Geomorphology of Paleosurfaces in the Sierras de Comechingones, Central Pampean Ranges, Argentina

M. Jimena Andreazzini and Susana B. Degiovanni

Abstract Remnants of pre-Andean erosion paleosurfaces have been already described by several authors in different sectors of the cratonic area of the Sierras Pampeanas of Argentina. Their origin and age are still under discussion, but in general, it is assumed that they correspond to etchplains and pediplains developed between the Middle-Late Jurassic and the Paleogene. The objective of this chapter is to present a morphological-morphometric characterization of the planation surfaces that are preserved in the summit portions of the Sierra de Comechingones (Sierras Grandes, Córdoba), between 32° 22′–32° 52′ S and 64° 45′–64° 57′ W, and propose genetic-evolutionary models that would consider the incidence of lithology and fracturing degree on the configuration and preservation of these paleolandforms. These features are located between 2,150 and 1,500 m a.s.l. and they are developed upon the Precambrian gneissic-migmatitic rocks (the Monte Guazú Complex), mylonites and ultramylonites (the Guacha Corral shear zone), and Devonian granites (the Cerro Áspero Batholith). The latter are accompanied by fluorite epithermal mineralizations (Early Cretaceous). The paleosurfaces were affected by the Andean orogeny and modeled by the Neogene erosion cycle, being partially covered by Quaternary loess units. To complete this analysis, petrographic, structural, stratigraphic, sedimentological, metalogenetic, and geochronological studies were performed both at the local and regional scales, thus generating our own information in the field and in the lab. Based upon topographic sheets, satellite images, and digital elevation models (DEM), the paleosurfaces were identified and mapped, with special attention to the different lithology on which they have been carved, the drainage network and the depth of fluvial incision were defined, the morphometric parameters were obtained (such as slope, area, elevation, drainage density, and mean length of first-order stream channels [Lm1]), and six topographic-geological

M.J. Andreazzini (✉) • S.B. Degiovanni
Departamento de Geología, Universidad Nacional de Río Cuarto, Ruta Nacional 36, Km. 601, X5804BYA Río Cuarto, Córdoba, Argentina
e-mail: jandreazzini@yahoo.com.ar

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sections, considered as representative of the regional conditions, were prepared. In the field, the existing landforms and morphology aspects, active processes, and lithology sections, among other parameters, were described. In the metamorphic environment, the erosion surfaces show a homogeneous relief (generally crest-like ridges) with low topographic and morphological variability (slope, 2–4 %; drainage density, $\mathrm{Dd} < 4$; $\mathrm{Lm1} = 150$–250 m; incision depth, 10–20 m), and, in general, they are better preserved than those corresponding to the granite environment. The latter are more heterogeneous (slope varying between 4.5 and 7.5 %); they exhibit landforms of varied size and type (crests, rounded boulders, tafoni, tors, domes, among other features) and show greater fluvial dissection (Dd, 6.5–7.5; Lm1, 70–110 m; incision depth, 100–110 m). The geomorphological analysis particularly integrated with metalogenetic and geochronological studies of the fluorite deposits and the stratigraphic and sedimentological investigation of the adjacent Cretaceous sedimentary basins allow the following considerations: (a) the studied cratonic area was a positive element of the landscape at least since the Carboniferous-Permian, and since then, it has been the subject of different denudation cycles; (b) previous to the Andean orogeny, there was a very long period of stability in which the tectonic and erosion processes, generally of low activity, favored the development of these erosion surfaces, which began to be denudated much later than these movements, with their remnants located today in the summit or water-divide areas; (c) at least since the Late Cretaceous, the Cerro Áspero Batholith was not being exhumed and, thus, the studied paleosurfaces may be assigned to a Late Cretaceous-Paleogene age; (d) the studied erosion surfaces belong to one single paleosurface and its altitudinal variations are due to the tilting during the Andean events; (e) the paleosurfaces are polygenetic, a result of the oscillation between wetter periods (dominant chemical weathering, channeled fluvial action) and more arid ones (pedimentation), thus conforming spatial arrangement of the palimpsest type; and (e) a marked lithological control on the morphology and degree of preservation of coeval paleosurfaces do exist.

Keywords Gondwana • Argentina • Sierras Pampeanas • Planation surfaces • Granite morphology

Introduction

The presence of planation surfaces in the Sierras Pampeanas region was recognized towards the end of the nineteenth century and the beginnings of the twentieth century, in the pioneering works of Stelzner (1885), Brackebush (1879, 1880, 1891), Bodenbender (1895, 1905, 1907, 1911, 1929), Rovereto (1911), Beder (1916), Rassmuss (1916), Rimann (1926), Penck (1914, 1920), and Schmieder (1921). In these first investigations, the origin, evolution, and age of these paleosurfaces were already considered controversial. Despite the time elapsed, the discussion is still alive today.

Some authors interpreted these surfaces as part of a single, unique "peneplain," in the sense of William M. Davis, which developed sometime between the Late Paleozoic and the Miocene and which was later faulted, tilted, and exhumed during the Andean orogeny (González Díaz 1981; Jordan et al. 1989; Costa et al. 1999; Beltramone 2007), whereas others have proposed a polygenetic model, strongly based on the concepts of Lester C. King (1963) and recognized several planation levels of different origin and age (Carignano et al. 1999; Carignano and Cioccale 1997, 2008; Cioccale and Carignano 2009; Rabassa et al. 1996, 1997, 2010; Rabassa 2010, 2014). The better examples of these paleosurfaces are preserved as remnants found in the higher areas (locally known as "pampas de altura") of the main mountain ranges which form these Sierras. In the Sierras Pampeanas of the province of Córdoba, several levels have been recognized between 2,000 and 500 m a.s.l., among which the Pampa de Achala and the Pampa de San Luis (2,000 and 1,800 m a.s.l., respectively), located in the Sierras Grandes, are noted for to their extension and elevation, followed in order of importance by the Pampa de Olaen (Sierras Grandes), Pampa de Pocho (Sierra de Pocho), and the summit surface of the Sierra Chica (1,500–1,000 m a.s.l.). These surfaces are generally covered by Late Cenozoic, but mainly Quaternary, colluvial, and loess sediments, with an average thickness of less than 1 m, with a few exceptions where the cover just exceeds 5 m.

According to Carignano et al. (1999) and Rabassa et al. (2010), the highest paleosurface is an "etchplain," mainly generated by deep chemical weathering under very warm and wet environmental conditions, during the Late Triassic-Middle Jurassic interval, whereas the paleosurfaces that occur in a step-like pattern around the nucleus of the larger Sierras blocks are the result of the activity of erosion agents related to mostly semiarid climates, basically by pedimentation processes, in this case corresponding to extensive denudation periods during the Late Jurassic-Cretaceous and Late Cretaceous-Miocene (Carignano et al. 1999; Cioccale 1999; Rabassa et al. 2010). Contrarily, Beltramone (2007) interpreted the different levels of erosion surfaces as corresponding to a unique pre-Jurassic peneplain, buried and later exhumed, which was dismembered by the Tertiary Andean tectonics.

The cited references show that the scientific works dealing with genetic-evolutionary aspects of the different paleosurfaces of the Sierras de Córdoba have greatly increased in recent decades, both at the local and regional scales, but much has still to be done. In the particular case of the Sierra de Comechingones, which comprises the southern part of the Sierras Grandes, there are very few studies about these relict paleosurfaces. Degiovanni et al. (2003) described the surfaces found in the southern sector of this mountain range, which are considered polygenetic (in the sense of Klein 1985). Coniglio et al. (2000) and Coniglio (2006) studied the fluorite mineralization in the Cerro Áspero Batholith (Sierra de Comechingones) and indicated that the formation of these epithermal deposits would have taken place in a scenario coeval with the development of erosion surfaces of regional extent. Finally, some papers have analyzed the Quaternary sequence found in the "pampas de altura" of these ranges, among them Andreazzini et al. (2012) and Krapovickas and Tauber (2012a, b).

To improve the knowledge of these geomorphological relicts, this chapter analyzes the planation surfaces of the north-central portion of the Sierras de Comechingones. These units are mainly preserved in the summit areas and, secondarily, in lower blocks of the eastern slope of the Sierras. The surfaces were developed on metamorphic and granitic rocks. We present a morphological and morphometric characterization of the surfaces and propose genetic-evolutionary models which discuss the influence of the lithology and degree of fracturing in the configuration and preservation of the paleolandforms.

Location of the Study Area

The observations presented here were made on the relict surfaces, located in the Sierra de Comechingones (Sierras Pampeanas de Córdoba, Argentina) between 32° 22′ and 32° 52′ south latitude and between 64° 45′ and 64° 57′ west longitude (Fig. 1). The Sierra de Comechingones constitutes the southern end of the Sierras Grandes, with an approximate length of 150 km, forming part of the boundary between the provinces of Córdoba and San Luis. Its elevation decreases towards the south, from 2,884 m a.s.l. (Cerro Champaquí) to 650 m a.s.l. at its terminal outcrops.

Regional Geological Setting

The Sierras Pampeanas are mountain ranges of roughly N-S orientation of approximately 500 km long and 200 km wide, which are mega-blocks of Precambrian-Early Paleozoic crystalline basement, faulted and tilted towards the east during the Andean (Tertiary) orogeny. They exhibit a markedly asymmetrical cross section. The western fault scarps have a steeper gradient, with variable displacements (200–1,000 m), whereas the eastern structural slopes are smoother and show well-defined steps, which have been associated with tectonics and/or erosion processes. In either case, these different levels are remnants of paleosurfaces affected by the Late Cenozoic geomorphological processes.

During Carboniferous and Permian times the Sierras were already a positive element under denudation conditions, and a thick sequence of silicoclastic sediments were deposited in the eastern area, adjacent to the ancient Pampean Arch, whose outcrops form today a narrow belt in the NW margin and the southern end of the Sierras (Hünicken and Pensa 1980a, b).

In Late Permian-Early Triassic times, an extensional regime created the Triassic rifts. Deposits of this age have not yet been identified either in the Mesozoic sedimentary column of the Chaco-Pampean Plains (Chebli et al. 1999) or in the ranges themselves, which are considered as of a positive nature. According to Carignano et al. (1999), the clastic continental sequences accumulated in the adjacent basins

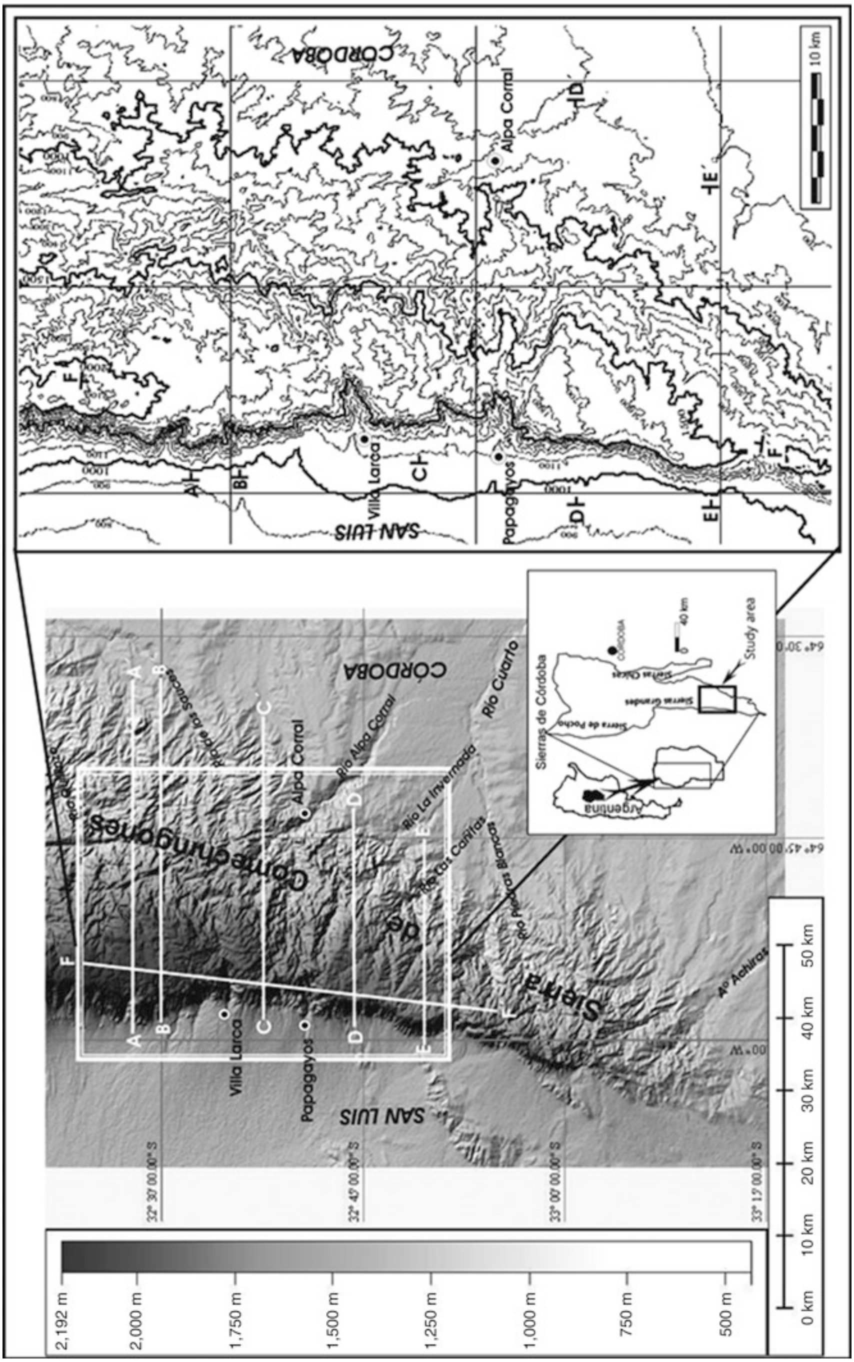

Fig. 1 Location of the study area. A DEM (digital elevation model) and details of the topography of the studied zone. The location of the analyzed sections is also shown in both figures

indicate that warm-wet environmental conditions had been relatively uniform and persistent, with some semiarid intercalated periods. These same authors, on the basis of earlier works, proposed that in between the end of the Middle Triassic and the Middle Jurassic, the Sierras Pampeanas were part of a major ridge that acted as a barrier to the moist air masses coming from the Pacific Ocean, thus favoring the development of a desert environment in the rain shadow towards the interior of the continent (the Botucatú paleodesert, southeastern Brazil), at a time when conditions of intense chemical weathering prevailed in the mountain ranges. Its relict products, such as tors and inselbergs, were exposed under subsequent erosion cycles (the Middle to Late Jurassic etchplain, according to Carignano et al. 1999).

The extension regime towards the end of the Gondwana orogenic cycle continued during the entire Cretaceous and the Paleocene. During this time, in the Sierras Pampeanas and Pampean Plains environment, the opening of sedimentary basins with associated alkaline volcanism took place (Uliana et al. 1990; Schmidt et al. 1995; among others). These basins are generally filled by two sedimentary megasequences which represent typical "bajada" environments (alluvial fans, calcretes, braided fluvial patterns, saline playas). One of them corresponds to the Late Jurassic-Early Cretaceous and the other to the Late Cretaceous (Carignano et al. 1999). In the Sierra de Los Cóndores (Sierras Chicas), east from the study area, a volcanoclastic sequence is exposed which represents the first cycle, where basalts have ages between 154 and 112 Ma (Gordillo and Lencinas 1967; Lencinas 1971; González 1971; Sánchez 2001). The second cycle has been recognized in the southern end of the Sierras de Comechingones (Cerro La Garrapata, La Leoncita, Madero), where basaltic rocks aged between 55 and 75 ± 5 Ma (López and Solá 1981) are associated with clastic continental sequences. Carignano et al. (1999) correlated these two sedimentary cycles with the development of two pediment surfaces found in Sierras Pampeanas.

Since the Eocene, the Andean movements determined the evolution of the Sierras Pampeanas, raising the mountain blocks and defining intermontane basins which, during the whole Paleogene and the Early Miocene, were filled by continental sediments corresponding to alluvial fans, braided channels, and subordinate subaqueous environments. During the great Atlantic transgression of the Middle to Late Miocene, the Sierras Pampeanas were surrounded by a shallow epicontinental sea and, even though they remained as a positive element, the erosion rate diminished significantly. In the Miocene-Pliocene transition, the segmentation of the Andes took place and the Early Paleozoic sutures and the normal faulting of the Paleozoic and Mesozoic were tectonically inverted, thus being in most cases transformed into high-angle, reverse faults, with east-dipping fault planes (Chebli et al. 1999; Schmidt et al. 1995). Between the end of the Late Miocene and the Early Pleistocene, the most powerful Cenozoic deformation event took place. In this period, as the large basement blocks were fragmented, elevated, and tilted, the erosion surfaces were dismembered and underwent long and intense denudation cycles (González Díaz 1981; Carignano et al. 1999; Degiovanni et al. 2003). There were two main episodes: one in the Pliocene and another in the Pleistocene heralded by a volcanic period that covered in some areas the third level of pedimentation (Carignano et al. 1999).

Finally, the Quaternary of the Pampean region is represented by an alternation of loess and alluvium, and to a smaller extent, lacustrine and colluvial deposits, in which paleosols and calcretes are interbedded. These sequences are in general associated with climatic variations (mostly glacial and interglacial cycles) which characterized this period (Cantú 1992; Iriondo 1997, 1999; among others) and also with neotectonic events (Sagripanti 2006; Degiovanni et al. 2003; Costa et al. 1999).

Local Geological Setting

The geological knowledge of the Sierra de Comechingones was for a long time restricted to the work of Sosic (1964) and Gordillo and Lencinas (1979). Later works discussed petrologic, geochemical, and structural conditions of the region, both in the metamorphic and granitoid rocks (Nullo et al. 1991; Fagiano et al. 1993; Feliú 1994; Otamendi 1995; Otamendi et al. 1996; Stuart-Smith and Skirrow 1997; Coniglio and Esparza 1988; Porta 1992; Pinotti et al. 1996, 1997, 2002; Martino 2003; Fagiano and Martino 2004; Fagiano 2007; Coniglio 2006; Coniglio et al. 2010; among others).

A geological map of the study area (Fig. 2) shows the distribution of metamorphic rocks of the Monte Guazú Complex, mylonitic rocks of the Guacha Corral shearing zone, and granitic rocks of the Cerro Áspero-Alpa Corral Batholith (Fagiano 2007; Rey Ripoll 2008; Coniglio et al. 2010).

The Monte Guazú Complex is recognized as the lithostratigraphic unit with wider distribution in the Sierra de Comechingones, and it is composed of rocks which are the product of regional metamorphism. Migmatites and paragneisses dominate, of homogeneous nature and poorly developed schistosity, and oval to lens-like bodies of tonalite and granodiorite orthogneisses are interposed. Second in importance are the amphibolites forming elongated, tabular, and elliptical outcrops. Small to medium granitic, simple pegmatite bodies, concordant with the metamorphic rocks, are common in the area. Veins of hydrothermal quartz, either concordant or discordant with bedrock structure, have been identified (Fagiano 2007).

The Guacha Corral shear zone is one of the more extensive found in the Sierras de Córdoba. It extends from the southern portion of the Achala Batholith to the southern end of the Sierra de Comechingones, with an approximate length of 120 km. It has a varying width with a maximum of 20 km in the northern part, but in its medial section is segmented by the intrusion of the Cerro Áspero Batholith. In the southern portion, the shear zone is in numerous narrow bands 100–200 m thick (Fagiano and Martino 2004). It is a wide zone of ductile deformation of N-S orientation, which provides a penetrating, mylonitic foliation superimposed to a previous one of regional development. The contacts between the shear zone and the migmatitic complex are gradual, and it is common to find sequences composed of, from the outer to the inner part of the belt, deformed stromatites, protomylonites, mylonites, and ultramylonites.

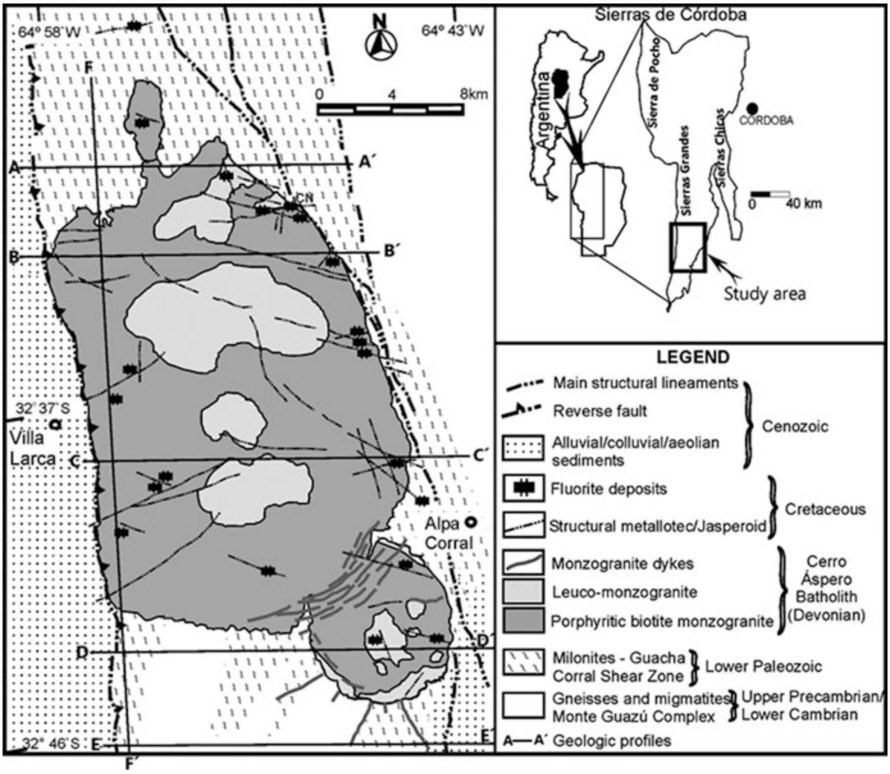

Fig. 2 Geological map of the study area (Modified from Coniglio et al. 2010). The location of six geological sections discussed in this chapter is also shown

The Cerro Áspero Batholith intrudes the medial section of the Monte Guazú Complex. It has an area of 440 km^2 and is the most important granitic complex of the Sierra de Comechingones. It is of Middle to Late Devonian age (Pinotti et al. 2002). According to these authors, this batholith was built up by the successive emplacement of three plutonic bodies (Los Cerros, El Talita, and Alpa Corral, located from N to S, respectively) which have individually developed facies variations (inner, outer, and summit units and a suite of associated dykes). As shown in Fig. 2, the inner units comprise most of 60 % of the batholith surface, and they are represented by very coarse-grained, porphyritic biotite monzogranites (Pinotti et al. 2002). In the outermost and summit units, as well as in the dykes, two-mica or exclusively muscovite leucogranites are dominant, whose composition varies between monzogranites and alkaline feldspar granites (Coniglio 2006).

Closer to the El Talita and Alpa Corral plutons (in the S and SE contacts), a discontinuous thermal contact aureole has been described, with an approximate thickness of 500 m, formed by rocks of hornblende hornfels and albite-epidote facies (Fagiano et al. 2006).

The contacts with the metamorphic rocks and the observed field relationships indicate a post-kinematic intrusive emplacement and, associated to this magmatism, wolfram and molybdenum-bearing hydrothermal deposits and epithermal fluorite veins are found.

Galindo et al. (1997) obtained two Sm-Nd ages of 117 ± 26 Ma and 131 ± 22 Ma, from fluorite found in the Cerro Áspero Batholith (Bubú Mine) and of the Achala Batholith (La Nueva Mine), respectively. The veins are emplaced in subvertical structures, which record several stages of opening and infilling with fluorite-chalcedony-dominated epithermal mineralization. Based on mineralogical, geochemical, and stable isotope studies, Coniglio et al. (2000, 2004, 2006) proposed as responsible for their genesis the action of heated meteoric fluids which, due to fluid-rock interaction processes, interchanged isotopically with the host granites and leached part of the fluorine content. According to Coniglio et al. (2000, 2004), changes in fluorite texture, from massive towards richer in open spaces, from I to IV stages, are accompanied by a gradual cooling of the hydrothermal fluid and isotopic restrictions that suggest depositional conditions for the minerals in successively shallower levels with respect to the paleosurface (from approximately 2 km), with the present exposition of the four stages at the same level. These authors have suggested the occurrence of erosion processes during the lifetime of the hydrothermal system as a possible scenario to explain the textural evolution of this mineralization, which was probably related to the development of erosion surfaces in the Sierras Pampeanas from the Late Jurassic to the Late Cretaceous (Coniglio 2006).

Over a clear erosional unconformity, the metamorphic rocks and granites are covered by loess and loess-like Quaternary deposits (Fig. 3), with thickness of a few centimeters up to more than 5 m, which are exposed in eroded channels (Fig. 3a, b). In some places, a discontinuous level of calcrete is interbedded in the sequence; the calcrete has been dated in 4,180 ± 80 ^{14}C yr BP (Andreazzini et al. 2012). The soils developed on the Quaternary cover show a significant degree of evolution, with abundant organic matter and clayey horizons (Bt).

It must be noted that the different rock types exposed in the Sierra de Comechingones, particularly in the paleosurfaces, do not exhibit a significant weathering profile and, in general, they occur with little or no alteration, both in the valleys and on the divides (Fig. 3a–c). In most cases regolith is absent, whereas in others a partial alteration is observed (mechanical disaggregation, with minimum oxidation and clay formation) of a few decimeters.

Methodology

The methodology used in this chapter is centered upon the synthesis of information coming from different fields of the Earth Sciences, with the purpose of adding evidence which would allow the discussion of several aspects of the genesis, age, evolution, and preservation of the studied paleolandforms. Numerous previous

Fig. 3 Different contact zones between the metamorphic crystalline basement (Late Precambrian-Early Paleozoic) and the sedimentary cover (Quaternary). (**a**) and (**b**) location in valleys; (**c**) location on the divides

papers (in geology, geomorphology, geochronology, metalogenesis, stratigraphy, etc.) were used together with our own field and laboratory information to characterize the paleosurfaces developed on different rocks (basically, metamorphic rocks and granites).

By means of the analysis of topographic sheets (scale 1:50.000, Instituto Geográfico Nacional of Argentina), Landsat and Google Earth satellite images, and digital elevation models (DEM) such as SRTM (90 m resolution), the relicts of the planation surfaces present in the study area were identified and delimited. Some morphometric parameters such as slope, area drainage density, and stream length were obtained. These last two indicators were obtained from the analysis of order 3 basins, considered to be representative of the lithological environments.

In the field, the morphology, stratigraphic profiles, and active processes were described.

Based upon this information, five E-W profiles transverse to the Sierra de Comechingones, and one N-S profile was constructed. These profiles were selected considering the presence of planation surface relicts on the different lithology types observed in the study zone.

Using the SAGA GIS software, the drainage network and the map of fluvial incision depth were compiled.

Finally, an integrated analysis of the available information was completed.

Results

The results presented here concern erosion surface remnants developed on the granitic rocks of the Cerro Áspero Batholith and on older metamorphic and mylonitic rocks located both N and S of the intrusive body. The paleolandforms are located between 2,150 and 1,500 m a.s.l., occupying an approximate area of 300 km^2. These landforms are tilted towards the E and S-SE, as is observed in the topographic-geological profiles of Fig. 4.

Figure 5 shows aerial views of these ancient surfaces in different geological contexts. The paleosurface relief within the metamorphic region shows great homogeneity (Fig. 5a), whereas those of the granitic environment present a much more irregular aspect (Fig. 5b, c). Among them, an erosion bench in the order of 100–110 m (up to 200 m in some places) may be observed, as it is shown in the topographic map of Fig. 1 and in the F–F′ section (Fig. 4), although exaggerated by fluvial incision of the Arroyo Papagayos, and in the aerial view of Fig. 5b.

Due to the differences that these surfaces present in both environments in relation to topography, landforms, and drainage network characteristics, among other variables, they will be treated separately.

Planation Surfaces in the Metamorphic Rock Environment

The planation surface occupies an approximate area of 60 km^2 over the metamorphic rocks located north of the Cerro Áspero Batholith. It is found between the 2,100 and 1,900 m a.s.l. contour lines and has a variable slope between 2 and 4 % (A–A′ section; Figs. 1, 2 and 4).

South of the batholith, the paleosurface is located between 1,800 and 1,400 m a.s.l., it covers an approximate area of 90 km^2, and its slope is in the order of 3–5 % (D–D′ and F–F′ sections; Figs. 1, 2 and 4).

These surfaces show a very homogeneous relief, smoothly undulating, with minimal internal elevation benches associated with fluvial valleys, which in general do not exceed 10–15 m. They have a Quaternary sediment cover, formed by loess and loess-like materials, which is preserved over most of the area (Figs. 6a, b).

Rocky outcrops are mainly restricted to the fluvial channels, and they exhibit low relief of crest-like landforms controlled by the orientation of the metamorphic structures. In some places where orthogneisses are exposed, the local relief is more heterogeneous and, with larger steps, composed of rounded blocks, tafoni, and pedestal rocks, among others (Fig. 6d), similar to those developed on granitoid rocks.

In the drainage network, the trunk streams of higher importance (order 3 and 4) are controlled by different structures of varying strike, where the NW-SE and NE-SW systems are dominant, the drainage pattern is angular, but the lower order streams present a dendritic pattern (Fig. 7). Drainage density is generally smaller than 4 and the mean length of the order 1 channels varies between 150 and 250 m.

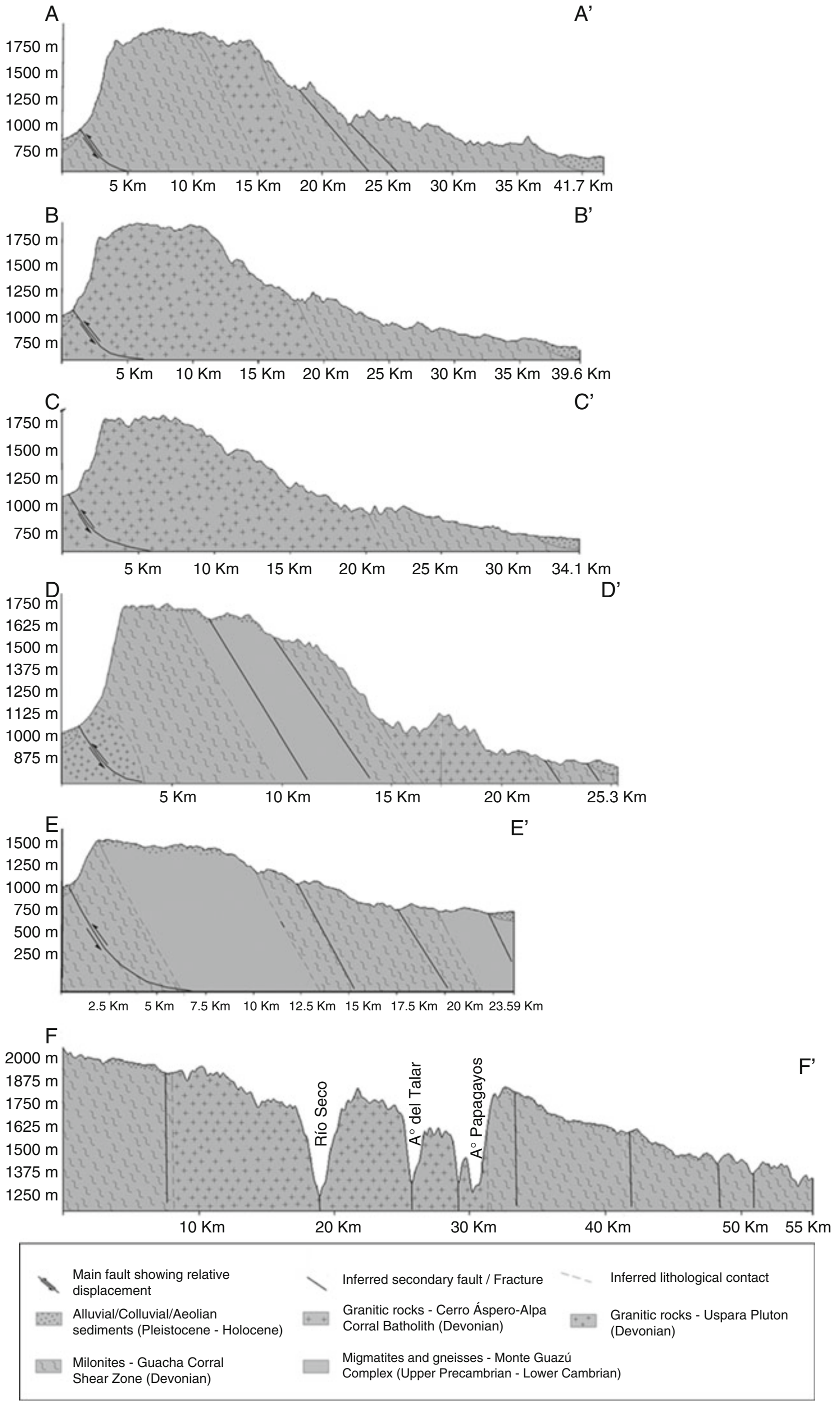

Fig. 4 Topographic-geological profiles of the central sector of the Sierra de Comechingones. The location of the profiles is presented in Figs. 1 and 2

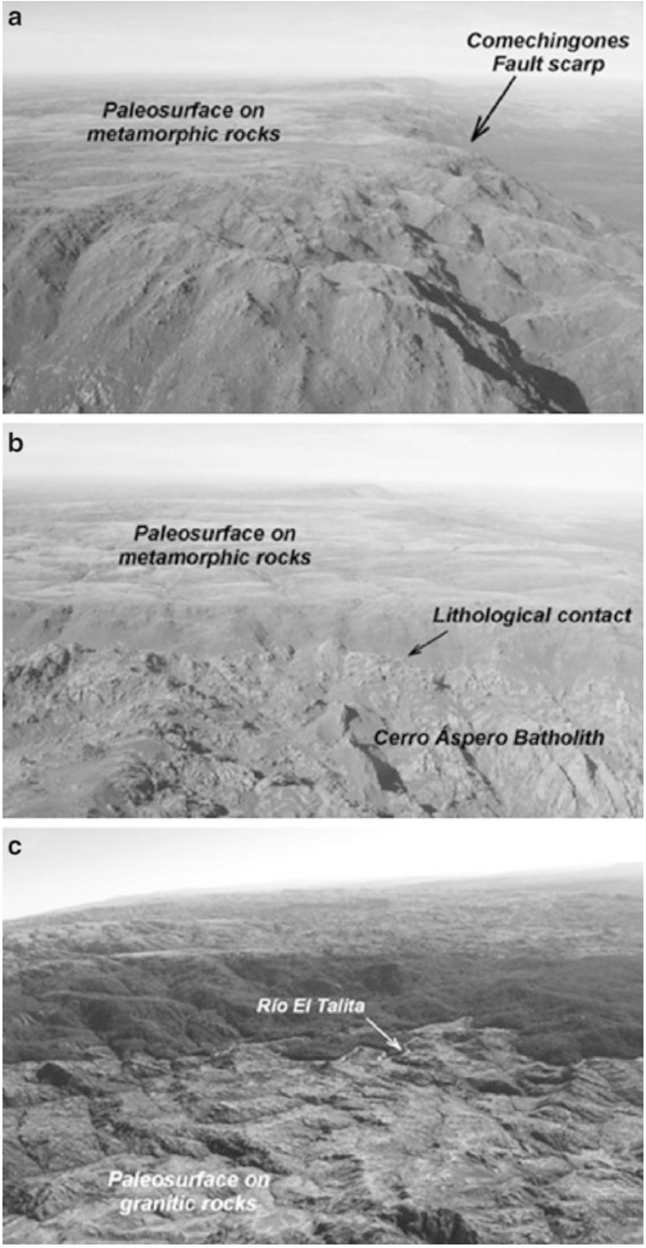

Fig. 5 (**a**) N-S view of the paleosurface on metamorphic rocks (Monte Guazú Complex, Río Las Cañitas upper basin). (**b**) N-S view of the contact between the Cerro Áspero Batholith and the paleosurface carved on metamorphic rocks. (**c**) S-N view of the paleosurface on granitic rocks (Cerro Áspero Batholith)

Fig. 6 (**a**) View of the paleosurface elaborated on the metamorphic rocks of the Monte Guazú Complex, where in the central sector channels developed on the Quaternary sediment sequence, covering the metamorphic rocks, are developed. (**b**) View of the paleosurface; at the background, the Comechingones fault scarp. (**c**) Fluvial valley carved on the paleosurface, Arroyo Los Comederos. (**d**) Mesoscale boulder type landforms, with partially developed tafoni

The fluvial valleys are not too deep, with a fluvial incision depth that in general does not exceed 10–15 m and a channel depth of only 3–5 m (Fig. 6c). In the drainage network and channel depth maps (Fig. 8), it is observed that these paleosurfaces correspond to the origin of the La Tapa, Guacha Corral, and Quillinzo stream basins and that, in these environments, the incision is normally smaller than 40 m, with dominant values of the order of 10–20 m. Locally, active rill formation processes are observed associated with the Quaternary sediments.

Planation Surfaces in the Granitic Environment

Within the area occupied by the Cerro Áspero Batholith, the remnants of the summit paleosurface occupy an approximate area of 150 km^2, with a variable slope between 4.5 and 7.5 % and an elevation between 2,000 and 1,800 m a.s.l. in the northern portion of the batholith and between 1,800 and 1,600 m a.s.l. in its southern sector (B–B′ and C–C′ profiles; Fig. 4).

Fig. 7 Google Earth satellite image showing the characteristic drainage network of the paleosurface when developed on metamorphic rocks

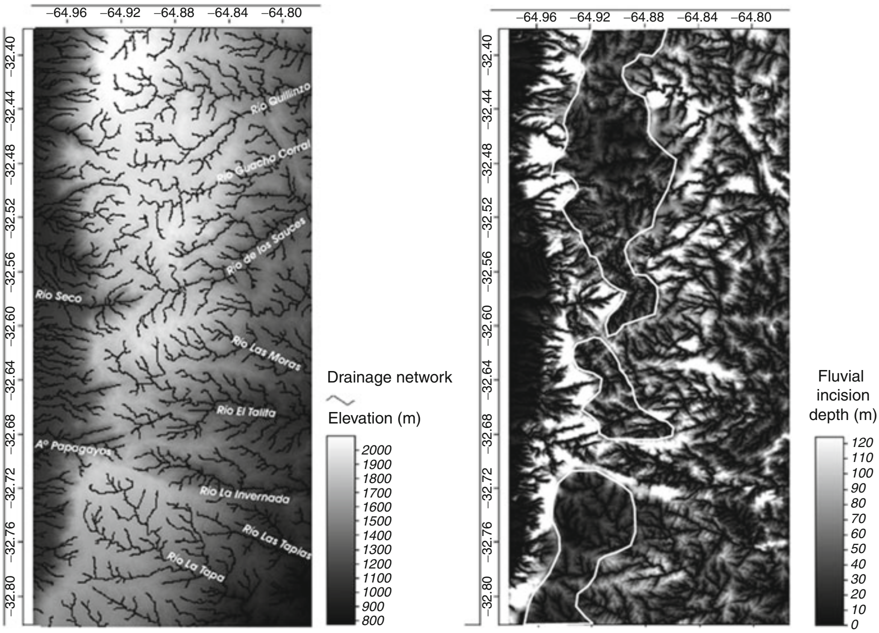

Fig. 8 Drainage network and fluvial incision depth maps, obtained from the SRTM DEM. The *whitish solid line* depicts the extent of the remnants of the paleosurface

Fig. 9 Bell-like morphology (**a** and **b**) and smaller landforms such as tors, rounded boulders, and tafoni (**c** and **d**), within the Cerro Áspero Batholith domain

The landscape of the granitic pampas combines rocky outcrops with sectors covered by Quaternary sediments. In the latter, rill formation is active.

On rocky outcrops medium-size landforms are dominant, associated with the batholith margin facies, where the rock shows a high degree of fracturing. In those portions where the granite exhibits high jointing density (western margin and the Comechingones fault scarp front), relatively small angular blocks dominate. To a lesser extent in the pampas and somewhat more common towards the east, large bell-like granitic landforms occur, like those presented in Fig. 9a, b. Minor granitic landforms such as rounded boulders, tafoni, and tors are also common (Fig. 9b–d).

This surface, unlike the surfaces on metamorphic rocks, is characterized by a larger degree of fluvial dissection. Drainage density reaches values of 6.5–7.5 and the mean length of the first-order channels is 70–110 m. As shown in Fig. 10, the drainage network pattern is of the rectangular-angular type, showing a high structural control that for the larger order streams is given by NNW-SSE and NE-SW conjugate system structures.

The valleys are only slightly incised and are very wide on the pampas (Fig. 11a), whereas towards the east, in the Cenozoic erosion front, the streams have reached a high level of incision in several sections (Fig. 11b). In these areas, the fluvial divides correspond to the level of the regional planation surface. In Fig. 8 and in the

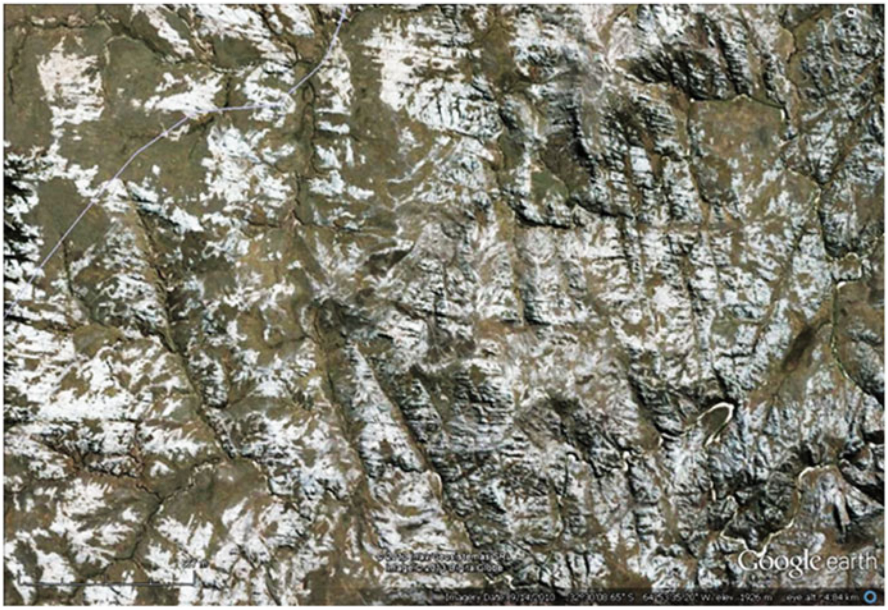

Fig. 10 Google Earth image showing the characteristic drainage network in granitic environments

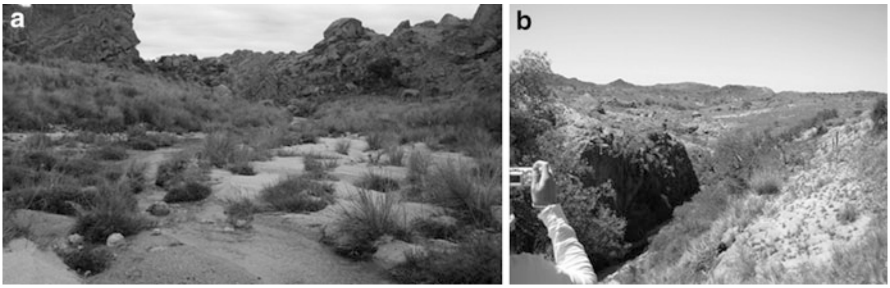

Fig. 11 (**a**) Fluvial valley in the granitic pampas; (**b**) deep stream incision section east of the Cerro Áspero Batholith

F–F′ profile (Fig. 4), the important erosion work performed by the La Invernada, El Talita, Las Moras, Papagayos, Seco, and other streams has been recognized, reaching incision depths of up to 100–110 m.

Discussion

The integrated analysis of the geomorphological, petrographic, structural, stratigraphic, sedimentological, metalogenetic, and geochronological information, both of the study area and of the regional setting, has allowed the discussion of various aspects related to the origin, age, and evolution of the studied paleosurfaces.

The mineralogical, geochemical, and stable isotope studies performed by Coniglio et al. (2004) and Coniglio (2006) on epithermal fluorite deposits found in the granitic paleosurfaces are herein of special interest. These papers indicated the large supply of meteoric waters to the hydrothermal system and the depositional conditions of these minerals which were particularly shallow (less than 2 km depth). Therefore, these contributions suggested that:

(a) During the development of the hydrothermal system, the climatic conditions of the area would have been wet enough to sustain such large water supply.
(b) The coexistence of erosion processes simultaneously with the mineralization period.

Taking into account the radiometric ages obtained by Galindo et al. (1997) on the fluorite deposits of the Sierras Pampeanas de Córdoba (Early Cretaceous) and the duration of the mineralization period dated by Jelinek et al. (1999), of approximately 50 Ma (Early Cretaceous-Early Paleogene), in similar fluorite deposits of Santa Catarina State (Brazil), Coniglio (2006) postulated that after the exhumation of the Sierras Pampeanas in the Early Carboniferous, the rate of uplifting and erosion should have been very slow, considering that the mineralization affected the summit units of the Cerro Áspero Batholith. According to this author, "although the possibility that part of the evolution of the epithermal system would have happened during the uplifting of the Sierras Pampeanas at the beginning of the Andean cycle cannot be ruled out, the banded-crust like dominium and the infilling of spaces generated in transtensive domain of the mineralization are not primarily coincident with clearly compressive kinematics."

This evidence allows us to point out that the studied paleosurfaces were being formed during the cited mineralization epoch and that, at least until the Late Cretaceous-Early Paleogene, the present levels that exhibit veins of fluorite in the Cerro Áspero Batholith which were formed at depths shallower than 2 km were not exposed yet.

The analysis of the sedimentary sequences that infilled the adjacent Mesozoic basins contributes to reinforce these interpretations. In the Sierra de los Cóndores Group (Late Jurassic-Early Cretaceous), the compositional and morphometric analyses of gravel and sandstones by Sánchez and Minudri (1993) and Minudri and Sánchez (1993) indicate that in the basal layers, the clasts are predominantly of metamorphic rocks, with some participation of pegmatite types, but towards the top of the sequence, the percentage of the pegmatites increases. This compositional change could be attributed to a gradual thickness diminution of the roof rocks of the Cerro Áspero Batholith, where increased content of such rocks is expected, suggesting that during the Early Cretaceous, the erosion surface has not reached yet the mineral-bearing plutonic rocks.

Besides, Sánchez and Minudri (1993) and Minudri and Sánchez (1993) pointed out that, in general, the studied clasts of conglomerates and sandstones pertaining to the Sierra de los Cóndores Group present a low grade of alteration and a highly variable degree of sphericity and roundness, depending upon their composition, which would be indicating moderate (or at least not extreme) weathering conditions in the source areas (i.e., the Sierras de Comechingones) for the Late Jurassic-Early Cretaceous period.

In relation to this, it should be noted that neither regolith levels have been found yet in the studied paleosurfaces nor observations about them in any of the accessed petrographic papers for this area of the Sierras Pampeanas (Fagiano 2007; Coniglio 2006; Otamendi 1995; among others). None of these papers report the presence of significant alteration levels in the outcropping crystalline basement rocks, while Sánchez (2001) described a weakly altered regolith bed underlying the basal sequence of the Sierra de los Cóndores Group.

Several authors studied the Cretaceous basins of the Sierras Pampeanas of Córdoba (Gordillo and Lencinas 1967; Sánchez et al. 1990; Astini et al. 1993; Piovano 1996; Sánchez 2001), and they interpreted the paleoenvironmental conditions for that period. Particularly, in the Sierras de los Cóndores Group, Sánchez et al. (1990) and Sánchez (2001) recognized facies intercalations of breccias and conglomerates, sandstones and conglomerates, sandstones and mudstones, mudstones and evaporates, which they interpreted as belonging to an alluvial fan paleoenvironment, with local variations in the production of sediments related to the activity of the main faults, volcanic activity, and, secondarily, climatic variations from subhumid to arid or semiarid. Therefore, the dominant erosion processes in such period would be associated to well-defined fluvial systems, developed in the mountain sectors, with the formation of alluvial/colluvial fans, and also to the penetration in sedimentary basins located farther east, where the intercalation of calcretes and evaporates is frequent. Similar conditions are described for the Late Cretaceous and Tertiary (López and Solá 1981) in volcano-clastic sequences of the southernmost part of Sierra de Comechingones and in the Tertiary deposits described in the Sierras Pampeanas environment.

The investigations steered by Linares et al. (1961) in the outcropping Tertiary sequences of the Valle de Punilla (the localities of Santa María de Punilla, Cosquín, Bialet Massé), farther north from the study area, in addition to confirm the recently described paleoenvironmental conditions, provided compositional information which is of great interest to establish the source areas. These authors indicated that in the basal levels (Early Eocene in age), the present lithology corresponds to the degradation of the granitic areas of Sierras Grandes, such as those comprising the Achala Batholith, whereas the upper levels incorporated metamorphic rock clasts which are pertaining to the Sierras Chicas, indicating the uplifting of this mountain range but only after the Eocene.

In the mineralogical descriptions, and particularly those of the basal sequence, Linares et al. (1961) did not mention the presence of fluorite-chalcedony clasts, with provenance from the Achala Batholith and the erosion of its mineral deposits, which are coeval with those of the Cerro Áspero Batholith. Towards the southern end of the Sierras Pampeanas of Córdoba, closer to the study area, there are neither records nor scientific studies concerning the sedimentary sequences of the Early Eocene, with the exception of Cantú (1992) when he assigned the basal sequences of the middle-outer fan of the Alpa Corral River to the Pliocene, although his work did not include rock compositional analyses. Thus, with the available evidence, it is assumed that the erosion processes had not reached yet the mineral-rich layers in the Early to Middle Tertiary (i.e., Eocene-Miocene), previous to the main Andean uplift in the Pliocene-Pleistocene.

As a consequence of such important tectonic event, the crystalline basement blocks were fragmented, tilted, and displaced, up to 1,000 m of vertical displacement in the main fault scarps, according to Gordillo and Lencinas (1979). The Cretaceous sequences were also uplifted as a result of the tectonic inversion, thus becoming exposed to subsequent erosion processes. The main fluvial systems, preceding the Andean uplift (González Díaz 1981; Carignano et al. 1999; Degiovanni et al. 2003, among others), started a marked process of incision and headwater erosion, which continues until present times.

The papers by Degiovanni et al. (2003) and Villegas et al. (2006) show that the longitudinal profiles of some stream channels which drain the eastern and southeastern slopes of the Sierra de Comechingones (Río La Tapa, Piedras Blancas, Cuenca Río Cuarto, and the Achiras and Las Lajas creeks, among others) are clearly unadjusted and the tributaries of lower order (1 and 2, basically) exhibit certain gradient values which are lower (1.5–3.0 %) than those of the collecting streams of higher order (essentially 3 and 4). This local anomaly to the gradient law, according to Horton (1945), is related to the presence of relict paleosurfaces which are still almost not incised in the headwater areas.

There are still very few studies in the Sierras Pampeanas environment that have taken into consideration the development, morphology, and preservation of the relict paleosurfaces, with a few references which basically described granitic landforms (Carignano et al. 1999; Cioccale and Carignano 2009). In this sense, it is understood that this chapter provides a valuable tool when analyzing in detail the existing morphology in different lithological environments. The paleosurfaces developed over the gneissic-migmatitic rocks of the Monte Guazú Complex and the mylonites of the Guacha Corral shear zone (north and south of the Cerro Áspero Batholith, respectively) show a very homogeneous morphology, with internal relief of quite small magnitude and equivalent elevations, probing a likely behavior of these lithological types and poor spatial variability. On the contrary, the degree of fracturing and the compositional and textural variations in granitic rocks, associated to the various facies present, favored the development of a more heterogeneous surface, where it is common to find residual landforms with higher topographic break than in the previous case. The comparative analysis of drainage density indicates that the dissection degree is twofold in the granitic environment, whereas the length of stream channels of order 1 diminishes to one half, showing a greater susceptibility for this lithological type though facing the same erosion processes.

These same lithological and structural characteristics are valid to explain the degree of preservation of these paleolandforms. Although the relict surfaces are located in the main water divides, the intensity of the erosion processes was larger in the southern portion of the batholith where, as it may be observed in the fluvial incision map, the La Invernada, El Talita, Las Moras, Seco, and Papagayos streams, controlled by larger structures (some of them with more recent activity), have generated an important elimination of materials with an incision depth of around 100–120 m in rocks corresponding to the porphyritic biotite monzogranite facies. The local relief that it is observed in the bedrock-intrusion contact is also attributed to differential erosion, and it is basically related to the presence of contact metamorphism rocks, which provide a larger resistance to bedrock in this area.

Concluding Remarks

Based upon the preceding discussion, the following conclusions may be forwarded:

1. The studied cratonic area was a positive element of the region at least since the Carboniferous and Permian, and since then, it has been subject to different denudation cycles, both associated to the distension tectonic environments of the Mesozoic and also the Andean compressive actions during the Cenozoic.
2. Previous to the Andean orogeny, during the Middle to Late Tertiary, there was a long period of relative stability, where the tectonic and erosion processes, generally of low energy and magnitude, favored the development of erosion surfaces, which began to be denudated after these movements, being preserved their remnants along the higher water divides.
3. At least until the Late Cretaceous, the Cerro Áspero Batholith was not exhumed; therefore, the age assigned to the studied paleosurfaces is comprised between the Late Cretaceous and the Paleogene.
4. The remnants of the studied erosion surfaces correspond to one single paleosurface and the altitudinal variations observed, both in N-S and W-E directions, correspond to the tilting of the basement blocks during the Andean episodes.
5. The paleosurfaces would have a polygenetic origin, a result of the alternation of wetter periods (humid/subhumid), in which chemical weathering processes and channel erosion would have been dominant, with others of more arid conditions, when mechanical weathering and disaggregation and overland and/or poorly organized surficial runoff would have been prevailing, with the development of pediment formation. Due to this, it could be explained that landforms corresponding to different landscape evolution cycles would be coexisting, with palimpsest spatial arrangements.
6. A marked lithological control over the geomorphology and the degree of preservation of coeval paleosurfaces exist, whether they are developed over high-grade metamorphic rocks and/or mylonites (Monte Guazú Complex, Guacha Corral shear zone) or over granitic rocks (Cerro Áspero Batholith). In the metamorphic rock environment, the erosion surfaces present a lesser topographic and morphological variation, and, in general, they are better preserved than those developed over granitic rocks, thus suggesting the great influence that compositional, textural, and structural variations exert over geomechanic properties.

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