A General Overview of Gondwana Landscapes in Argentina

Jorge Rabassa, Claudio Carignano, and Marcela Cioccale

Abstract Gondwana Landscapes in Argentina were already identified by Juan Keidel and Walther Penck at the beginnings of the twentieth 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 the existence of such ancient landforms, when one of the paradigms of the time was that "practically there is no landscape older than the Pleistocene." These landforms are the result of the process of both deep chemical weathering, developed in very stable tectonic and climatic environments, under hyper-tropical climates, and pediment processes in semiarid to humid environments.

The Gondwana Landscapes 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

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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 downwarped in tectonic basins and are covered by sedimentary and/or volcanic units of various ages. The ages for the development of the Gondwana Landscapes have been estimated in between the Middle Jurassic and the Paleogene.

The Argentine Gondwana Landscapes were uplifted, fragmented, and eroded during the Middle to Late Tertiary. They have remained as mute testimony of the past above extensive pediplains and piedmont deposits, as climates and environments became more arid and cooler, approaching the present conditions.

Keywords Gondwana landscapes • Argentina • Cratonic areas • Planation surfaces • Etchplains

Introduction

Gondwana Landscapes were originally defined by Fairbridge (1968a, p. 483) 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, and other smaller regions (see Ollier 2014a). Remnants of these surfaces are found also in India and the Arabian Peninsula, and it is assumed they have been also preserved in Eastern Antarctica, both on the surface and also underneath the Antarctic ice sheet which covers that region with an average thickness of 3,000 m. These landscapes were generated when the former Gondwana supercontinent was still intact and similar tectonic conditions in its drifted fragments have allowed their preservation (Fig. 1). These are ancient, Mesozoic landscapes that were later never fully covered by marine sediments and most of them have been exposed at the surface since their genesis.

This chapter is a revision of a former contribution by Rabassa et al. (2010) at the light of new evidence and information. The Mesozoic paleoclimates and tectonic conditions in Gondwana allowed the formation of landscape systems in all portions of the ancient supercontinent. In South America, these surfaces have been studied in Brazil, Uruguay, Venezuela, the Guyana Massif, and Argentina. These geomorphological systems were generated when the former Gondwana supercontinent was still intact and similar tectonic conditions in its drifted fragments have allowed their preservation. The nature and genesis of these landscapes have been thoroughly discussed by Rabassa (2010, 2014) and Ollier (2014b).

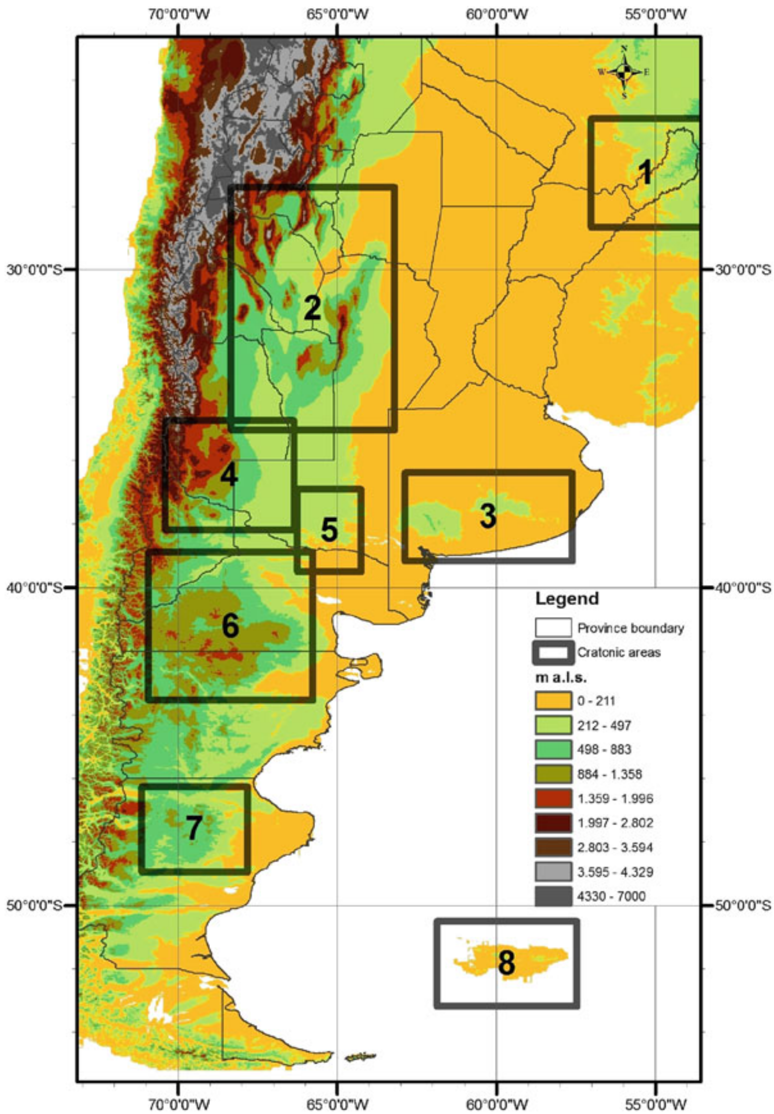

Fig. 1 Map of Argentina, showing the area in which significant extensions of Gondwana Landscapes are present. All ancient surfaces rise at least above 300–500 m a.s.l. These paleosurfaces reach their highest locations in the western Pampean Ranges. (*1*) The basaltic hills of the province of Misiones; (*2*) the Sierras Pampeanas of Córdoba, San Luis, La Rioja, San Juan, and Catamarca; (*3*) the Central Buenos Aires Positive area, including the Sierras Septentrionales (Tandilia), the Sierras Australes (Ventania), and the Pampa Interserrana; (*4*) the San Rafael or Sierra Pintada Block in Mendoza; (*5*) the Sierras de Lihuel Calel in La Pampa; (*6*) the Northern Patagonian Massif; (*7*) the Deseado Massif; and (*8*) the Malvinas-Falklands Islands

The Gondwana Landscapes were studied in Argentina by Stelzner (1885), Brackebush (1879, 1880, 1891), Bodenbender (1905), and Rovereto (1911), who analyzed the possible Cretaceous age of the summit surfaces of the Sierras de Córdoba; Walther (1912), who was the first one in mentioning the existence of subtropical climate landforms in the Sierras de Tandil; Schmieder (1921), who identified inselbergs and "rumpffläche"; and Keidel (1916, 1922), who described paleosurfaces in Sierra de la Ventana. Finally, it should be noted that Rolleri (1975) and Yrigoyen (1975) proposed the idea of the Buenos Aires Positive morphostructure and its ancient surfaces.

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

Gondwana Landscapes in Argentina

In Argentina, Gondwana Landscapes are recognized in all exposed cratonic areas (see Carignano et al. 1999, p. 249; see Fig. 1). They have been observed in the following regions: (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; (f) the Deseado Massif; and (g) the Malvinas-Falklands Islands. The nature and characteristics of the Gondwana Paleolandscapes in these areas are described and discussed in this chapter, and most of these regions have been studied in detail by different authors in this same volume.

Basaltic Hills of the Province of Misiones

The province of Misiones, in the northeastern end of Argentina (Figs. 1 and 2), is presently under a 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. For a careful discussion, see the chapter by Kröhling et al. (2014). The entire region was covered by a huge basaltic plateau, the Paraná Plateau. These volcanic eruptions produced more than 1.5 million km^3 in 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

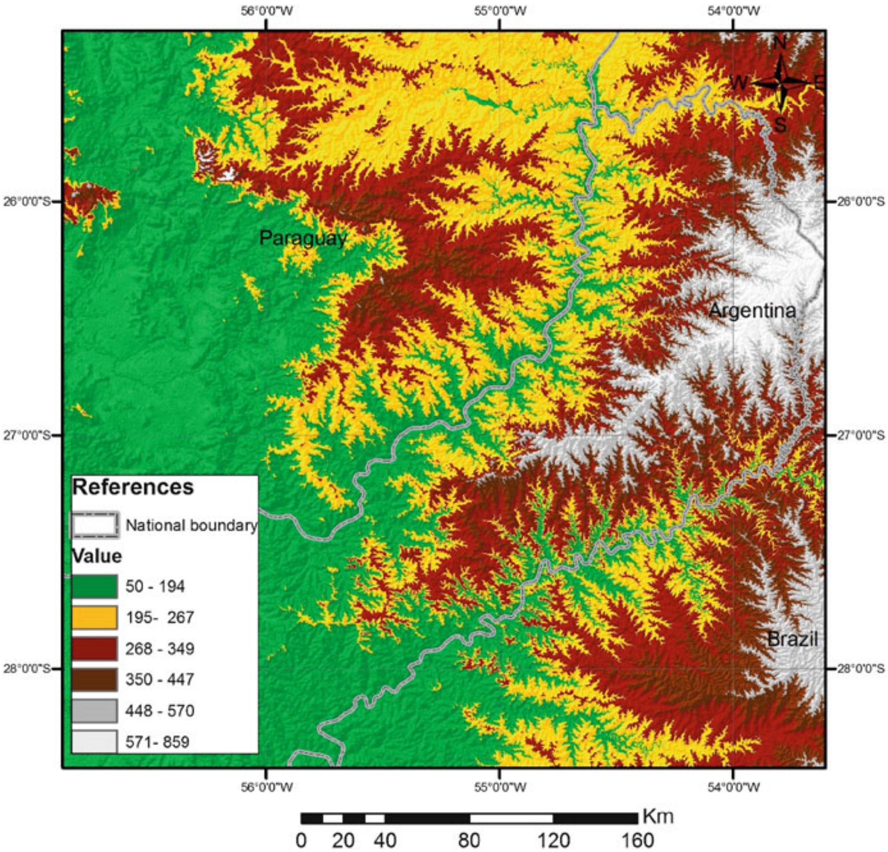

Fig. 2 Basaltic hills of the province of Misiones. Hypsographical map. This region is located southwest of the Paraná Plateau, presenting altitudes between 200 and 860 m a.s.l

units were partially covered afterwards by continental, Oligocene, Miocene, and Pliocene deposits. Where they remained exposed at the surface, they started a period of long-term landscape evolution under tropical climate which was probably sustained during the end of the Mesozoic and most of the Tertiary. 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 upon the Early Cretaceous basalts, between 950 and 1,100 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.

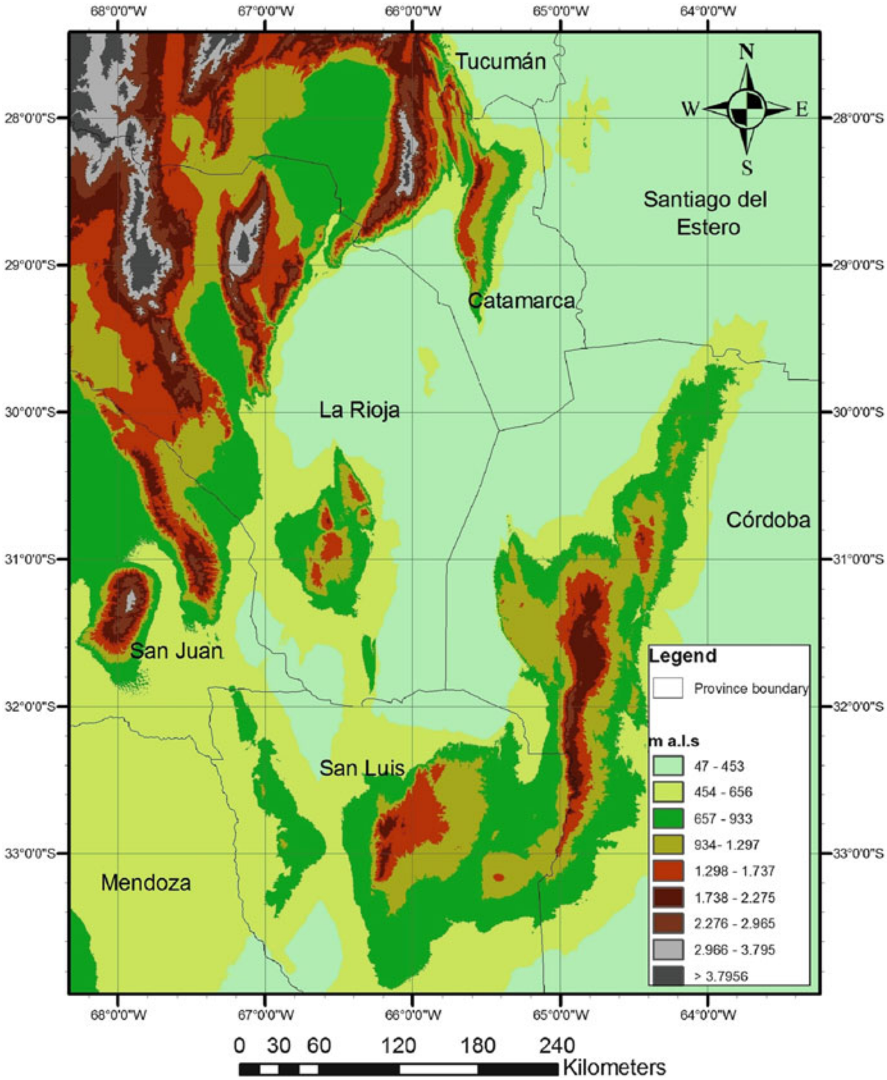

Fig. 3 Sierras Pampeanas of Córdoba, San Luis, La Rioja, San Juan, and Catamarca. Hypsographic map. They are divided into two main regions, the northwestern mountains reaching heights above 3,500 m a.s.l. and the eastern mountains showing heights below 3,000 m a.s.l

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

The Pampean Ranges (Figs. 1 and 3) are characterized by extensive planation surfaces at or near their summits, which have usually been considered as a single unit and named a "peneplain" or erosion surface, with assigned ages ranging between the Paleozoic and the end of the Mesozoic, and which would have been exhumed during the Tertiary orogeny. These concepts were strongly challenged by Carignano et al. (1999), who proposed that there is no 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 and Cioccale 2008). A detailed reconstruction of the ancient landscapes of the southernmost extreme of the Sierras de Córdoba has been presented by Andreazzini and Degiovanni (2014).

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 basis 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 the geomorphological interpretation of the Sierras Pampeanas to the present day. 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 that, in the Sierras de Córdoba, a superposition of the Andean and Brazilian-Uruguayan structural styles existed. 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 Permian-Triassic age for these beds was sustained until the 1970s, when, thanks to radiometric dating, their Cretaceous age was confirmed.

The observations and deductions by Rovereto (1911) 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 Permian-Carboniferous age. Gerth (1914) proposed also that such erosion surface would have been exhumed.

The following purely geomorphological investigation of 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 caused several problems in the present knowledge of the Sierras Pampeanas geomorphology.

One of the most relevant steps forwards of modern geomorphology was when Walther Penck published his theory on the geomorphological evolution and modeling of the Earth landscape (Penck 1924). His theories were in fact firstly conceived following his fieldwork in Argentina (Gross 1948), where he lead reconnaissance work in Northwestern Sierras Pampeanas (Penck 1914, 1920). From his observations in that area and the Sierras de Córdoba, Penck (1924) suggested the existence of four erosion surfaces, generated by gradual slope retreat by a complex mechanism, each one with its own characteristics and different ages, clearly rejecting the idea of one single planation surface. All of Penck’s conclusions are founded in a very careful geomorphological reconstruction, supported by a strict stratigraphic and structural control.

The first quarter of the twentieth century was characterized by the development of important geological and geomorphological theories, such 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 and Reed (1927). Contrarily, in the 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 is that there was only one erosion surface, called a “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. This author 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 still remains 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 suggested 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. Note that these techniques always require a few kilometers of erosion more than geomorphic evidence suggests, but it is a good approximation. There are no 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 extreme eastern and in some of the western Triassic depositional centers. It is therefore 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/Ma, though still much faster than in the Australian craton. The available data suggest that some of the planation surfaces are in fact exhumed Early Paleozoic surfaces, but most of the surfaces were formed by deep weathering after the Middle Triassic and continuing denudation which persisted until the Neogene. The most important results of this study are that the so-called basement peneplain is in fact a diachronic group of erosion surfaces, separated in time by 300–400 Ma, and that the younger unit was formed later than the Middle Triassic.

In recent years, thanks to the collaboration with distinguished South African colleagues such as Tim Partridge and Rodney Maud, it has become clear that it is necessary to return 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 and Maud (1987) on the study of equivalent erosion surfaces in Southern Africa.

The Sierra Norte and Sierra de Ambargasta (30° 40′–26° 30′ S; 65° 25′–63° 15′W) have an elongated shape in a N-S direction, with an extension of over 65,000 km^2 and a maximum altitude of 1,140 m a.s.l. (Carignano and Cioccale 2008). These ranges are very useful to understand the genesis of these paleolandscapes. They are composed of 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. These subhorizontal 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 having progressive decreasing age. The uppermost level cuts Late Paleozoic sedimentary rocks, whereas the 2nd surface is covered by Cretaceous breccias and fanglomerates 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 and Cioccale 2008). In the 1st and 2nd levels, extensive remnants of the weathering profiles have been preserved, with in situ corestones and gruss and huge, dome-shaped inselbergs. These conditions allow the interpretation of these surfaces as etchplains, with later partial removal of the saprolite. 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 (see Linton 1955), of up to several hundred meters. The upper planation surfaces were likely uncovered ever since their formation (Carignano and Cioccale 2008).

The Sierras Chicas and the 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; Figs. 4 and 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. Corestones, bornhardts, tors, and deep weathering profiles and their occurrence are interpreted as residual landforms pertaining to that primeval surface. The Late Jurassic-Early Cretaceous interval was marked by continental rifting and the ranges degradation under less humid, semiarid climates. During this rifting interval, each major faulting event generated its own particular erosion cycle. Thus, two additional 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 (Figs. 6 and 7). Such surfaces were weathered again during the latest Cretaceous-Paleocene times, and further erosion developed a fourth planation surface.

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.

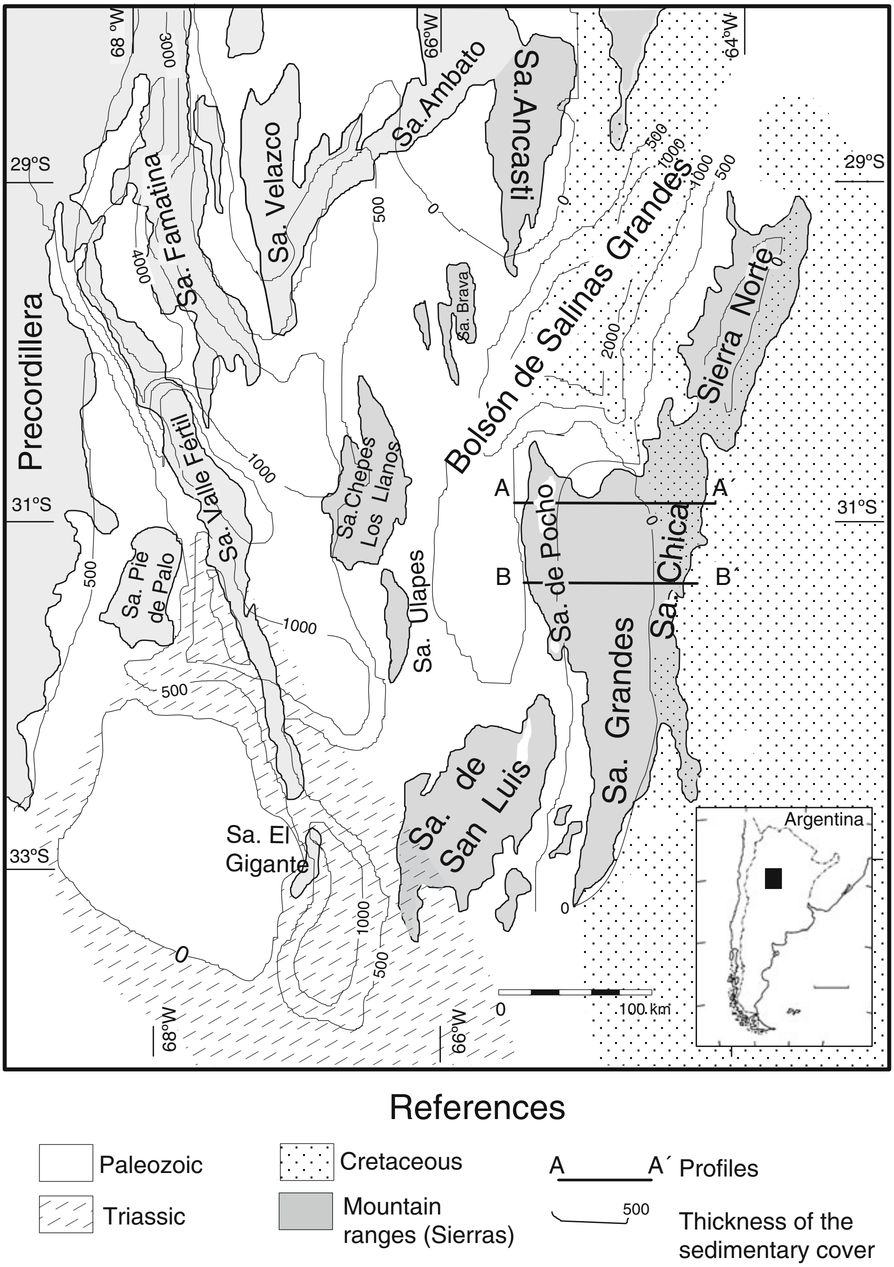

Fig. 4 Geographical distribution of Sierras Pampeanas, with local names for each of the ranges (Modified from Carignano et al. 1999)

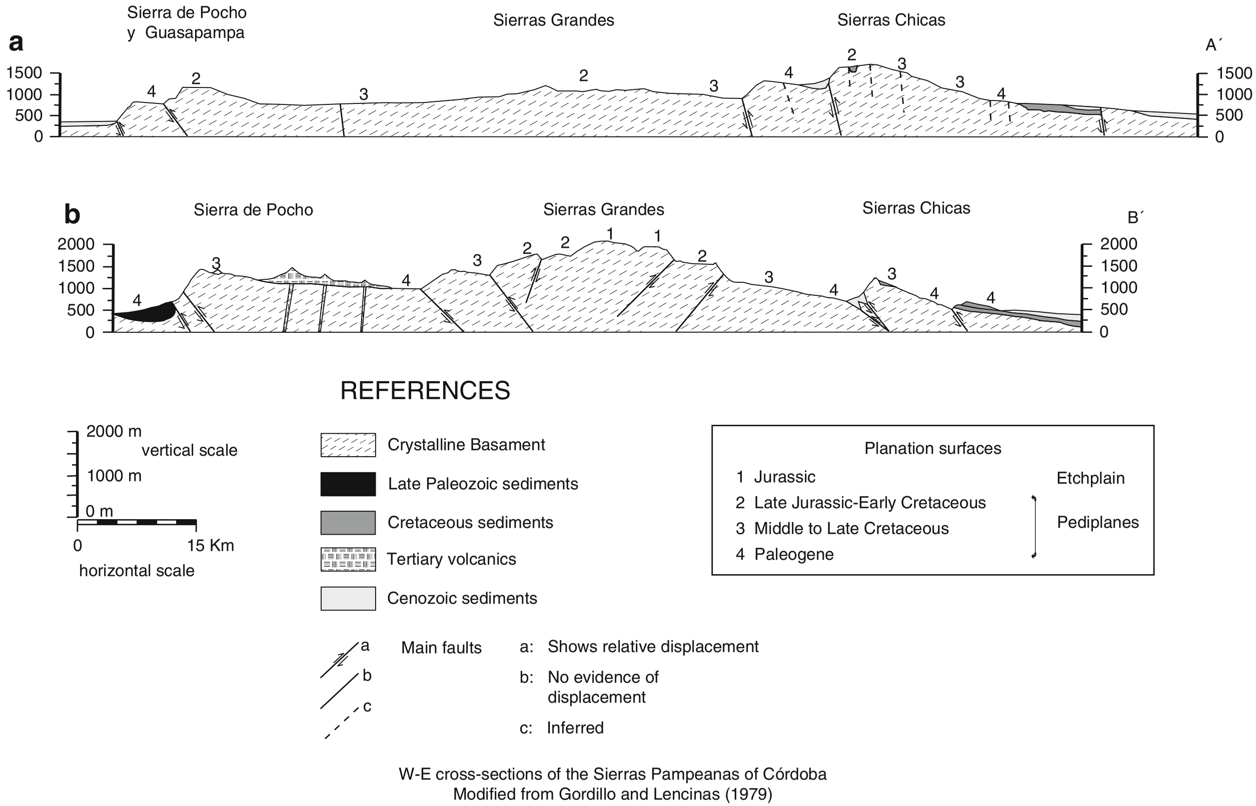

Fig. 5 Sierras Pampeanas of Córdoba, San Luis, and eastern La Rioja. Cross sections showing the identified paleosurfaces (Based on Carignano et al. 1999)

Fig. 6 Pampa de Achala, Sierras Grandes de Córdoba. Uppermost paleosurface showing its 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)

Fig. 7 Sierras Chicas de Córdoba. Paleoweathering, base of a laterite profile. *On top*, Holocene soils

Fig. 8 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 a Cretaceous planation surface (Photograph by J. Rabassa 2005)

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 Gondwana 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, 2014) at Sierra de Olta, province of La Rioja (Fig. 8). However, this planation surface is a Devonian or Early Carboniferous (?) etchplain, which was uplifted by the Late Paleozoic orogeny and later deeply eroded by mountain glaciers during the Middle to Late Carboniferous, in the core of the classical Gondwana glaciations. These were mountain glaciers 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 probably affected by deep chemical weathering in tropical climate during the Middle to Late Mesozoic, forming a younger etchplain at a lower topographical level, which was later denudated during the Cenozoic.

Glaciers covered Gondwana during the Late Paleozoic (Carboniferous and Permian), and then the Sierra de Olta was covered by mountain glaciers, which geomorphological evidence has been preserved (see Socha et al. 2014). 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 glaciogenic 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 glaciogenic deposits are resting on top of Ordovician granites and metamorphic rocks, which are the preglacial bedrock. The basal contact of the glaciogenic deposits is showing relict preglacial weathering profiles, with the presence of paleoweathering fronts and corestones. The valley moraines are composed of very large Ordovician granite boulders, up to several meters in diameter, very well rounded, strongly equidimensional, and all of very similar dimensions.

These characteristics of high rounding and strong sphericity are very rare in normal glaciogenic systems. It is interpreted that the boulders are in fact preexisting 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 paleoweathering fronts and the corestones is only compatible with the existence of planation surfaces due to deep chemical weathering, developed in continental environments, perhaps under conditions of tropical and hypertropical climates during the Late Devonian or the earliest Carboniferous. These paleoclimatic conditions would have been maintained until the regional mountain glaciation of the Carboniferous and, most likely, the Middle Carboniferous, when the preexisting paleosurfaces were strongly eroded by the mountain ice sheet. The mountain glaciations landscape was later buried under Permian marine sandstones and remained so perhaps even up to the Middle Jurassic, when the deep weathering and erosion 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) are 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 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 denudated 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 underlying the Triassic (?)-Cretaceous infilling of adjacent basins, and they considered that all surface remnants are part of the same paleosurface, though they quoted Jordan et al.'s (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 Triassic-Middle Cretaceous times. Basaltic domes of ages between 60 and 70 Ma are lying on top of the surface. Though the published information is still scarce, it may be suggested that the San Luis surfaces are in fact diachronic and perhaps the buried one is of Paleozoic age. The summit surface, in contrast, could be at least partially an etchplain or a pediplain of Late Mesozoic age, as in the Sierras de Córdoba (Carignano et al. 1999), though the possibility that part of it could be a Paleozoic exhumed feature cannot be ruled out. Spectacular weathering features have been observed in the uppermost granite surface (gnammas; Fig. 9). It is clear that deeper studies are needed on these paleolandscapes of the Sierras de San Luis in the future.

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

The Central Buenos Aires Positive area is a large cratonic region which is clearly related to the southern margin of the Brazilian Shield. This cratonic unit extends for more than 300,000 km^2 (Figs. 1 and 10). Charles Darwin (1876, p. 319) was the first author to mention features of ancient surfaces in Buenos Aires province. Note that his actual observations were much earlier, during the 1830s. Darwin observed, on the flanks of the Ventania ranges, remnants of small patches of conglomerates and breccias, at a height of 300–400 ft (100–130 m) above the plain, "firmly cemented by ferruginous matter to the abrupt and battered face of the quartz." Darwin (1876) also described very precisely and 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. These continental deposits also confirm that the age of the underlying landscape is, at least, clearly pre-Miocene in age. Darwin (1876, p. 353) 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 fraction 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. Undoubtedly, though famous for his theory of Biological Evolution, Charles Darwin was indeed a brilliant geologist, and his writings after his South American trip in the 1830s prove it.

Fig. 9 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 a sort of geochemical levees (Photographs by J. Rabassa 2003)

Du Toit and Reed (1927) and Du Toit (1937) considered the Tandilia ranges as a buried and partially exhumed mountain chain. Also, Du Toit and Reed (1927, p. 26) 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." According to Du Toit and Reed (1927), Keidel (1916, pp. 37–42) 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 and 550 m a.s.l. This second surface bears caps of

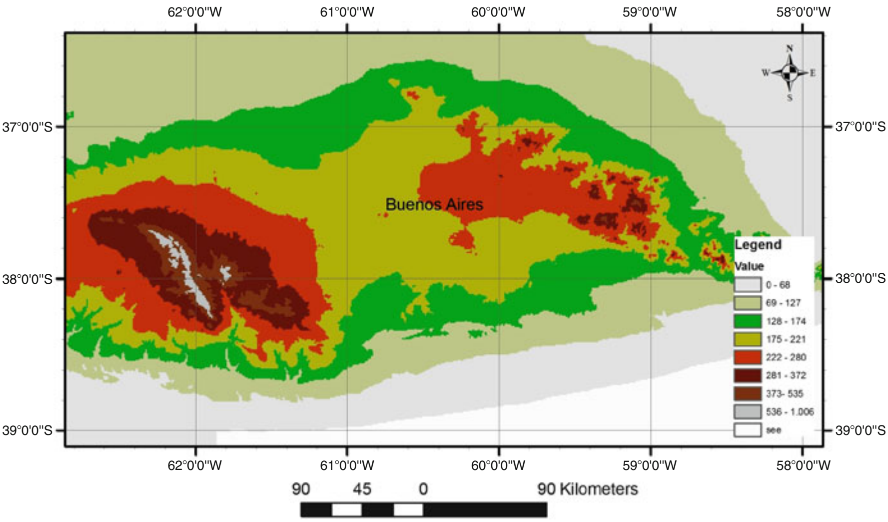

Fig. 10 Central Buenos Aires Positive area. Hypsographic map. This set is composed of the Sierras of Tandil or Tandilia, to the east, and the Sierra de la Ventana or Ventania, to the west. They are low ranges with heights between 300 and 1,000 m a.s.l., with the higher values in the western ranges

hard, bright-red conglomerates and breccias, in sandy cement with iron oxide. The material resembled the so-called High-Level Gravels and the 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. 1995, 1996, 1997, 1998) and if these units may be correlated as suggested by Du Toit and 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, Middle Cretaceous ("Inter-Senonian") uplifting of western Argentina and its corresponding influence in the cratonic areas (the authors are greatly indebted to the late Professor Edgardo Rolleri for these ideas). 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 and 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 and Reed (1927, p. 107) noted also that there is no evidence of marine Early to Middle Cretaceous along the Pampean coastal region, showing that this area was still united to South Africa. Contrarily, the Late Cretaceous sea penetrated very deeply along the western margin of the Buenos Aires Positive "as far inland as the Sierra Pintada." Therefore, the Buenos Aires Positive had been continuously above sea level perhaps at least since the latest Permian, and all of its landscape was formed subaerially since then.

The Buenos Aires Positive morphostructural unit (Fig. 10; 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, and the Llanura or Pampa Interserrana, in the sense of Rolleri (1975) (see Harrington 1980; Zárate and 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 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 display thicknesses of Cretaceous and younger sediments up to 6–7 km. At the base of the Salado basin infill are continental deposits interlayered with volcanic and volcano-clastic 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 Late Cretaceous-Paleocene and the Miocene-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; see Figs. 11 and 12). Along the SE section (Mar del Plata-Balcarce), the summit of the ranges lies as a high surface between 200 and 250 m a.s.l. The relative elevation is variable between 100 and 150 m and rises progressively from the coast towards the hinterland. NW of the city 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 has a slightly 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 Cambrian-Ordovician quartzites, the mesas and tablelands dominate. They usually 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 (Fig. 13). The weathering products occur along the slopes. They are corestones with concentric weathering rinds in a matrix of gruss-like, weathered

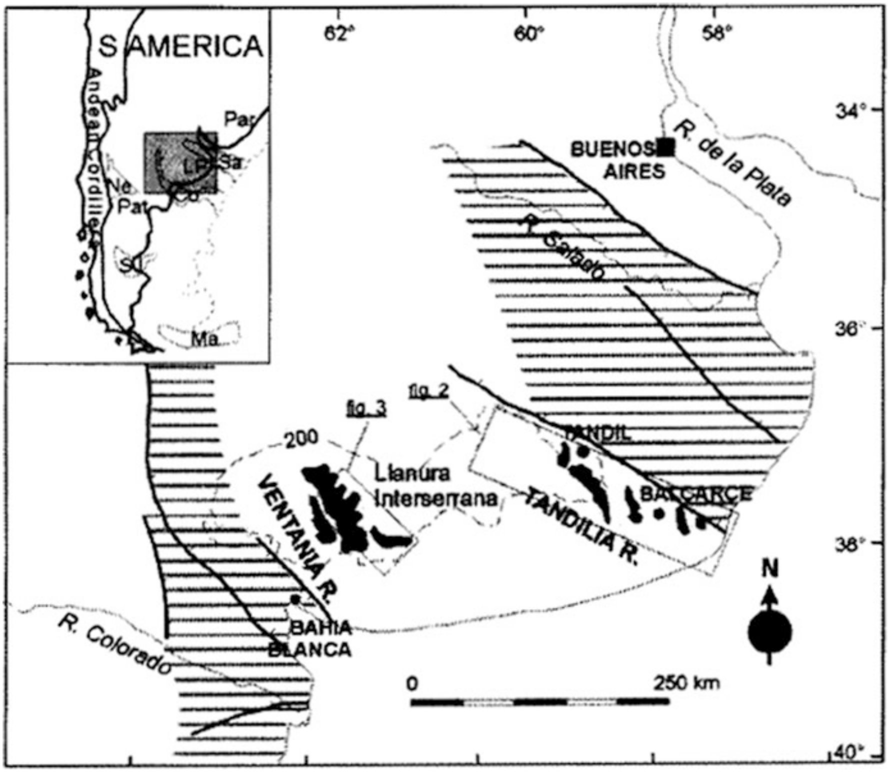

Fig. 11 Buenos Aires Positive tectonic element, including the Ventania and Tandilia ranges, and the intermediate, loess covered Llanura Interserrana (Inter-ranges plains). The Tandilia ranges are geologically and structurally related to similar areas in Uruguay and Southern Brazil. The hatched areas 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)

rock (Cerro El Centinela) or fresh granite (Cerro La Movediza; Fig. 14). 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 (see Linton 1955), near the city of Tandil (Fig. 15). Its nature and origin was surprisingly described by Estanislao Zeballos as early as 1876, and quite correctly interpreted it 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 by us or other authors), 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 never existed in the area after the Paleogene) was very early recognized by Walther (1924; in: Fairbridge 1968b). There is no evidence of marked kaolinization, suggesting that either other clays were formed in the

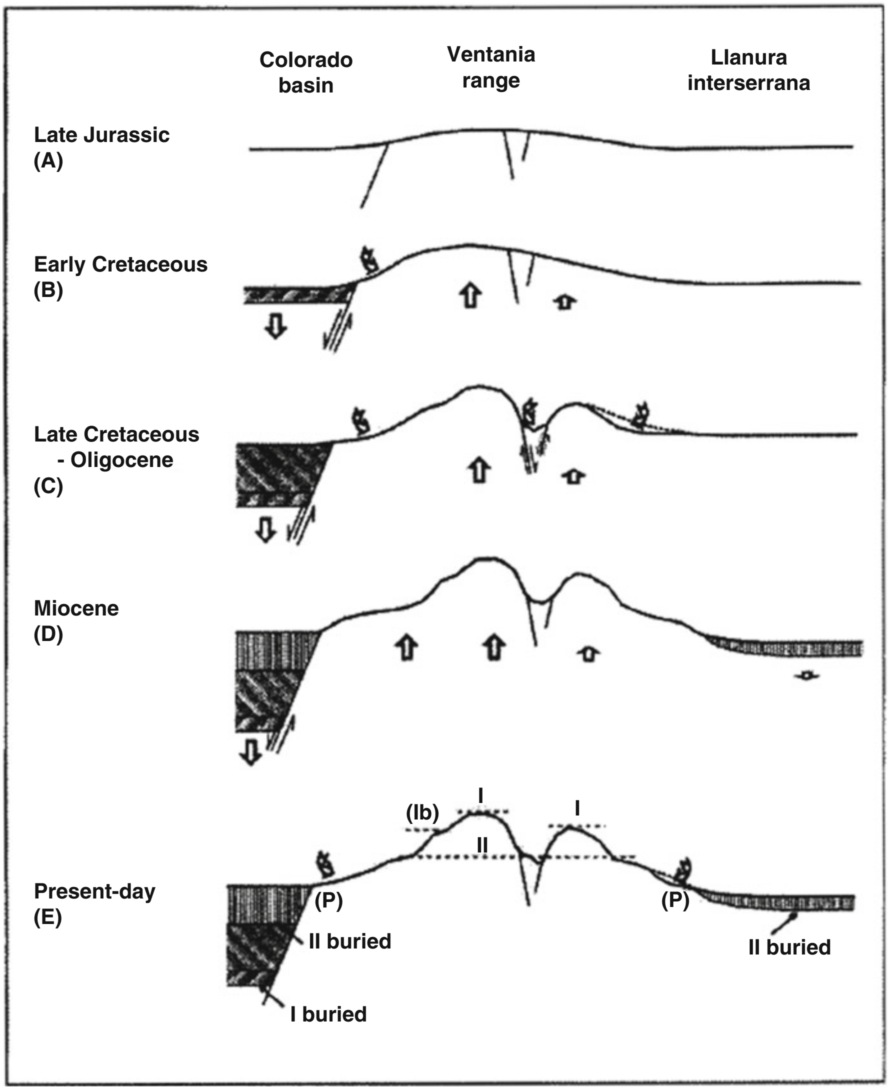

Fig. 12 Structural and geomorphological evolution of the Ventania ranges, with the adjacent Llanura Interserrana and the Colorado basin. The evolution started in Late Jurassic times. (*I*) Pre-Cretaceous landscape; (*Ib*) Intermediate inter-Cretaceous surface; (*II*) Paleogene planation surface; *P* 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)

weathering process or only the roots of the weathering front have been preserved with a very irregular distribution. 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

Fig. 13 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") (We acknowledge this photograph taken by Marcelo Zárate 1998)

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 and tors 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 and Rabassa 2005).

The Ventania ranges, or Sierra de la Ventana, are a mountain system about 180 km by 60 km, composed of subparallel ranges. They reach between 400 and 700 m above the surrounding plains, with maximum elevation of 1,240 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 to describe and precisely map them. More recently, Pereyra and 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

Fig. 14 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)

Africa, whereas 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 and 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 intermountain basin of Las Vertientes, developed between 450 and 500 m a.s.l. In this surface, the Río Sauce Grande valley is excavated up to 100 m. In the northern part of the sierras, the surface is found at both sides of 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 sole difference that

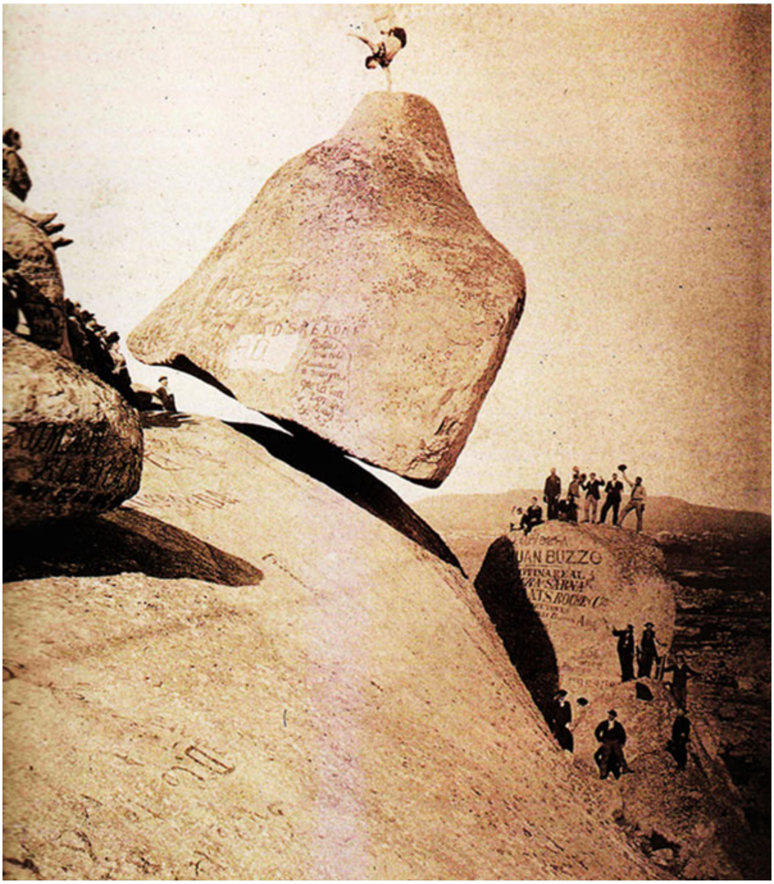

Fig. 15 Cerro La Movediza, Sierras de Tandil. The "Piedra Movediza," the rocking stone, as it was in place until the beginnings of the twentieth century. The acrobat, exposing his circus abilities, tries to show that he can keep himself as balanced as the "Piedra Modeviza" itself. This rocking stone was a very early touristic attraction for the area (Photograph kindly provided by Professor Hugo Nario, Tandil, from his collection)

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 draining the sierras, and they are formed by fans or slope deposits, in a whitish to reddish, sandy matrix, cemented with silica 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 or Early Paleocene 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 southwards towards the Atlantic Ocean. 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 meters to a couple of hundred meters 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 Middle to Late Triassic (Uliana and Biddle 1988), but perhaps even since the latest Permian. Thus, this is probably one of the most spectacular examples of long-term landscape evolution in Argentina, with a continued geomorphological history of over 230 Ma of subaerial 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 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 uplift (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 $\sim$4 m per million year, are explained by the very limited (if any) Meso-Cenozoic uplift experienced 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 Ocean. Therefore, the unification of the pre-Cretaceous surfaces on both sides of the South Atlantic is acceptable since they were part of the same continent and were sharing a similar topography, as Du Toit and Reed (1927) indicated. However, the asymmetric character of the South Atlantic rifting induced different uplift amplitudes in South Africa than those in Southern Brazil-Uruguay-Argentina, opposing the South African Great Escarpment on one side to insignificant along-rift slopes in southern South America. Denudation was consequently much smaller in eastern Argentina than along the South African coast, further north in the rift zone. 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 is located in the central portion of the province of Mendoza, not far from the Andean Cordillera but with a distinctive geological history (see Zárate and Folguera 2014; Figs. 1 and 16). It shares some stratigraphical 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 since the Triassic. Criado Roque (1972a) recognized the existence of two main paleolandscapes. The first one developed after the recession of the sea, in the Early Carboniferous, when a steep relief was generated. Later, after the deposition of Late Triassic volcano-clastic sediments, the entire Jurassic and Cretaceous period is not represented. This huge hiatus is characterized by ample "erosion and peneplanization" (Criado Roque 1972a, p. 295) of this geological unit. These surfaces were covered by Tertiary sediments, mostly related to the Andean uplift. No further information was provided for the nature and genesis of these landforms, but they may be correlated to the Gondwana paleosurfaces of the Sierras Pampeanas.

Later, Criado Roque and 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 predating 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 very 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 nearness to 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).

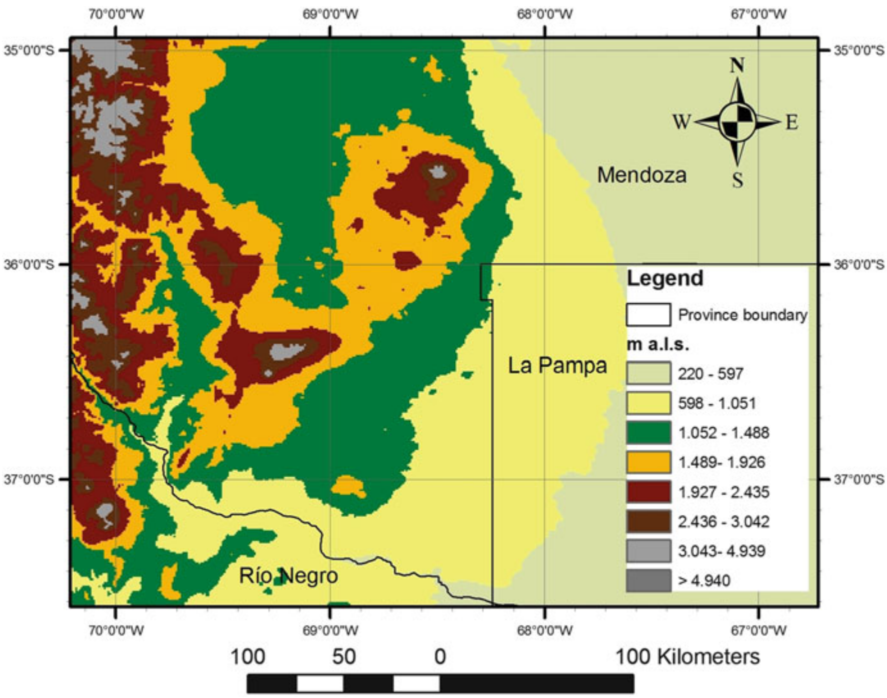

Fig. 16 San Rafael Massif or Sierra Pintada Block. Hypsographic map. The relief of this area is generally bounded by the contours of 450–1,800 m a.s.l. The highest peaks correspond to isolated mountain ranges and volcanoes, among which the Nevado volcano (3,810 m a.s.l.) stands in the southern part. 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 were preserved as relicts

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. 36° and 39° S. These remnants are bounded to the NE by the Macachín Basin and to the SW by the Neuquén Basin, both tectonic depressions related to the late Mesozoic rifting processes.

This unit has been considered by Criado Roque (1972b) and Criado Roque and Ibáñez (1980) as a continuation of the San Rafael Block towards the SE (Figs. 1 and 17). The petrology, structure, and geomorphology of this area have been thoroughly discussed by Zárate and Folguera (2014) and Aguilera et al. (2014a). 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 and Quaternary

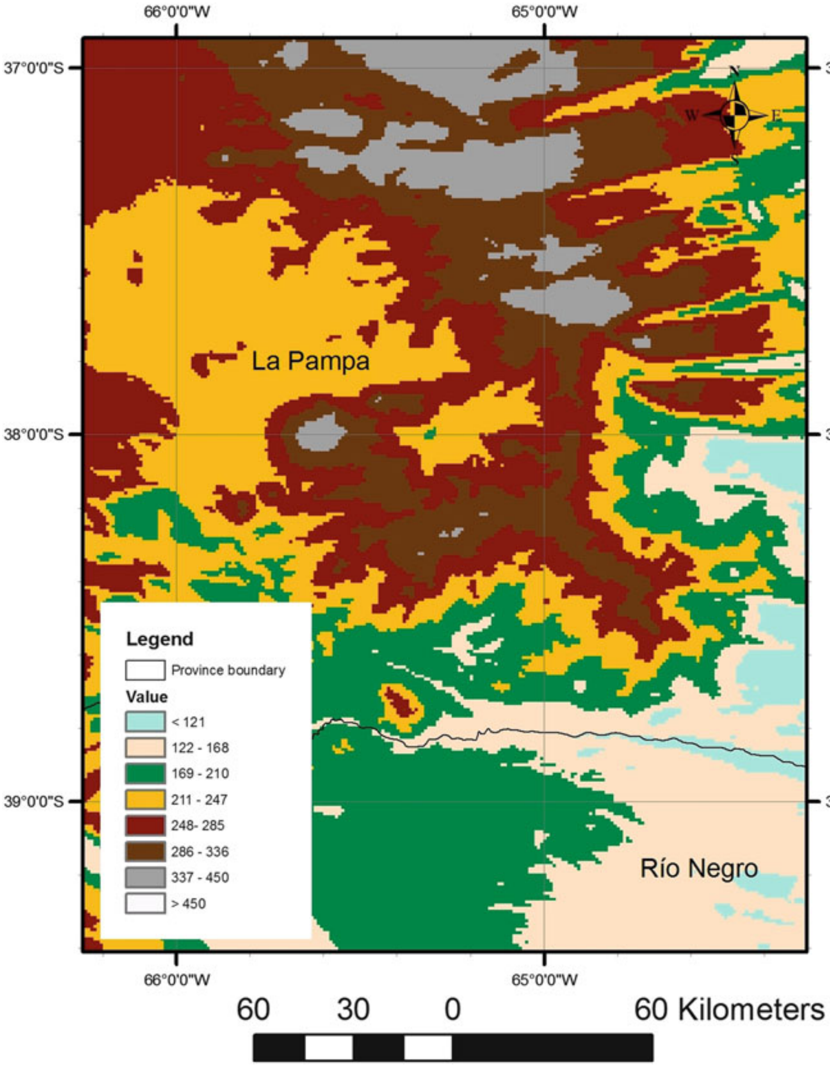

Fig. 17 The Sierras de Lihuel Calel in the province of La Pampa, Central Argentina. Hypsographic map. The ranges are oriented in a northwest-southeast direction, forming several chains with different orientation, covering a square area of approximately 15 km per side. The highest peak reaches 589 m a.s.l

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 still very poorly known from a paleogeomorphological point of view and clearly deserves further attention.

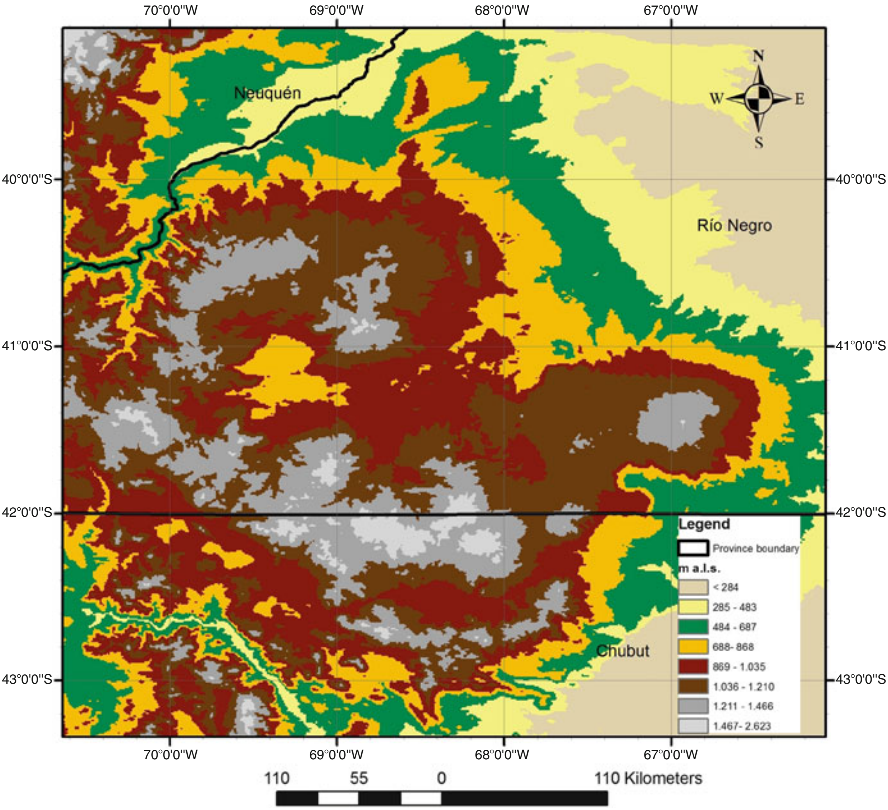

Fig. 18 The Northern Patagonian Massif. Hypsographic map

The Northern Patagonian Massif

The Northern Patagonian Massif is an isolated craton which occupies the northernmost portion of Patagonia (Figs. 1 and 18). 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 Middle 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 modified during the

Fig. 19 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)

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 (Figs. 19, 20 and 21). Humid tropical climates vanished forever 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 and the Paleocene-Eocene volcano-sedimentary sequence of the Ventana Fm. (Rabassa 1975, 1978a, b; Fig. 22). 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 was 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

Fig. 20 Inselbergs in a planation surface developed on Permian granites, Pilcaniyeu, province of Río Negro (Photograph: J. Rabassa 2000)

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 clay 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 landscapes developed under tropical climates in the Northern Patagonian Massif has been recently recognized by Aguilera (2006), Aguilera and Rabassa (2010), Aguilera et al. (2010, 2014b), Martínez and Rabassa (2014), and Aragón et al. (2010, 2014). The huge planation surfaces described in these papers are one of the most extensive Gondwana Landscapes in Argentina, and they merit the continuation of these studies (Fig. 23).

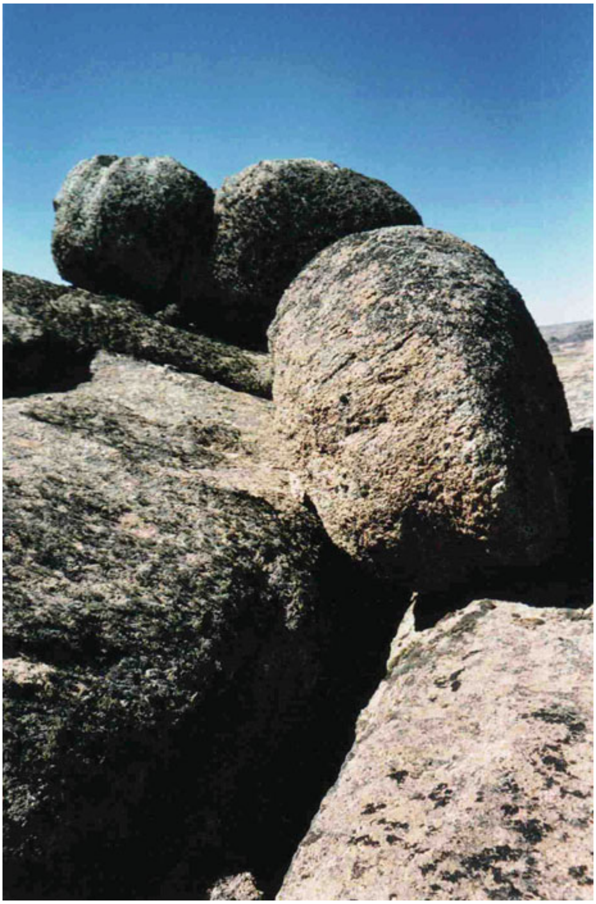

Fig. 21 Granite corestones developed on Permian granites, Pilcaniyeu, province of Rio Negro. The corestones have piled up as the tors formed as part of a Cretaceous planation surface are dismantled by Cenozoic denudation (Photograph: J. Rabassa 2000)

The Deseado Massif

The Deseado Massif is an isolated craton which was named as "nesocraton" by Harrington (1962), who identified it as a long-term positive, stable, and undeformed structural unit. 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 Andes by the Austral Basin (De Giusto et al. 1980; Figs. 1 and 24). 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 about 1,000 m a.s.l. Gondwana Landscapes in the Deseado Massif were briefly mentioned by Rabassa et al. (1996), who cited extensive planation

Fig. 22 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)

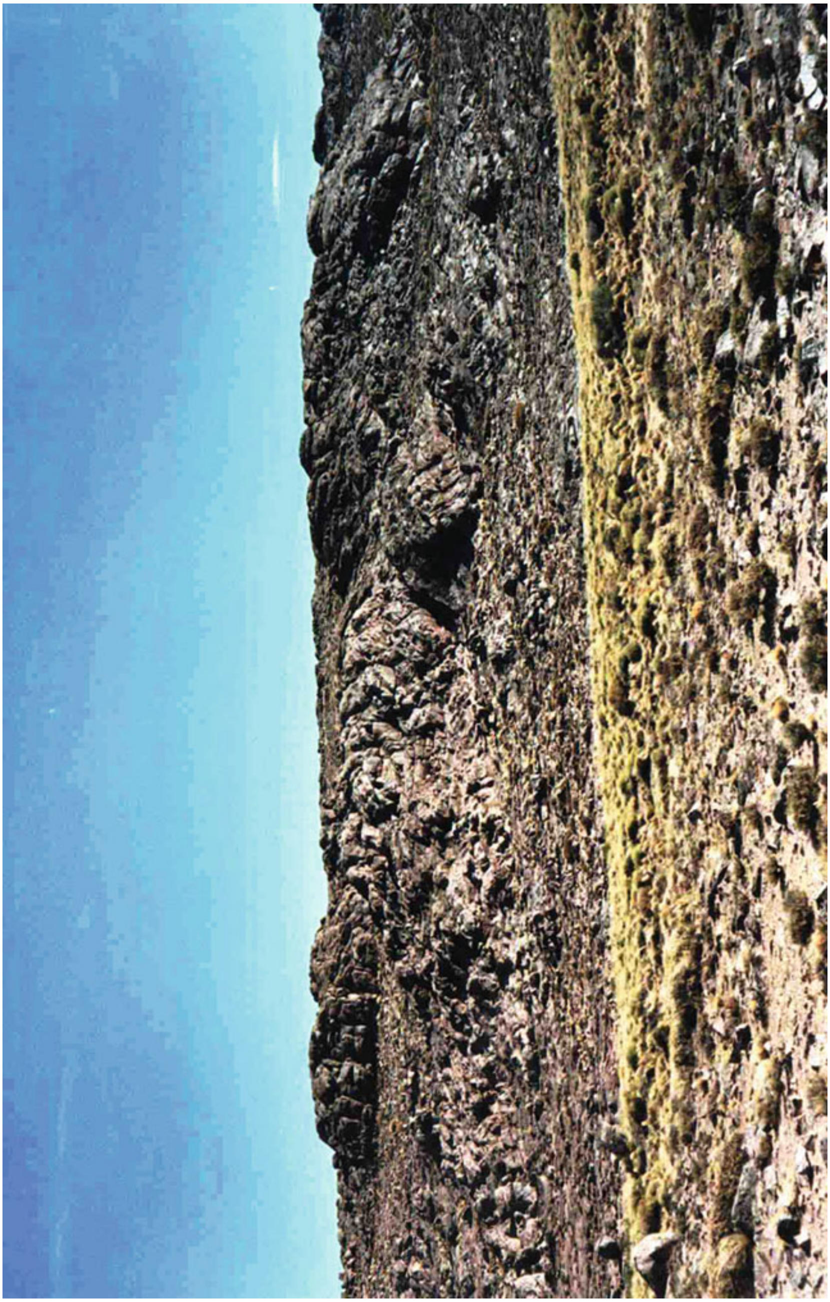

Fig. 23 Planation surface developed on granite, El Cuy-Los Menucos, province of Río Negro. Note the abundant granite corestones and the tors under dismantling processes (Photograph: J. Rabassa 2000)

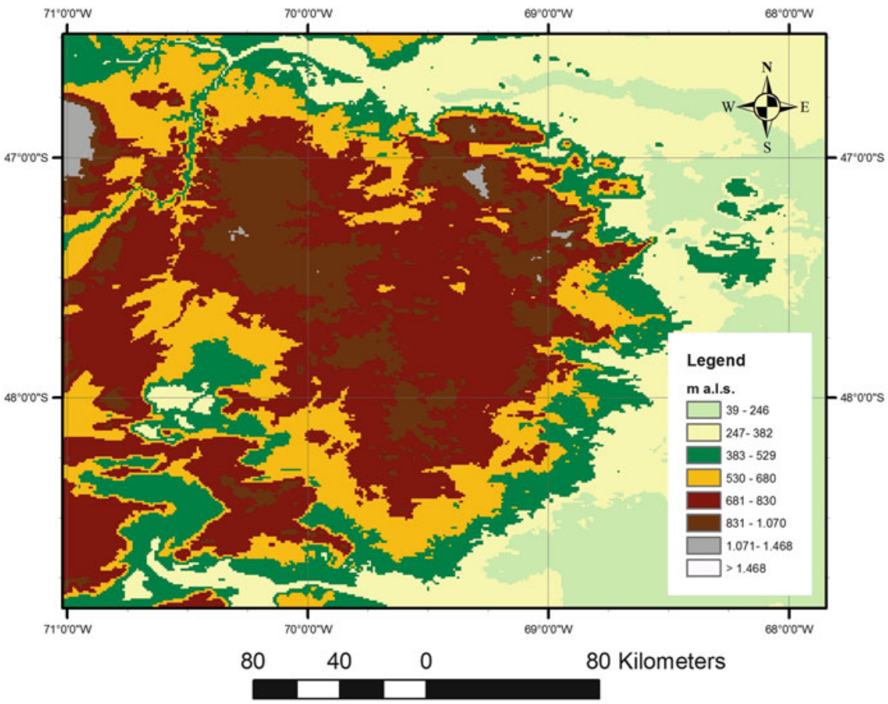

Fig. 24 The Deseado Massif, southern Patagonia. Hypsographic map

surfaces on the Middle to Late Jurassic volcanics and volcano-clastics of the Chon-Aike Formation and other units of the Bahía Laura Group. The region is presently under study, and a preliminary report has been presented by Bétard et al. (2014), based upon much modern methodology and scientific criteria. 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 paleolandscape 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 Tertiary volcanics are found, together with erosion remnants, such as inselbergs and tors, and younger 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, 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 and 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, developed within the Baqueró Formation (Middle to Late Cretaceous) over Middle Jurassic ash-flows (Chon-Aike Formation) to Early Cretaceous ashfall 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 subaerial, fluvial processes in the Middle to Late Cretaceous and deposited in the accumulation areas surrounding the Deseado Massif.

The work of Bétard et al. (2014) will undoubtedly lead the way for further investigations on the paleolandscapes of this remote, isolated, unpopulated region, where the southernmost remnants of Gondwana Landscapes in any continent outside of Antarctica are found.

The Malvinas-Falklands Archipelago

The Malvinas-Falklands archipelago is a continental fragment which drifted away from the southernmost portion of Africa. Clapperton (1993, p. 543) 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 subaerial denudation, as expected in a former portion of Gondwanaland (Fig. 25). These topographic levels have been interpreted by Clapperton (1993) as remains of planation surfaces, but their age is still unknown, although they are clearly Triassic or younger.

Concluding Remarks

The analysis of the different studies on the Gondwana Landscapes performed in Argentina since the end of the nineteenth century suggests the following conclusions:

(a) During the Mesozoic and most of the Paleogene, the Sierras Pampeanas had long periods of stability that have favored the development of deep weathering and the formation of etchplains, under hyper-tropical climates.
(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 denuded since the "hyper-tropical" climates changed towards drier and highly seasonal climates in the Tertiary.

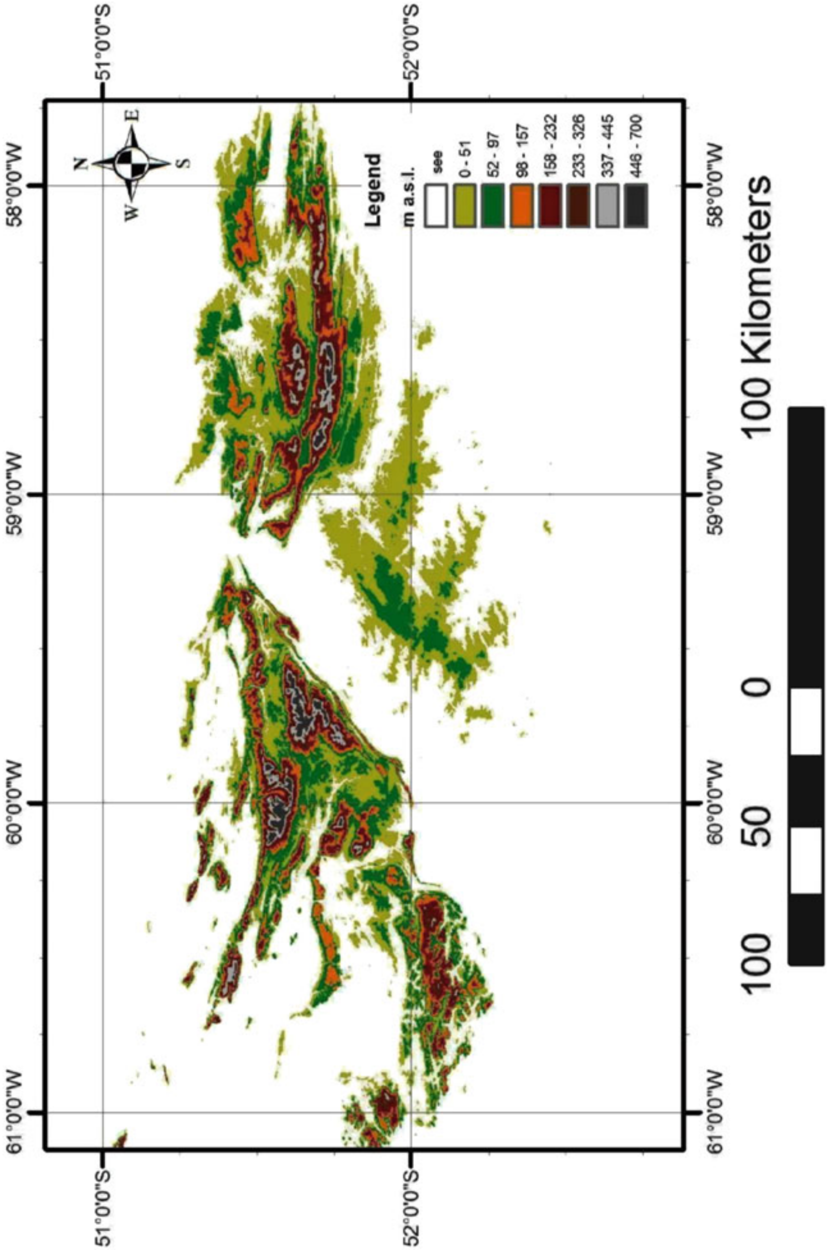

Fig. 25 The Malvinas-Falklands archipelago. Hypsographic map

(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 (for further details on these topics, see 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 has been shown in many other areas of the world.
(h) The proposed "hyper-tropical" climate (Rabassa 2010, 2014) has no analogues among the present climates of Argentina, and perhaps not even on Earth, and its actual parameters and extension should be further investigated.
(i) Moreover, tropical climates disappeared from western, central, and southern Argentina by 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-Middle 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, formed under warm-wet, tropical conditions, and pediplains, developed under semiarid, seasonally wet climates. In general terms, etchplains are older than the pediplains. It is possible that several geomorphologic cycles are superposed in some areas, forming true palimpsests that should be further studied and unraveled.
(l) Some of the studied landscapes have been exposed to the atmosphere repeatedly for very long periods, in some cases continuously for more than 100 million years.
(m) The co-genetic relationship of the ancient landscapes 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, has been strongly supported by field studies. However, the coevolution of the landscapes in both continents was interrupted by the opening of the South Atlantic Ocean. Later on in the Cenozoic, when the ocean at these latitudes became wider, a change in ocean circulation took place and, therefore, profound modifications in the distribution of climate belts occurred.

(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 developed simultaneously in all areas of Argentina where these Gondwana Landscapes are found.
(o) Inselbergs, bornhardts, perched rocks, rocking boulders, weathering profiles, weathering fronts, granite landforms, granite micro-landforms, quartzite disintegration, and other features and landforms have been very useful in the identification of ancient landscapes.
(p) Old landscapes are indicators of the persistence of most of the studied cratonic regions as positive elements since at least the Jurassic and perhaps even since the Permian.
(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 a cratonic area.
(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 stability of both tectonics and climate in southern South America.
(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 a Devonian (?)-Early Carboniferous (?) etchplain, later eroded by the Carboniferous-Permian Gondwana glaciations and exhumed during the Late Cenozoic, has been proven for at least the Sierra de Olta, La Rioja, but it may be also found in other areas in the western Sierras Pampeanas.
(v) Gondwana Landscapes 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 also that “if they exist” (showing 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 maintained that “99% of the present Earth surface has an age later than the Middle Miocene.”

The evidence presented here for the frequent existence of these ancient landforms in the cratonic regions of Argentina contradicts Thornbury’s (1954) ideas. We need to revise the geomorphology of the cratonic areas of Argentina (and other South American countries, such as Brazil, Venezuela, Guyana, Uruguay, and Paraguay) in terms of long-term landscape evolution. This revision should be conducted from a Gondwana viewpoint instead of the present dominant Andean vision.

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Finally, JR would like to express his deepest thanks to the memory of the late Professor Edgardo Rolleri, who supported our studies with his valuable experience, comments, and opinions and his helpful encouragement about the scientific problems mentioned in this chapter, during unforgettable talks in his house of La Plata along his last years.

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