (Carignano & Cioccale, 2008). In the 1st and 2nd levels, extensive remnants of the weathering profiles have been preserved, with in situ corestones and gruss, with huge, dome-shaped inselbergs. These conditions allow the interpretation of these surfaces as etchplains, with later removal of the saprolite debris. The ancient weathering fronts are also observed affecting Permian sedimentary rocks below the Cretaceous sedimentary cover; therefore, regional weathering took place probably during the Late Jurassic or Early Cretaceous. The thickness of the original weathered zone is estimated based upon the local relief of inselbergs, in the sense of Linton (1955), of up to several hundred meters. The upper planation surfaces were likely uncovered even since their formation (Carignano & Cioccale, 2008).

The Sierras Chicas and Sierras Grandes de Córdoba have a very complex and illustrative geomorphological history. Several erosion surfaces have been identified, using geomorphological, geometrical-structural and sedimentological criteria (Carignano et al., 1999; Figure 5). The morphogenetic evolution of these ranges, which represent the most impressive of the Central-Eastern Sierras Pampeanas, has been reconstructed based on such criteria. During Jurassic times, a long period of tectonic quiescence and predominantly humid tropical climate enabled the progressive development of a broad planation surface. The occurrence of corestones, bornhardts, tors and deep weathering profiles are interpreted as residual landforms pertaining to that primeval surface (Pictures 1, 2). The Late Jurassic-Early Cretaceous interval was marked by continental rifting and the ranges degradation under less humid, semi-arid climates. During this rifting interval, each major faulting event generated a peculiar, erosion geomorphic cycle. Thus, two more planation surfaces were developed in a very long and complex denudation cycle. Remnants of these surfaces are still preserved around the nuclei of each of the larger blocks of the Sierras Pampeanas. Such surfaces were weathered again during the latest Cretaceous-Paleocene times, further developing a fourth planation surface.
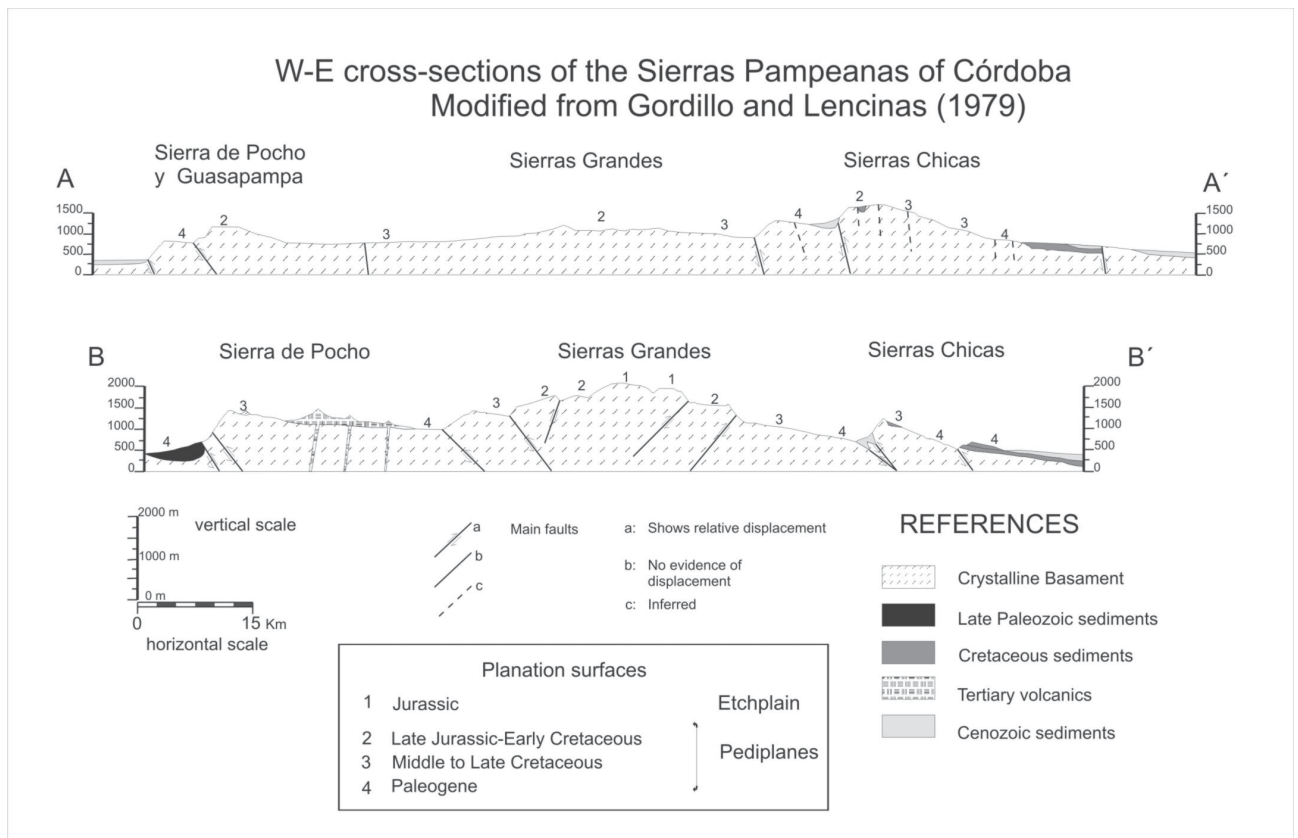
FIGURE 5. Sierras Pampeanas of Córdoba, San Luis and eastern La Rioja.
Cross sections showing the identified paleosurfaces. Based on Carignano et al. (1999).

PICTURE 1. Pampa de Achala, Sierras Grandes de Córdoba. Uppermost paleosurface showing ample extension. Granite landscape corresponding to the base of the ancient weathering front, with granite corestones and many other minor features (Photograph by J. Rabassa, 2000).

PICTURE 2. Sierras Chicas de Córdoba. Paleoweathering, base of a laterite profile. On top, Holocene soils.

During the Miocene, a fifth planation surface was developed. Thick and mature calcretes remain as evidence of long-term, climate stability conditions. Due to the faulting and uplifting during the last 10 Ma, almost all of these surfaces have been broken and partially tilted.

Carignano et al. (1999) proposed that at least the oldest of these surfaces may be tentatively correlated with similar landscapes in Eastern Brazil, Uruguay and Southern Africa.

The nature and age of these ancient Gondwanic paleosurfaces are clearly exceeding the Late Mesozoic tectonic and climatic cycle in the Sierras Pampeanas. In fact, evidence of an ancient planation surface has been found by Socha et al. (2006) at Sierra de Olta, province of La Rioja, which is part of the Sierras Pampeanas craton, forming the eastern portion of the Paganzo basin. However, the cited planation surface was a Devonian or Early Carboniferous (?) etchplain, which was uplifted and later deeply eroded by glaciers during the Middle to Late Carboniferous, in the core of the classical Gondwanic glaciations (Picture 3). These were mountain glaciers whose geomorphological evidence has been preserved and which were located in high, mountainous, coastal ranges, marginally situated in relation with the huge continental ice sheet centered in the present territories of Brazil and South Africa. The whole paleolandscape complex was then affected by weathering in tropical climate during the Middle to Late Mesozoic, forming a younger planation surface at a lower topographical level, which was later denudated during the Cenozoic.

PICTURE 3. Sierra de Olta, eastern La Rioja. Carboniferous mountain glacial valley in cross section, carved in Ordovician granites and schists. The valley and the glacial sediments contained within it have been denudated during the late Cenozoic. In the upper portion, remnants of Cretaceous planation surface. Photograph by J. Rabassa, 2005.

Glacial sediments are very well exposed at the bottom of the present valley. Basal and ablation till deposits have been found at the bottom and sides of the ancient glacial valleys, forming terminal valley moraines, with the presence of sequences of advancing and retreating glaciers, and other glacigenic sediments corresponding to ice-contact glaciofluvial and glaciolacustrine environments. Main and tributary glacial valleys have been recognized and the paleoslopes of the glacial valleys have been reconstructed, as well as their sizes and gradients. The glacigenic deposits are resting on top of Ordovician granites and metamorphic rocks, which are the pre-glacial bedrock. The basal contact of the glacigenic deposits is showing relict pre-glacial weathering profiles, with the presence of paleo-weathering fronts and corestones. The valley moraines are composed of very large Ordovician granite boulders, up to several meters in diameter, very well rounded, all of them of very similar size, strongly equidimensional in shape.

These characteristics of high rounding and strong sphericity are very rare in normal glaciogenic systems. It is interpreted that the boulders are in fact pre-existing corestones, pre-rounded by deep chemical weathering processes in an etchplain, and then incorporated by the glacier to its sedimentary load, very likely transported mainly in supraglacial position and deposited in terminal moraine environments. The presence of the paleo-weathering fronts and the corestones is only compatible with the existence of planation surfaces due to deep chemical weathering, developed in continental environments, under conditions of tropical and hyper-tropical climates during the Late Devonian or the Early Cretaceous. These paleoclimatic conditions would have been maintained until the regional, most likely Middle Carboniferous mountain glaciations developed, when the pre-existing planation surfaces were strongly eroded by the mountain ice sheet. The mountain glaciations landscape was buried afterwards during the Permian and perhaps even up to the Middle Jurassic, when the deep weathering processes developed new planation surfaces in the Late Jurassic and the Cretaceous, whose remnants are still forming the summit surfaces of the mountains in the region. The following denudation during the Cenozoic completed the exhumation of the Paleozoic paleolandscapes until reaching their present distribution and location.

The Sierras de San Luis (33° S, 66° W) is an extension of the Sierras de Córdoba towards the southwest. Their composition and structural style are similar to the Sierras Pampeanas (Costa et al., 1999). The block mountain ranges were uplifted during the Neogene due to the Andean orogeny movements along regional faults. These authors have noticed the uncertain age of the interior

paleosurfaces found in these ranges, which is a serious inconvenience for understanding the Neogene evolution of this region. This paleosurface is widely preserved on the eastern slope (the slope away from the Andes) but it is disrupted by the Neogene tectonics. The paleosurface was studied to understand their contribution to neotectonic activity. It is characterized by a gentle, undulating landscape, slightly tilted to the east. It is composed of denuded crystalline basement and it lacks any sedimentary cover older than the Pleistocene, except for Miocene-Pliocene volcanics. The surface had been described as a "peneplain" (González Díaz, 1981), "shaped by fluvial systems". Costa et al. (1999) describe also a planation surface below the Triassic (?)-Cretaceous in-filling of adjacent basins, and they considered that all surface remnants are part of the same paleosurface, though they quoted Jordan et al.

(1989) findings that the Sierras Pampeanas were mountains and not plains during the Late Paleozoic sedimentation. Based on the available information, Costa et al. (1999) concluded that this surface was formed between the Carboniferous and perhaps Triassic-Late Cretaceous times. Though the published information is still scarce, it may be suggested that the cited San Luis surfaces are in fact diachronic, perhaps being the buried one of Paleozoic age. The summit surface, instead, could be at least partially an etchplain or pediplain of Late Mesozoic age, as in the Sierras de Córdoba, with outstanding examples of granite landscape (Plate 1 a-d) (Carignano et al., 1999) though it cannot be ruled out the possibility that portion of it could be a Paleozoic exhumed feature. It is clear that deeper studies are needed on these paleolandscapes in the future.

PLATE 1. Paleoweathering features in a granite landscape, Sierras de San Luis. **a**) Granite landscape, gnammas and channels; **b**) Gnammas in granite; **c**) integrated gnammas by runoff erosion; **d**) channels in granite, with redeposited silica along the margins of the channel as geochemical levees. Photographs by J. Rabassa, 2003.

The Central Buenos Aires Positive Area, Including the Sierras Septentrionales (Tandilia), the Sierras Australes (Ventania) and the Pampa Interserrana

Darwin (1876) was the first author to mention features of ancient surfaces in Buenos Aires province. He observed, on the flanks of the Ventania ranges, remnants of small patches of conglomerates and breccias, at a height of 300-400 feet (100-130 meters) above the plain, "firmly cemented by ferruginous matter to the abrupt and battered face of the quartz". Darwin (1876) also described in a precise way for the first time the La Toma Section on the Río Sauce Grande valley, where Miocene and other Late Cenozoic sedimentary deposits are forming the base of the post-Permian sequence. Darwin (1876) suggested as the origin of the materials of the Pampean formation, "the enormous area of Brazil consisting on gneissic and other granitic rocks which have suffered decomposition and been converted into a red, gritty, argillaceous mass to a greater depth than in any other country". Though it is known today that only a minor portion of the Pampean deposits has such an origin, it is very interesting that Darwin realized at such an early date the importance of the supply of weathered debris coming from the Brazilian shield into the surrounding sedimentary basins.

Du Toit & Reed (1927) and Du Toit (1937) considered the Tandilia ranges as a buried and partially exhumed mountain chain. Also, Du Toit & Reed (1927) vividly described the "consolidated gravels and breccias resting on benches and terraces cut along the inner side of the quartzite chain of the Sierra de la Ventana". They were referring to the "Conglomerado Rojo", formally known as the Cerro Colorado Breccia, and pointed that: "I (Du Toit) had great difficulty in realizing that this was another continent and not some portion of one of the southern districts of the Cape" (Du Toit, 1954). He noted that the "parallelism is so wonderfully close that the geological histories of these two countries must have been all but identical from mid-Paleozoic down to early Tertiary". See below (also Du Toit, 1954).

According to Du Toit and Reed (1927), Keidel (1916) described an uppermost terrace that it is incised in the quartzites beneath the crest of the range, at a level of around 800 m a.s.l. The second has an altitude between 450-550 m a.s.l. This second surface bears caps of hard, bright-red conglomerates and breccias, in sandy, arenaceous cement with iron oxide. The material resembled the so-called "High-Level Gravels" or silcretes/ferricretes of the Southern Cape, which are assigned to be formed in planation surfaces "during the early part of the Tertiary" (Du Toit, 1954). If the conglomerates in South Africa have an Early Tertiary

age (younger than 63 Ma and older than 54.8 Ma, as indicated by Rabassa et al., 1976) and if these units may be correlated as suggested by Du Toit & Reed (1927), then the valleys in which they are found were eroded at least during the Late Cretaceous or earliest Paleogene. It is then possible that these valleys were formed following the well-known, mid-Cretaceous (inter-Senonian) uplifting of western Argentina and its corresponding effect in the cratonic areas. Later, the landscape dissected on both bedrock and the conglomerates was "in great part buried beneath the mantle of Pampean loess", whereas in South Africa, the general uplift has left it unexposed (Du Toit & Reed, 1927). This is perhaps the first scientific explanation of the origin of the Pampa Interserrana buried surface as an extensive planation surface of Early Tertiary age. Du Toit & Reed (1927) noted also that there is no evidence of early to middle marine Cretaceous along the Pampean coastal region, showing that this area was still united to South Africa. Contrarily, the Late Cretaceous sea penetrating very deeply along the western margin of the Buenos Aires Positive "as far inland as the Sierra Pintada". Therefore, at least part of the Buenos Aires Positive has been continuously above sea level perhaps since the latest Permian, and all of its landscape was formed sub-aerially since then. It should be further investigated if some areas of the Tandilia ranges have been in fact a positive element since the late Paleozoic, when the Carboniferous and Permian seas were washing their western slopes.

The Buenos Aires Positive morphostructural unit (Figures 6, 7; Yrigoyen, 1975), whose geomorphological features allow to consider it as of complex landscape, is composed of the following geological provinces: Tandilia or Sierras de Tandil, Ventania, or Sierra de la Ventana (Figure 8) and the Llanura or Pampa Interserrana, in the sense of Rolleri (1975) (see Zárate & Rabassa, 2005). Tandilia is defined as a system of block-shaped mountains and it is composed of a discontinuous group of hills and low ranges, extending for more than 350 km, with elevations from 50 m to 250 m above the surrounding sedimentary plain. The cross section of the system is clearly asymmetrical, with a very neat and abrupt northeastern margin (known as the "Costa de Heusser") and a very smooth southwestern one (named as the "Costa de Claraz"). The first one corresponds to a NW-SE fault escarpment representing the huge fault that bounds the Tandilia system and the Salado tectonic basin. The western border of the Buenos Aires Positive is bounded by the Colorado-Macachín basin. These basins were initiated during the late Jurassic/early Cretaceous (Demoulin et al., 2005). The orientation of the Salado basin is inherited from late Precambrian structures. Both basins
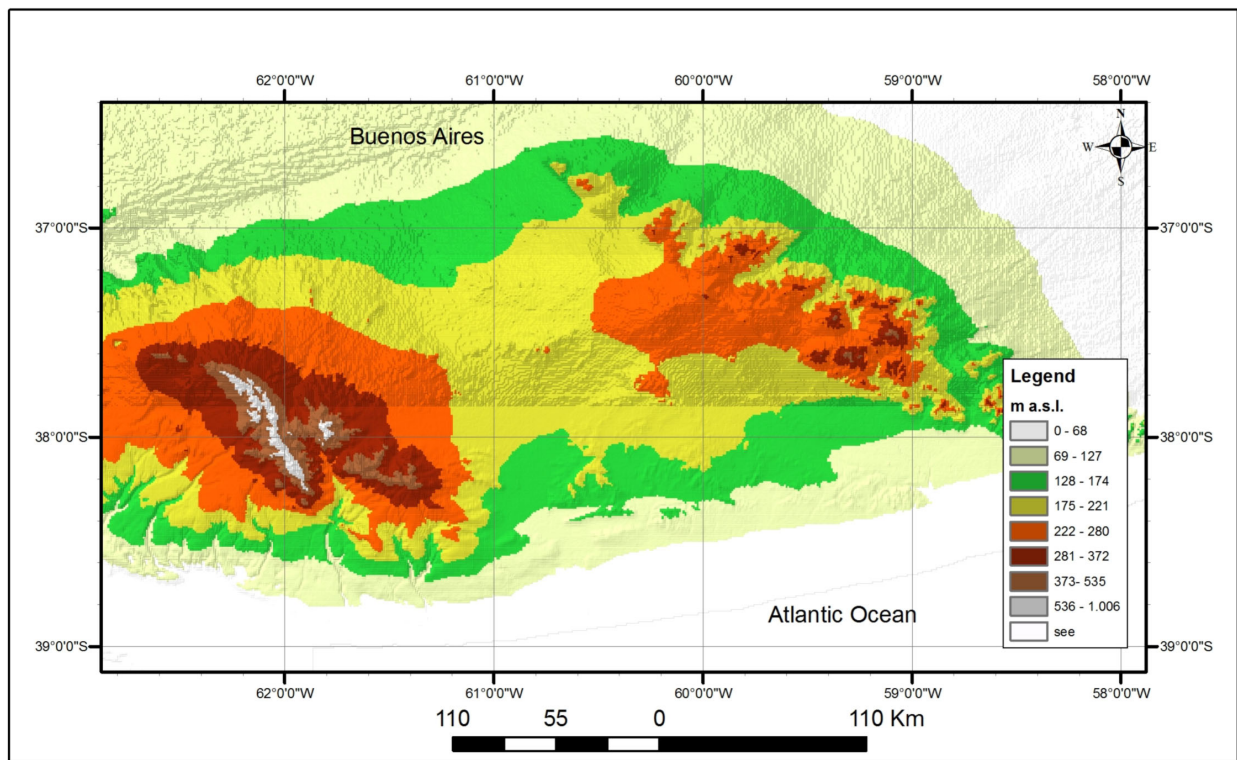
FIGURE 6. Central Buenos Aires Positive area. Hypsographic map. This set is composed of the Sierras of Tandil or Tandilia, to the east, and the Sierra de la Ventana or Ventania, to the west. They are low ranges with heights between 300 and 1000 m a.s.l., with the higher values in the western ranges.
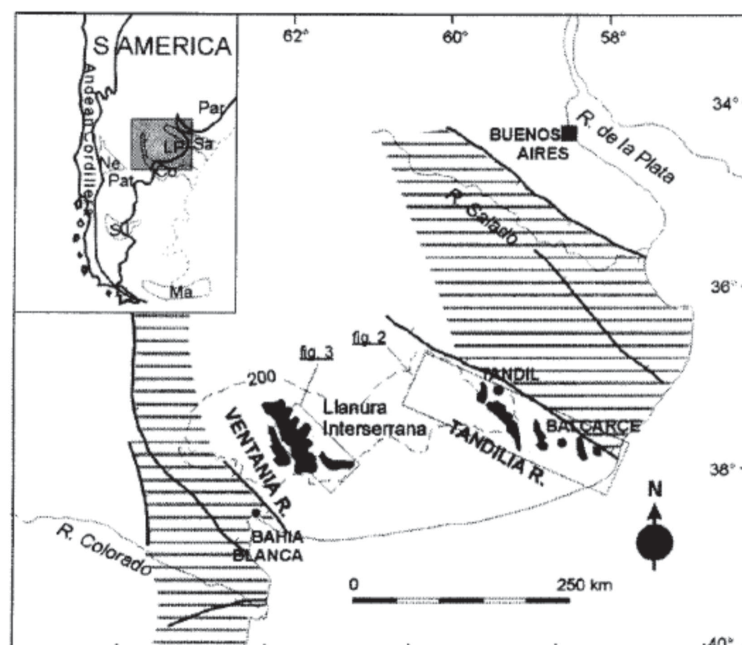

FIGURE 7. Buenos Aires Positive tectonic element, including the Ventania and Tandilia ranges, and the intermediate, loess covered Llanura Interserrana (Inter-ranges plains). The Tandilia ranges are geologically and structurally related to similar areas in Uruguay and Southern Brazil. The hatched areas are sedimentary basins developed in Cretaceous times, due to the Gondwana rifting process, which isolated the positive area described. To the east, the Salado Basin; to the west, the Colorado-Macachín basin. Modified from Demoulin et al. (2005).

FIGURE 8. Structural and geomorphological evolution of the Ventania ranges, with the adjacent Llanura Interserrana and the Colorado basin. The evolution started in late Jurassic times. I. Pre-Cretaceous landscape; Ib. Intermediate inter-Cretaceous surface; II. Paleogene planation surface; P, Pliocene pediments. The hatched sections correspond to sediments coming from the Sierras that deposited in the adjacent Colorado basin, as the weathered materials were denudated. Modified from Demoulin et al. (2005).
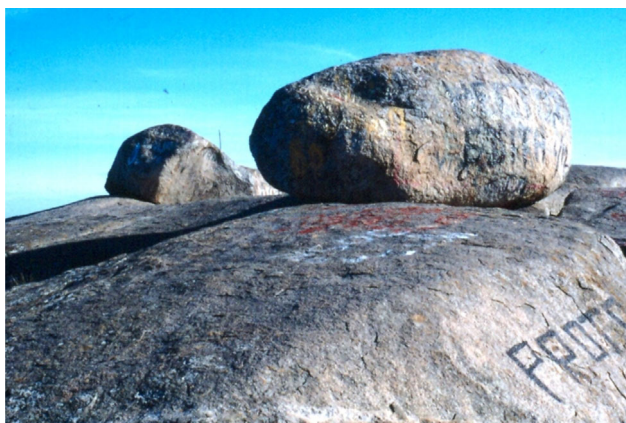
display thicknesses of Cretaceous and younger sediments up to 6-7 km. At the base of the Salado basin infill are continental deposits inter-layered with volcanic and volcaniclastic rocks associated with the early Cretaceous rifting phase. Above an angular unconformity, the next sequence corresponds to marine environments, with major phases of marine deposition taking place in the upper Cretaceous-Paleocene and the Mio-Pliocene and a well-defined Eocene/Oligocene regression.

Large scale geomorphological units, basically ancient planation surfaces, have been recognized during recent studies (Rabassa et al., 1995, 1998; Demoulin et al., 2005). Along the SE section (Mar del Plata-Balcarce), the summit of the ranges lie as a high surface between 200 and 250 m a.s.l. The relative elevation is variable between 100-150 m and rises progressively form the coast towards the hintherland.

NW of Balcarce, the surface continues as an erosion feature that cuts the Proterozoic granites and migmatites at elevations of 300-350 m a.s.l. At Tandil, the surface is preserved at the summits of numerous granitic hills. At the regional scale, the surface is slightly combed and a smoothly undulating topography, with a small relief of a few tens of meters between 300 and 350 m a.s.l. contour lines. The morphological features at a smaller scale vary with bedrock lithology. In the segment bearing Cambro-Ordovician quartzites, the mesas and tablelands are dominating. They show solution features in quartz. In the area of Balcarce, Tandil and Olavarría the sections of weathered granitoids are frequent, sometimes with the presence of kaolinite. Other authors have interpreted them as hydrothermal products. However, the surface distribution, their relationship with the surface and the associated geomorphological features suggest that they

are related to continuous weathering profiles instead. NW of Balcarce, on the granitoid basement, the surface presents low elevation inselbergs, whose summits are covered by frequent granitic corestones, occasionally resting on a gruss bed. Around the city of Tandil, the surface is highly dissected, with a few remnants as inselbergs and tors covered by corestones. The weathering products occur in the slopes. They are corestones with concentric weathering rinds in a matrix of gruss-like, weathered rock (El Centinela) or fresh granite (La Movediza). The "Piedra Movediza" (i.e., the "moving rock") was a rocking stone found on top of a huge inselberg, as part of a partially dismantled tor (in the sense of Linton, 1955), near the city of Tandil (Pictures 4, 5, 6). Its nature and origin was surprisingly described by Estanislao Zeballos as early as 1876, and quite correctly interpreted as the result of chemical weathering (Zeballos, 1876), although the impact of lighting was also partially invoked. This author also suggested that there were many other rocking boulders at the top of neighboring hills (which was never confirmed later on), wisely observing the relationship between the finding of boulders as remnants on the hill tops. It should be noted that its genesis under humid subtropical climate (a climate type that did not exist in the area after the Paleogene) was very early recognized by Walther (1924; in: Fairbridge, 1968). There is no evidence of kaolin or other clay formation, thus suggesting that only the roots of the weathering front have been preserved in a very irregular mantle. In Balcarce, isolated remnants of a higher surface occur (Cerro El Sombrero, 420 m a.s.l.). In Tandil, there are several remnants of this surface in the flat summits of the higher ranges (La Juanita, Alta de Vela, Cerro La Blanca), carved in the Proterozoic granitoids at 450-500 m a.s.l. Where no remnants of the weathered cover have been preserved, corestones are the local-scale morphological features associated with these surfaces. The third morphological unit is represented by pediments and alluvial fans, surrounding the ranges, but they belong to the Late Cenozoic (Rabassa, 1973; Zárate & Rabassa, 2005).

PICTURE 5. Cerro La Movediza, Sierras de Tandil. Paleoweathering front with granite corestones in situ, surrounded by chemically altered granite transformed in clays. Photograph by J. Rabassa, 1998.

PICTURE 4. Cerro La Movediza, Sierras de Tandil. Ancient granite corestones as remnants of paleoweathering under warm/wet tropical climates, at the base of the weathering front. At least one of these corestones evolved into a perched rocking stone (La Movediza, i.e., "the moving one"). Photograph by M. Zárate, 1998.

PICTURE 6. Cerro La Movediza, Sierras de Tandil. Artificial reconstruction of the ancient La Movediza rocking stone, as it was in place until the beginnings of the 20th. century. Photograph by E. Soibelzon, 2010.

The Ventania ranges, or Sierra de la Ventana, are a mountain system about 180 km by 60 km, composed of sub-parallel ranges. It reaches between 400-700 m above the surrounding plains, with maximum elevation of 1240 m a.s.l. The Curamalal, Bravard and de la Ventana ranges have preserved remnants of two paleosurfaces located at different topographic heights. Keidel (1916) was the first author in describing and precisely mapping them. More recently, Pereyra & Ferrer (1995) and Pereyra (1996) pointed out that the higher planation surface of the northeastern ranges of Ventania was probably formed in the time between the Permian collision of Patagonia and central Argentina and the late Jurassic opening of the Colorado basin. They recognized only one erosion surface, and considered that the differences in elevation were due to differential erosion on various lithological types. Rabassa et al. (1995) suggested that the relict landscapes of the Sierras de La Ventana and Tandil, along with the morphology of other cratonic areas of Argentina, should be reinterpreted in a Gondwanic perspective. The sequence of uplifted surfaces would be then linked to the Late Jurassic/Early Cretaceous rifting of South America and Africa, while their intensely weathered bedrock might point to Mesozoic and Paleocene tropical conditions rather than to the cooler and drier Neogene.

Demoulin et al. (2005) indicated that the oldest paleosurface is forming the summit surface of the ranges, with elevations between 800-900 m a.s.l. The lower surface, less extensive, has been excavated at elevations of 600-700 m a.s.l., in the southern slope of Sierra de la Ventana. Another extensive surface is located in the inter-mountain basin of Las Vertientes, developed between 450-500 m a.s.l. In this surface, the Río Sauce Grande valley is excavated 100 m. Northward it is formed by the longitudinal depression of Valle de las Grutas; it is also preserved in the outer piedmont of the eastern sierras (Las Tunas, Pillahuincó). Eastwards, the Sierra de Las Tunas presents a pattern of step-like surfaces similar to that of the western ranges, with the solely difference that the summit surface is at 700-750 m a.s.l. and the lower one at 550-600 m a.s.l. Along the outer segments of Ventania, pediments have been developed, connecting outwards with the Llanura or Pampa Interserrana plains.

The Ventania paleosurfaces are much less leveled than those of Tandilia, basically due to their lithological differences (Rabassa et al., 1998). Relict sedimentary deposits have been found in some of these surfaces, such as silicified breccias and conglomerates, which occur in different locations of the group of western sierras (Harrington, 1936), closely associated to the 450 m a.s.l. surface (Keidel, 1916; Zárate et al., 1995).

Known as the "Conglomerado Rojo" (Harrington, 1936) and later formally named as the Cerro Colorado Breccia (Andreis et al., 1971), these deposits are present in the Valle de las Grutas and both sides of Sierra de la Ventana. They are generally located in front of small valleys training the sierras and they are formed by fans or slope deposits, in a whitish to reddish, sandy matrix, cemented with opal and iron oxides and hydroxides (Andreis et al., 1971; Zárate et al., 1998). The hills with silicified deposits are covered by boulder-rich layers. Though these boulders were firstly considered as a separate unit (Las Malvinas Formation, De Francesco, 1971, in Fidalgo et al., 1975), the age and nature of this unit should be revised. The age of the Cerro Colorado Breccia, which traditionally had been considered as of Miocene age, has been reinterpreted and a Cretaceous age has been proposed as the most likely (Zárate et al., 1995, 1998). It is possible that new studies may then reconsider the age of the Las Malvinas Formation, or part of it, which could be in fact a residual lixiviated breccia of the Cerro Colorado Breccia, and therefore part of the latter.

The Llanura or Pampa Interserrana includes the "Pampa Interserrana" as named by Frenguelli (1950) and also the piedmont areas of Ventania and the SW piedmont of Tandilia. It is composed of a plain with elevations of little above 200 m a.s.l. in the central portion in between both mountain systems, and lowering gradually towards the Atlantic Ocean southwards. The landscape of the Pampa Interserrana is composed of Late Cenozoic continental deposits which are capped by a thick calcareous duricrusts. The dominant landforms are pediments and loess accumulation plains. These Late Cenozoic units overlie a vast planation surface, which is found a few tens of m to a couple of hundred m below the present surface. This ancient surface, clearly pre-Miocene at least, is probably related to the ancient surfaces described for both main ranges. It is in fact developed most on top of the Late Paleozoic deposits of the eastern Ventania ranges. However, further studies are needed to confirm the nature and age of this ancient planation surface, since it is totally buried by the Late Cenozoic sedimentary cover, with the exception of a few, small and isolated, highly weathered outcrops of Carboniferous and Permian rocks.

In summary, the Buenos Aires Positive region was never covered by the sea since at least the mid-Late Triassic (Uliana & Biddle, 1988), but perhaps even since the latest Permian or partially, even before. Thus, this is probably the most spectacular example of long-term landscape evolution in Argentina, with a geomorphological history of over 230 Myr of sub-aerial geomorphological development. The large-scale morphological units and associated weathering products

in the Tandilia and Ventania ranges have been described, together with two main planation surfaces, encountered at varying altitudes in different sectors of these ranges. The lower surface is characterized by the occurrence of roots of kaolinized weathering profiles in Tandilia and by silicified conglomerates around Sierra de la Ventana. In an interpretative model linking the range morphogenesis to the tectono-sedimentary evolution of the bordering Salado and Colorado basins, it has been suggested that the main morphogenetic stages are actually related to the Late Jurassic/Early Cretaceous South Atlantic rifting and, afterwards, to the Miocene tectonic reactivation induced by the Andean orogeny (Demoulin et al., 2005). Thus, the uplifted surfaces appear much older than commonly believed, being respectively of pre-Cretaceous and Late Cretaceous-Paleogene (?) ages. The very low denudation rates that have been established (Demoulin et al., 2005), such as ~ 4 m/Myr, are explained by the very limited (if any) Meso-Cenozoic uplift suffered by the Buenos Aires ranges.

According to Rabassa et al. (1995), the main tectonic event affecting the Pampean long-term morphogenesis has been the Late Jurassic-Early Cretaceous rifting of the South Atlantic. Therefore, the unification of the pre-Cretaceous surfaces on both sides of the South Atlantic is acceptable since they were part of the same topography, as Du Toit & Reed (1927) indicated. However, the asymmetric character of the South Atlantic rifting induced different uplift amplitudes in South Africa and Southern Brazil-Uruguay-Argentina, opposing the South African Great Escarpment on one side to insignificant along-rift slopes on the other. Denudation was consequently much smaller in eastern Argentina than along the South African coast. Finally, the poor preservation of kaolinized bedrock on the Argentine surfaces with respect to the extended weathering mantles covering African or Brazilian surfaces possibly points to a superimposed climatic influence on denudation effectiveness (Demoulin et al., 2005).

THE SAN RAFAEL OR SIERRA PINTADA BLOCK IN MENDOZA

The Sierra Pintada or San Rafael Block (Figure 9) is located in the central portion of the province of Mendoza, not far from the Andean Cordillera but with a particular geological history. It shares some
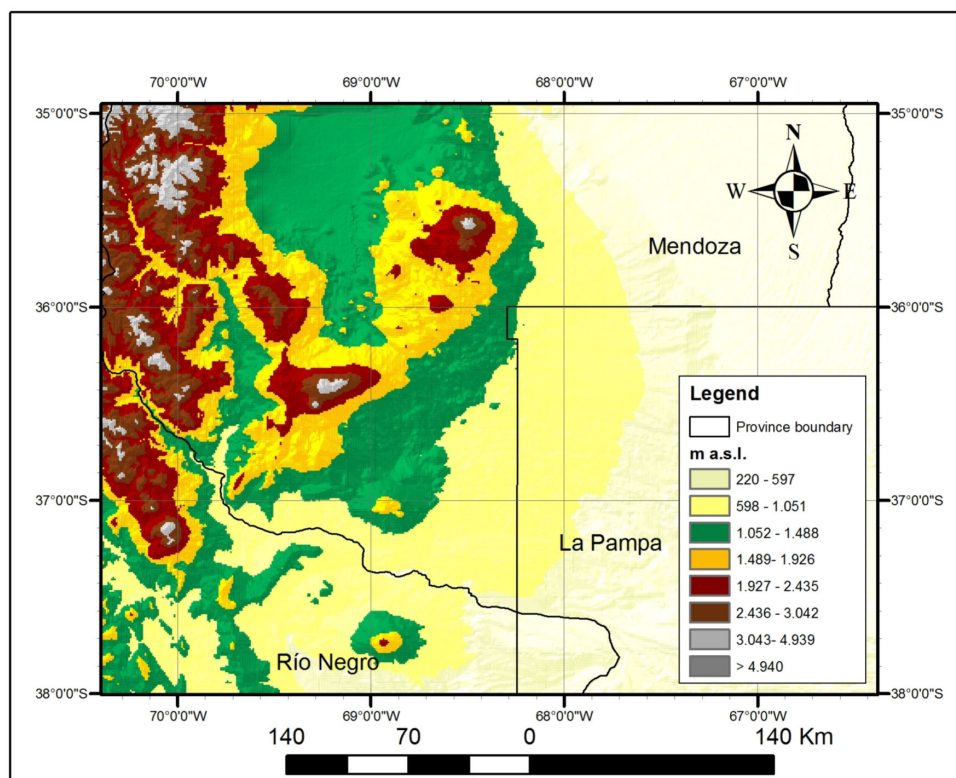

FIGURE 9. San Rafael Massif or Sierra Pintada Block. Hypsographic map. The relief of this area is generally bounded by the contours of 450-1800 m a.s.l. The highest peaks correspond to isolated mountain ranges and volcanoes, among which the Nevado volcano (3810 m a.s.l.) stands in the southern part. In this sector the basalts have partially covered the ancient relief developed during the Paleozoic, Triassic and Tertiary. The surrounding hills and a raised range werw preserved as relicts.

stratigraphic and structural characteristics with the Precordillera and the Cordillera Frontal, but it was never covered by the Mesozoic seas, and it has probably remained as a positive element in the landscape at least partially since the Triassic. Criado Roque (1972) recognized the existence of two main paleolandscapes. The first one developed after the definitive recession of the sea, already in the Early Carboniferous, when an abrupt relief was generated. Later, after the deposition of Late Triassic volcaniclastic sediments, the entire Jurassic and Cretaceous period is not represented. This huge hiatus is characterized by ample "erosion and peneplanization" (Criado Roque, 1972) of this geological unit. These surfaces were covered by Tertiary sediments related to the Andean Orogeny. No further information was provided for the nature and genesis of these landforms, but they may be correlated to the Gondwanic paleosurfaces of the Sierras Pampeanas.

Later, Criado Roque & Ibáñez (1980) confirmed the existence of these two paleolandscapes, and the persistence of the block as a positive area throughout the Mesozoic, when it underwent intensive erosion.

These authors identified also the youngest bedrock unit pre-dating the surface as of Early Triassic age and then Late Cretaceous sediments on top of the paleolandscape, thus providing limiting ages for this ancient surface. These conditions are highly similar to those identified in the Sierras Chicas de Córdoba (Carignano et al., 1999).

The San Rafael Block has shown no tectonic deformation whatsoever since the Triassic, in spite of its indubitable geological connections with the Andean Cordillera, thus making it a highly stable, cratonic area of Western Argentina. This unit may be geologically connected with the Sierras de Lihuel Calel (see below).

THE SIERRAS DE LIHUEL CALEL IN LA PAMPA

The name Sierras de Lihuel Calel is a general term used to name a belt of remnants of barely outcropping ancient rocks in the province of La Pampa, between lat. 36º and 39 ºS (Figure 10). These remnants are bounded to the NE by the Macachín Basin and to the SW by the Neuquén Basin, both tectonic depressions related with the late Mesozoic rifting processes.
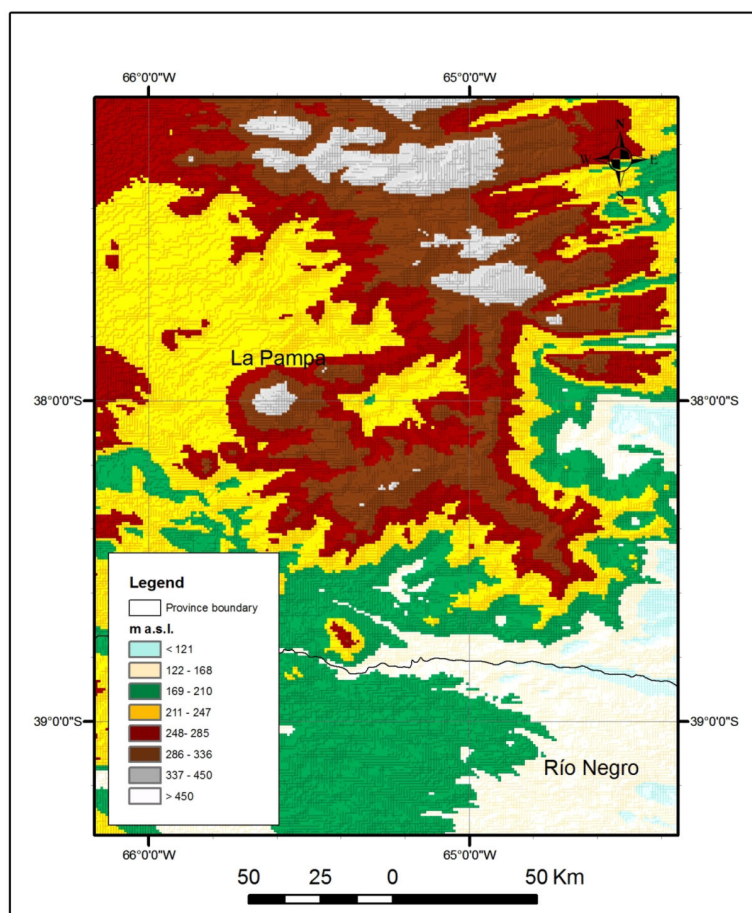

FIGURE 10. The Sierras de Lihuel Calel in the province of La Pampa, Central Argentina. Hypsographic map. The ranges are oriented in a northwest-southeast direction, forming several chains with different orientation, covering a square area of approximately 15 kilometers per side. The highest peak reaches 589 m a.s.l.

This unit has been considered by Criado Roque (1972) and Criado Roque & Ibáñez (1980) as a continuation of the San Rafael Block towards the SE. As in the San Rafael Block, the stratigraphic sequence ends in the Early Triassic, with the tuffs and ignimbrites of the Lihuel Calel Fm. These rocks have been thoroughly eroded during the rest of the Mesozoic and most likely, even the Early Tertiary. The scarce outcrops of these units are almost totally covered by Tertiary rocks of various ages and Quaternary sediments. Therefore, their relationship with the original paleosurfaces is not clear, though the visible portion of it may be related to inselbergs and other residual features. It is highly possible that the existing paleosurface is in fact part of the Gondwana or Post-Gondwana surfaces, as recognized in the Sierras de Córdoba by Carignano et al. (1999).

This unit, together with the previous one, is very poorly known from a paleogeomorphological point of view and clearly deserves further attention.

THE NORTHERN PATAGONIAN MASSIF

The Northern Patagonian Massif is an isolated craton which occupies the northernmost portion of Patagonia (Figure 11). It is bounded by Late Mesozoic basins like the Colorado-Negro basin to the north and the San Jorge Gulf basin to the south, and the Northern Patagonian Andes, including the Ñirihuau-Ñorquinco basin, to the west, which were uplifted in the mid to late Tertiary. This massif has been a positive element of the crust at least since the Permian. The sea flooded its margins during various events in the Jurassic and Cretaceous. Moreover, occasional platform sea transgressions extended locally in several episodes during the Maastrichtian and the Tertiary.

Rabassa (1975, 1978a, b) described the existence of three superposed paleolandscapes in the western portion of the massif, successively developed in the Late Cretaceous-Paleocene, the Oligocene-Early Miocene and the Pliocene. Some of these paleolandscapes have been exhumed and slightly
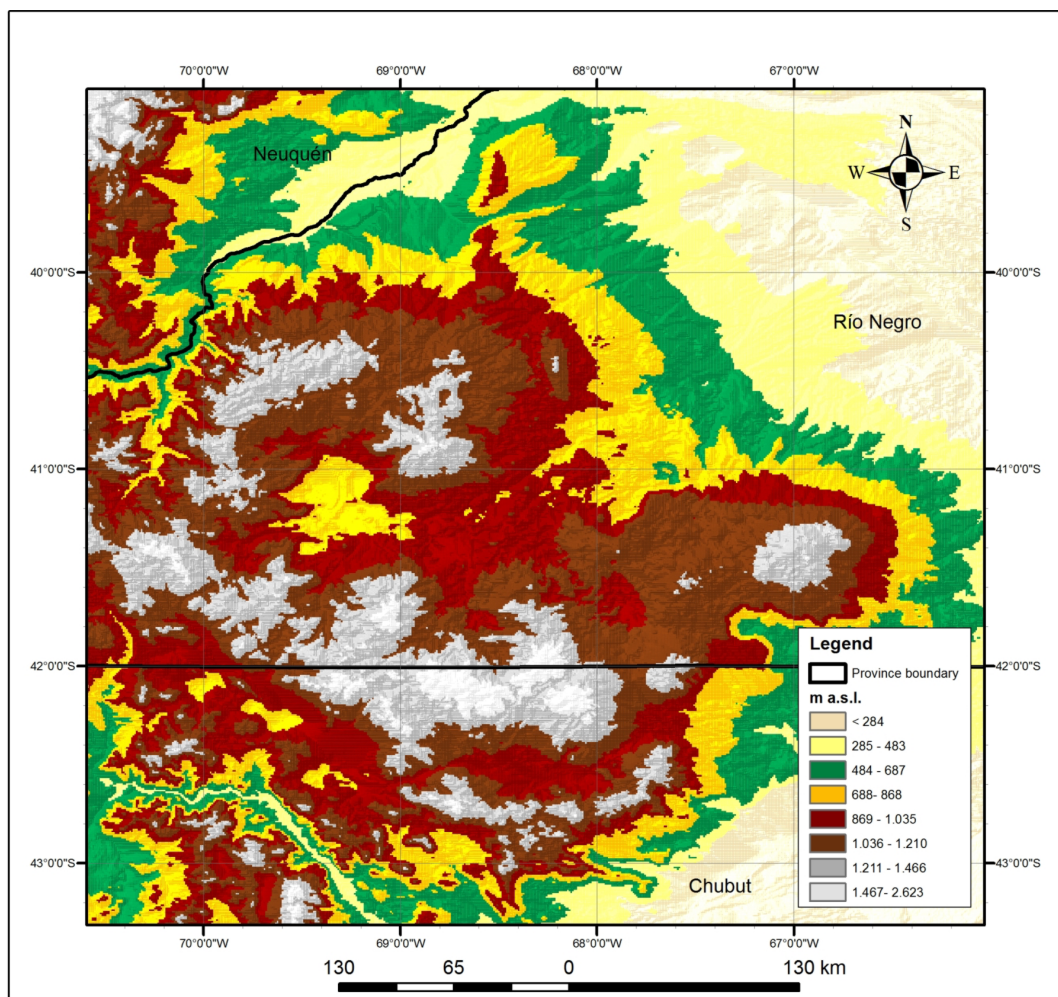

FIGURE 11. The Northern Patagonian Massif. Hypsographic map.

modified during the Quaternary. The reconstruction of the landscape has been favored by the presence of several volcano-sedimentary sequences that had buried the ancient landscapes and preserved them from denudation. The oldest landscape developed over the Paleozoic Crystalline Basement, mostly granites, migmatites and other metamorphic rocks, and Early Mesozoic units, of Triassic and Early Jurassic age. The western area has then drainage towards the Pacific Ocean, before the uplifting of the Patagonian Andes, a fact which had been already mentioned by Groeber (1929). The paleolandscape is a partially exhumed etchplain, formed under wet tropical climate, widely extended across the massif, with the development of inselbergs and tors (Pictures 7, 8, 9, 10, 11). Humid tropical climates vanished for ever from the massif since perhaps the Middle Cretaceous; therefore the etchplains are preserved remnants of these old climates. This ancient landscape was fluvially eroded and buried by latest Cretaceous continental sediments (Picture 10) and the Paleocene-Eocene volcano-sedimentary sequence of the Ventana Fm. (Rabassa, 1975). Therefore, this landscape was generated between the Middle Jurassic and the Late Cretaceous, although it is possible that it is in fact a palimpsest of several geomorphological cycles, including at least one or two pediplains and a fluvial cycle during that period. Later on, when the Patagonian Andes were uplifted, the drainage direction switched towards the Atlantic Ocean in the Late Oligocene-Early Miocene, and by the Middle Miocene the basic lines of the present drainage system had been established. A deep, fluvial valley landscape developed in this latter epoch, and it was filled by the ignimbrites and other pyroclastic and sedimentary deposits of the Collón Curá Fm., of undisputed Middle to Late Miocene age (ca. 15 Ma). The fluvial landscape was buried and then Pliocene pediments, extending from the rising mountain front to the west, leveled most of the area.

The action of deep chemical weathering in ancient times over the massif is confirmed by the presence of clays and other residual materials accumulated in those basins marginal to the craton, which are of high economic interest. Domínguez (1988) has identified residual kaolins and other clays deposits in the sediments of the Challacó Formation, marine units of the Jurassic of the Central Neuquén Basin deposits. The source for these sediments was located SE and SW of the study area, that is, the western margin of the Northern Patagonian Massif. The clays were the consequence of intense weathering of the Choiyoy Volcanic Group, rhyolites and rhyodacites. Similar origin would have had comparable deposits of the lower Río Chubut valley. In this case, the source area would have been the

southern margin of the Massif. Therefore, the entire massif was under similar deep weathering conditions. The kaolinite materials would have been then the result of intensive erosion of a former planation surface, probably of Late Triassic or Early Jurassic age.

The presence of ancient tropical landscapes in the Northern Patagonian Massif has been recently recognized by Aguilera (2006), Aragón et al. (2010) and Aguilera et al. (2010), the latter two in this volume.

THE DESEADO MASSIF

The Deseado Massif is an isolated craton and named as "nesocraton" by Harrington, 1962), who identified it as a long-term positive, stable and not deformed structural unit (Figure 12). The Deseado Massif is located in Southern Patagonia, separated from the Northern Patagonian Massif by the San Jorge Gulf Basin, and from the Southern Patagonian and Fuegian by the Austral Basin (Di Giusto et al., 1980). Both these basins are tectonic depressions related to the Late Mesozoic rifting events. It is basically a very large tableland, with very small local relief, located at ca. 1000 m a.s.l. Gondwanic landscapes in the Deseado Massif were briefly mentioned by Rabassa et al. (1996), who cited extensive erosion surfaces, notably homogenously leveled on the Middle to Late Jurassic volcanics and volcaniclastics of the Chon Aike Formation and other units of the Bahía Laura Group. The Bajo Grande and Baqueró formations of latest Jurassic to Late Cretaceous age are deposited unconformably over this surface, but De Giusto et al. (1980) mentioned also the existence of an angular unconformity and a true paleorelief in between the latter two units. The possibility of younger planation surfaces, eroded on top of the Cretaceous units should be investigated further. Earliest Tertiary marine deposits of the Salamanca Fm. are found on top of a planation surface, eroded on top of the Cretaceous continental sediments. Above the cited surface, only scattered outcrops of Tertary volcanics are found, together with erosion remnants, such as inselbergs and tors, and youger volcanic cones. Although no detailed paleogeomorphological studies have been developed yet in this area, it is clear that at least three very well developed Late Mesozoic paleosurfaces are present in this unit, making this unit exceptionally attractive for future investigations.
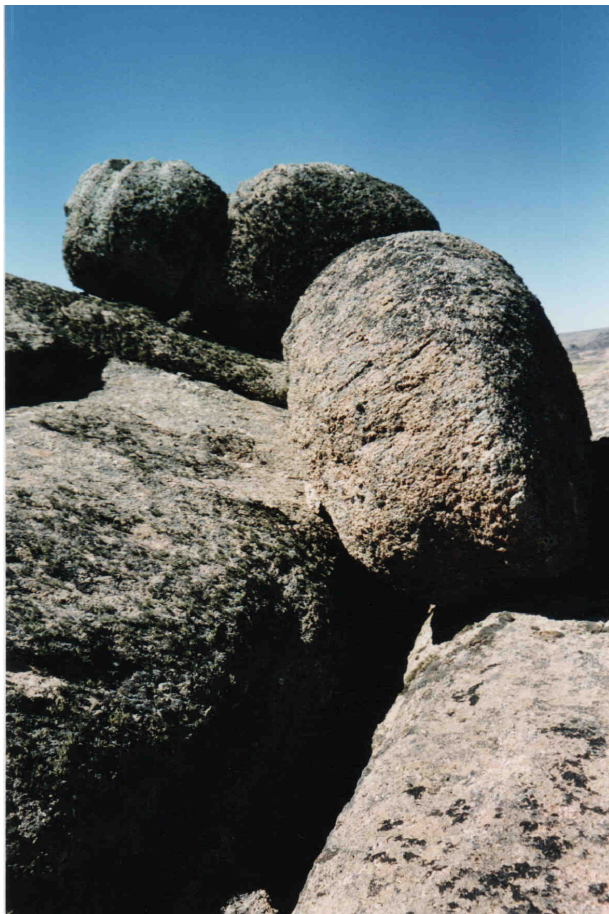
The existence of residual deposits due to deep chemical weathering in tropical climates was recognized by Cravero & Domínguez (1992, and papers cited there), who described kaolin deposits in Santa Cruz, at the southern portion of the Deseado Massif. These kaolin-bearing units are of fluvial origin,

PICTURE 7. The Northern Patagonian Massif. Comallo paleosurface, developed as a planation surface on metamorphic rocks of the crystalline basement, in pre-Late Cretaceous times. Photograph: J. Rabassa, 2000.

PICTURE 8. Inselbergs in a planation surface developed on Permian granites, Pilcaniyeu, province of Río Negro. Photograph: J. Rabassa, 2000.

PICTURE 9. Granite corestones developed on Permian granites, Pilcaniyeu, province of Rio Negro. The corestones have piled up as the tors formed as part of a Cretaceous planation surface are dismantled by Cenozoic denudation. Photograph: J. Rabassa, 2000.

PICTURE 10. Late Cretaceous sediments lying on planation surface developed on crystalline basement, metamorphic rocks and granites, Comallo, province of Río Negro. The surface is possibly Late Jurassic-Early Cretaceous in age. Photograph: J. Rabassa, 2000.

PICTURE 11. Planation surface developed on granite, El Cuy-Los Menucos, province of Río Negro. Note the abundant granite corestones and the tors under dismantling processes. Photograph: J. Rabassa, 2000.

FIGURE 12. The Deseado Massif, southern Patagonia. Hypsographic map.

developed within the Baqueró Formation (Middle to Late Cretaceous) over Middle Jurassic ash-flows (Chon-Aike Formation) to Early Cretaceous ash-fall tuffs (Bajo Grande Formation). These volcanic units had been previously altered to kaolinite, illite and smectites. Therefore, the authors suggested that kaolin was formed by regional, chemical weathering under humid tropical climates sometimes in the latest Jurassic to the Early Cretaceous, being these the dominant environments on the Deseado Massif in those times. Afterwards, when the climate changed, the weathering products were removed by sub-aerial, fluvial processes to the accumulation areas in the Middle to Late Cretaceous.

THE MALVINAS-FALKLANDS ARCHIPELAGO

The Malvinas-Falkland archipelago is a continental fragment which drifted away from the southernmost portion of Africa (Figure 13). Clapperton (1993) described smoothly rolling uplands, at an average height of 500-600 m a.s.l., with highest summits around 700 m a.s.l., closely adjusted to underlying structure and lithology, which reflect prolonged evolution by sub-aerial denudation, as expected in a former portion of Gondwanaland. These topographic levels have been interpreted as remains of planation surfaces, but their age is still unknown, although they are clearly Triassic or younger (Clapperton, 1993).

CONCLUDING REMARKS

The observations of the different studies are suggesting the following conclusions (Carignano et al., 1999; Carignano & Cioccale, 2008):

a) During the Mesozoic and most of the Paleogene,

the Sierras Pampeanas have had long periods of stability that have favored the development of deep weathering processes and the formation of etchplains, under hyper-tropical climates (Rabassa, 2010);
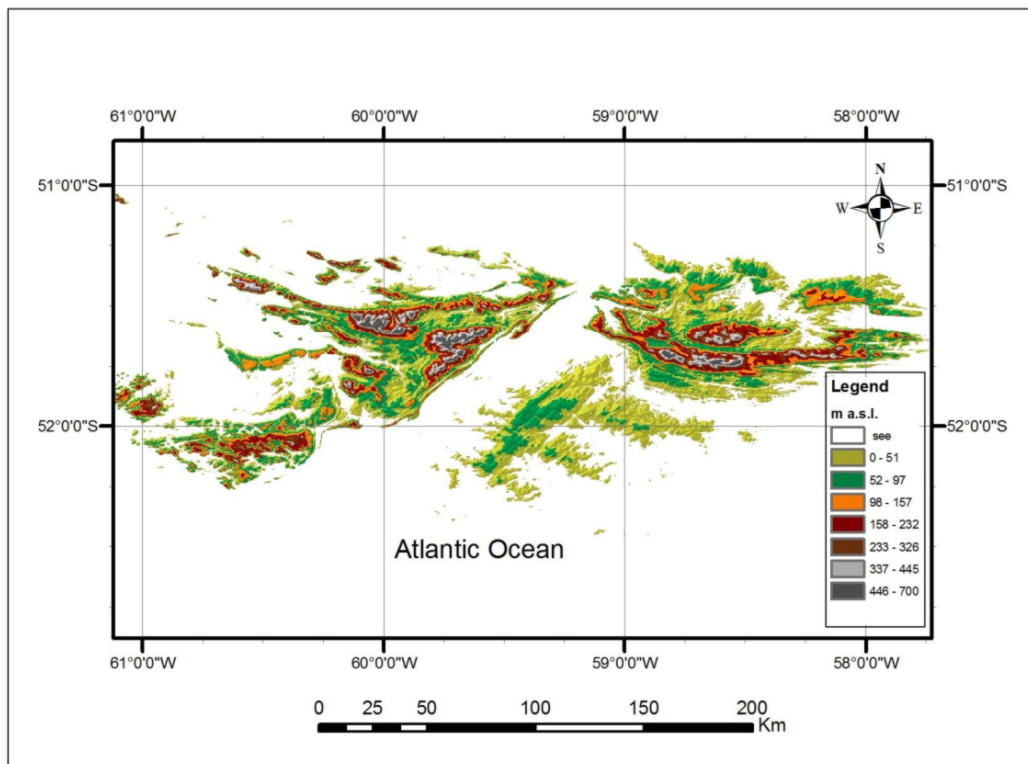
FIGURE 13. The Malvinas-Falklands Archipelago. Hypsographic map.

b) The Sierras Pampeanas show remnants of exhumed surfaces as well as relict landscapes that were never covered by sediments after their formation and have been denudated since the "hyper-tropical" climates changed towards drier and highly seasonal climates in the Tertiary;

c) The relict and exhumed landforms may be related to the surrounding sedimentary record;

d) The exhumed landscapes are associated with areas of the ranges that were covered by Cretaceous sediments, due to relief inversion due to the process of tectonic inversion following the impact of the Andean orogeny over extensional structures formed during the rifting (Schmidt et al., 1995).

e) The relict landscapes are found in the higher portions of the ranges where the deep weathering profiles are found, and also in the sites that are surrounded by Cretaceous and/or Miocene sediments.

f) Surfaces and erosion escarpments are genetically and chronologically different, with the oldest ones located in the inner and higher parts of the ranges and the younger ones along their margins.

g) The relationship between deep chemical weathering and wet tropical or even "hyper-tropical" climate is undisputable, because the generated landforms cannot be generated under drier climatic conditions,

as it has been shown in many other areas of the world.

h) The proposed "hyper-tropical" climate (Rabassa, 2010) has no analogue among the present climates on Earth and its actual parameters and extension should be further investigated.

i) Moreover, tropical climates disappeared from western, central and southern Argentina already in the Early Tertiary, and never returned to these areas. Therefore, any erosion remnants or residual deposits which may be assigned to these environmental conditions should necessarily be formed in pre-Mid Tertiary times.

j) Kaolin formation, ferricretes and silcretes are features clearly associated with the observed etchplains in several regions of Argentina.

k) Several types of planation surfaces have been recognized, particularly etchplains, under very wet climates, and pediplains, formed under semiarid or strong seasonal climates. In general terms, etchplains are older than the pediplains. It is possible that several geomorphologic cycles are superposed for a certain area, forming true palimpsests that should be further studied and unraveled.

l) Some of the studied landscapes have been exposed to the atmosphere uninterruptedly for very long periods, in cases during more than 100 million years.

m) The co-genetic relationship of the paleolandscapes of Argentina with South Africa, such as the Late Jurassic Gondwana surfaces, the Cretaceous etchplains, the Late Cretaceous and Early Tertiary pediplains and the "High Level Gravels" of the Sierras de la Ventana and the Southern Cape have been confirmed by field studies. However, the co-evolution of the landscapes in both continents was interrupted by the final opening of the South Atlantic Ocean which forced a changed in the ocean circulation and therefore, profound modifications in the distribution of climate belts.

n) The pediplains are of a much more local nature and should be analyzed within the framework of regional landscape evolution and may not be present simultaneously in both continents.

o) A large variety of landforms and paleoweathering features are present in these paleolandscapes, such as inselbergs, bornhardts, perched rocks, rocking boulders, weathering profiles, weathering front, several types of duricrusts such as laterites, ferricretes and silcretes, granite landforms and microlandforms, arenization of quartzites, among other features. This entire set of geomorphological features has been very useful in the identification of ancient landscapes.

p) Old landscapes are indicators of the persistence of most of the studied cratons regions as positive elements since at least the Permian and perhaps even before.

q) The presently observed mountains in the Ventania landscape would be of Late Mesozoic age, which were then slowly and barely modified after denudation in the Tertiary, forming an outstanding example of long-term landscape evolution in cratonic areas.

r) The observed paleolandscapes are very useful in understanding the morphogenetic and environmental conditions of cratonic areas, and the associated marginal sedimentary basins, during the Late Mesozoic and the Paleogene.

s) These landscapes are an undisputable proof of conditions of long-term, absolute stability (at least relatively to orogenic areas), both considering tectonics and climate.

t) The studied landscapes were never again covered by transgressive seas, nor covered by large thicknesses of continental deposits, with the exception of late Cretaceous-Tertiary shallow seas and Cretaceous and Tertiary pyroclastics.

u) The existence of relics of a Devonian (?) - Early Carboniferous (?) etchplain, later eroded by the Carboniferous-Permian Gondwana glaciations, and finally affected by Mesozoic planation processes and exhumed during the Tertiary has been proved for at least the Sierra de Olta in the western Sierras Pampeanas.

v) Gondwanic paleolandscapes are an important part of the surviving relief in the cratonic areas of Argentina and should be treated appropriately.

Thornbury (1954) presented his personal view about ancient landscapes. In his well-known "fundamental concepts of Geomorphology", he stated that most of the Earth topography has an age that is not older than the Pleistocene, whereas the topography older than the Tertiary is almost negligible. He added that *"if they exist"* (however exposing his profound doubts about these landscapes) it is likely that they are in fact exhumed landforms, which do not correspond to features which would have been exposed to degradation through vast periods of time". Finally, he sustained that "99% of the present Earth surface has an age later than the Middle Miocene".

It is understood that the evidence presented here is very clear in terms of proving the frequent existence of these ancient landforms in the cratonic regions of Argentina, contradicting Thornbury's (1954) ideas. Thus, it is suggested that the need of revising the Geomorphology of the cratonic areas of Argentina (and other South American countries as well, such as Brazil, Venezuela, the Guyanas, Uruguay and Paraguay) is arising and it should be a definite commitment of South American geomorphologists in the near future. This revision should be conducted under a Gondwanic point of view instead of the presently dominant Andean vision.

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