The Rhyolitic Plateau of the Marifil Formation (Jurassic): A Gondwana Paleosurface in the Southeastern Portion of the Northern Patagonia Massif

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Abstract Along the southeastern border of the Northern Patagonian Massif of the provinces of Río Negro and Chubut, an extensive surface is presently called the "Rhyolitic" or "Ignimbritic Plateau." This large geomorphological unit has a geographical extension which exceeds 50,000 km^2 and it is located between 40°30′ and 44° lat. S and between the Atlantic Ocean coast and 67°30′ long. W. It is characterized by a smooth topography of low and rounded hills, shallow endorheic basins, and a poorly integrated drainage network. The drainage network is mostly nonfunctional and roughly coincident with the bedrock fracture system. Bedrock is almost exclusively composed of the acid volcanic and pyroclastic rocks of the Marifil Formation of Early to Middle Jurassic age. A significant proportion of the identified positive landforms present form and nature very similar to that of "bornhardts," as defined by Twidale (Revista de la Asociación Geológica Argentina 62(1):139–153, 2007), basically for granites. Bornhardts are uncovered dome hills (Twidale, Revista de la Asociación Geológica Argentina 62(1):139–153, 2007) which are usually frequent in Gondwana landscapes (Fairbridge, Encyclopedia of geomorphology. Ronald, New York, 1968). Furthermore, the ubiquitous presence of "corestones" (isolated, large, rounded boulders), which are taken as indicators of an ancient, deep weathering front, supports the hypothesis that these paleosurfaces were generated by long-term, intense chemical weathering processes. The deep weathering would have occurred over at least 25 Ma, between the Middle and Late Jurassic, under a hot and moist paleoenvironment and under extremely stable

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J. Rabassa and C. Ollier (eds.), *Gondwana Landscapes in southern South America*,
Springer Earth System Sciences, DOI 10.1007/978-94-007-7702-6_16,

tectonic conditions. The mobilization, denudation, and later sedimentation of the regolith/saprolite formed under such conditions would have taken place during several erosion episodes, mostly under tectonic forcing, between the Late Jurassic and the Late Cretaceous. The important clay and other secondary mineral accumulations (some of them significant sources of uranium) in the region would have a direct genetic relationship with the development of these paleosurfaces. From the Late Miocene onwards, the colder and drier conditions that were imposed in the region by the uprising Andes and the establishment of mountain glaciers and ice caps during numerous glaciations allowed the modification of this landscape by hydro-eolian processes which generated the widely distributed endorheic depressions (locally known as "bajos sin salida") by deflation and occasionally reworked the surviving rocky hills by abrasion.

Keywords Gondwana • Argentina • Ignimbrite plateau • Etchplains • Granitic geomorphology

Introduction

Extensive paleosurfaces remnants, ranging in age from the Jurassic to the Early Tertiary, are found in cratonic areas of Argentina (Rabassa et al. 2010), such as the Sierras Pampeanas of central and northern Argentina, the Tandilia and Ventania ranges of Buenos Aires province, the Northern Patagonian Massif, and the Deseado Massif. They have been found even in the Malvinas/Falklands islands (Clapperton 1993). These paleosurface remnants are developed over igneous and metamorphic rocks and their origin has been related to intense, deep chemical weathering during long periods of tectonic stability (Rabassa et al. 1996, 2010). These landscapes are characterized and identified by the presence of peneplains, etchplains, and pediplains and smaller scale landforms such as dome hills (bornhardts), inselbergs, corestones, rocking stones, weathering front and weathering profile remnants, and duricrusts, such as ferricretes, silcretes, and calcretes. Some of these features may be found also in similar landscapes of South America and South Africa, in times when both continents were still united or very close to each other in the Gondwana supercontinent (Rabassa 2010). For this reason, these paleolandscapes may be referred to as Gondwana surfaces, as they were described by Fairbridge (1968).

The results of some preliminary observations in a remote area of Argentine Patagonia are presented in this chapter. Work has been developed along the Jurassic Ignimbritic Plateau (Malvicini and Llambías 1974), an extensive geological unit that is part of the basement of the Northern Patagonian Massif (Fig. 1) corresponding to the outcropping volcanics of the Marifil Formation. In the framework of this chapter, these outcrops have been grouped in two main areas. The northern area (Fig. 2) extends between the town of Sierra Grande in the NE, the Somuncurá basaltic plain in the NW and W, the Bajo de la Tierra Colorada in the SW, and the Sierra Chata in the S (approximately at 42°50′ S). The southern area is roughly coincident with a section of the Río Chubut valley (Fig. 3) and it extends between the towns of Las Plumas and Dolavon, in the surroundings of the Florentino Ameghino Dam.

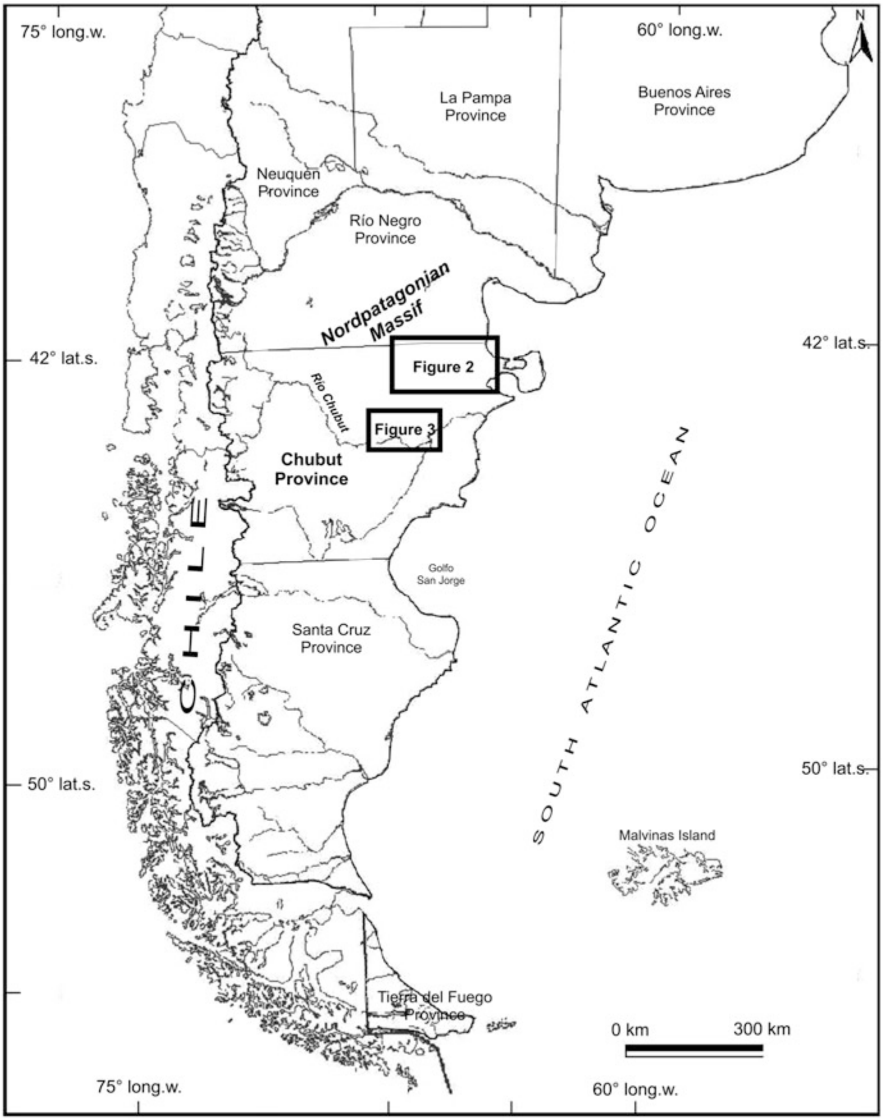

Fig. 1 Map of Patagonia, in which the position of the Northern Patagonian Massif is indicated. The two study areas are depicted in boxes corresponding to Figs. 2 and 3

There are many important previous contributions related to the nature of the geological units found in the area. See, for instance, Stipanicic et al. (1968), Malvicini and Llambías (1974), Ramos (1975), Aliotta et al. (1977), Haller (1978), Cortés (1981a, b), Panza et al. (2002), and Sacomani and Panza (2007). Others have described the magmatic events (Malvicini and Llambías 1974; Llambías et al. 1984;

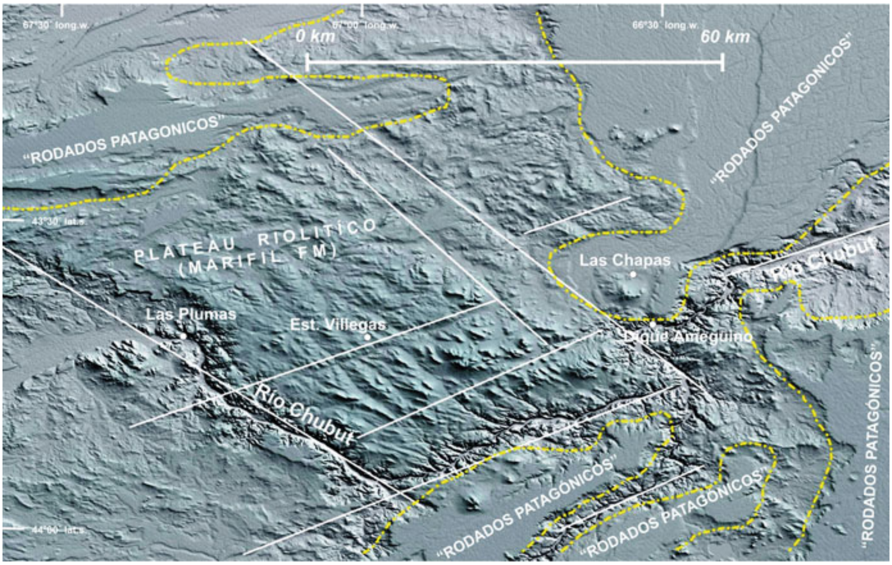

Fig. 2 Northern sector of the study area. The *dashed lines* indicate the boundaries of the Marifil Formation outcrops, which are named as the "Plateau Riolítico" or "Rhyolitic Plateau". The main tectonic alignments have been represented with *straight lines* on the SRTM image. "Rodados Patagónicos" are fluvial and pediment gravels and sands forming tablelands of Late Cenozoic age

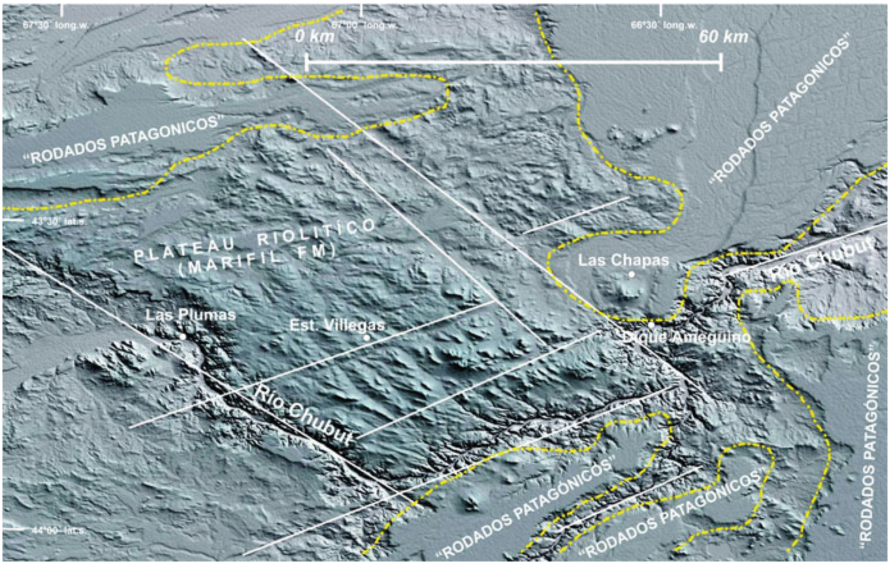

Fig. 3 Southern sector of the study area that corresponds to the lower valley of the Río Chubut. The approximate boundaries of the outer outcrops of the Marifil Formation (the southernmost portion of the Rhyolitic Plateau) have been indicated with *dashed lines* on the SRTM image. For the "Plateau Riolítico" and "Rodados Patagónicos" terms, see Fig. 2

Rapela and Pankhurst 1993; Aragón et al. 1996), the geochronology (Malvicini and Llambías 1974; Rapela and Pankhurst 1993; Pankhurst and Rapela 1995; Alric et al. 1996), and the structure and tectonics of the region (Cortés 1981b). Some other works relevant to the objectives of this chapter are those which have described and genetically interpreted the clay mineral deposits of the area (Angelelli and Stegman 1948; Olivieri and Terrero 1952; Hayase 1969; Hayase and Maiza 1969; Romero et al. 1974, 1975; Maiza and Hayase 1980; Cravero et al. 1991; Domínguez and Murray 1995) or the uranium mineral deposits that lie upon or near the Rhyolitic Plateau outcrops. The origin of these outstanding landscapes has not been studied previously and this chapter is the first scientific geomorphology paper on these topics, in this area.

As a conceptual framework, this chapter relates to the regional and extra-regional works of Rabassa (1978), Rabassa et al. (1996, 2010), and Aguilera and Rabassa (2010).

Geological Units of the Study Area

The eastern and southeastern slope of the Northern Patagonian Massif presents a relatively simple geology. The sequence starts with an igneous-metamorphic basement of Precambrian-Paleozoic age, represented by very few outcrops. The basement is overlain by a quite thick and extensive volcanic/pyroclastic cover, composed by the Marifil Formation (Malvicini and Llambías 1974), also known as the Marifil Complex (Cortés 1981a). This unit includes subordinate lava flows, with dominant pyroclastic and sub-volcanic units of acidic composition, mostly of Early to Middle Jurassic age, which outcrop in eastern Patagonia from southern Río Negro province (40° 30′ S) up to Bahía Bustamante (45° S) and which would probably extend under the sea into the Gulf of San Jorge (Fig. 1), covering an area of over 50,000 km^2 (Page et al. 1999). Due to the abundance of several ignimbritic varieties and the general mantle-like form, these enormously extensive outcrops are referred to as the Jurassic Ignimbritic Plateau or the Rhyolitic Plateau. The maximum thickness that has been mentioned for this unit is around 900 m (Malvicini and Llambías 1974; Page et al. 1999). It has been suggested that the emplacement mechanics of this large unit is related to a fissure-type model (Malvicini and Llambías 1974), to an intense volcanic activity through multiple volcanic vents (Llambías et al. 1984), and to the eruptive activity of wide calderas (Aragón et al. 1996). In all cases, the volcanic events would have taken place coevally during the initial stages of the opening of the southern Atlantic Ocean (Ramos 1983). Absolute radiometric dating obtained in several localities of the region (Cortés 1981a; Rapela and Pankhurst 1993; Pankhurst and Rapela 1995; Alric et al. 1996) has yielded minimum ages of 177 Ma for these rocks (Las Plumas locality, Fig. 3) and maximum ages around 183/187 Ma (in the area of Arroyo Verde, Fig. 2), which has defined an eruptive period in the region of approximately 10 Ma, with decreasing ages from N to S.

Fig. 4 Outcrops of the continental sandstones of the Chubut Group nearby the town of Telsen (Fig. 2)

Cortés (1981a) has proposed that this volcanism evolved from NW to SE. This same author has noted the intense fracturing of these outcrops, forming blocks of different dimensions and varied vertical and horizontal displacement. During the Middle and Late Cretaceous, the sedimentary rocks of the Chubut Group accumulated, corresponding to whitish ashfall tuffs, yellowish and reddish sandstones, light brown conglomerates, and grayish and greenish mudstones (Franchi et al. 2001, Fig. 4). According to Codignotto et al. (1978), these rocks would be distributed, with rather small thickness, from the west to the east with decreasing age. According to Page et al. (1999), they are just a very thin but extensive cover. On the other hand, Labudía et al. (2011) confirmed a thickness of 750 m for the same area (in a tectonic block south of the town of Telsen, Fig. 2), which increases towards the south and southeast, due to the inclination of bedrock in that direction (Cortiñas 1996). The geological section continues with the deposits corresponding to the La Colonia, Roca, and Salamanca formations, products of Eocene marine transgressions from the Atlantic Ocean during the Maastrichtian/Danian. The Atlantic transgressions during the Eocene and the Neogene are also represented in the region. A distinctive characteristic of the Northern Patagonian Massif is basaltic volcanism, ranging in age from the Eocene to the Miocene. Aragón et al. (2011a, b) believed this plateau (the basaltic plain or Somuncurá Meseta), located to the northeast of the study area with a mean altitude of around 1,200 m a.s.l., was formed before the extrusion of the Somuncurá basalts (30 Ma, Early Oligocene, Fig. 2).

Structure and Tectonics

A brief description of the post-Paleozoic geodynamics in the region is needed to allow the genetic interpretation of the regional landscape, taking into consideration, especially, that the present surficial aspect of the Rhyolitic Plateau is, to a large extent, the result of tectonic and epeirogenic differential movements of the various blocks that form it (Fig. 2). These displacements (uplifting, downwarping, tilting) have favored the erosion processes but have also contributed to the preservation of ancient rocks and landforms.

The structure of the area is the product of the action of different diastrophic phases corresponding to the Patagonian (Mesozoic) and Andean (Neogene) orogenic events. During the Early and Middle Jurassic, block fracturing, thinning, and fusion of the lower crust, associated to the initial phases of the southern Atlantic Ocean opening, took place in the region when these terrains were located in southwestern Gondwana (Ramos 1999). These tensional and transtensional movements permitted the extrusion of the ignimbrites and acid volcanic rocks that formed the Ignimbritic Plateau. Some of the regional fractures corresponding to this tectonic event, possibly of extra-regional scale (Coira et al. 1975; Panza et al. 2002; Sacomani and Panza 2007), were reactivated during the later tectonic or epeirogenic episodes and have a usually surficial expression as alignments and fracturing zones.

A significant tectonic episode for the region was the Araucanian phase (or intra-Malm movements) which took place in the Late Jurassic (Kimmeridgian). This extensional/transtensive deformation was caused by a fracturing process that alternatively elevated and downwarped the blocks of the pre-Jurassic basement and the Jurassic volcanic cover. These movements forced the Northern Patagonian Massif to become a positive element since the Early Cretaceous, which divided two important depositional centers of continental accumulation to the north and south, with red beds facies. The sediments that were deposited in the southern sector, that is, in the area surveyed in this chapter, are now the Chubut Group sedimentary rocks, deposited between 110 and 90 Ma, Middle to Late Cretaceous.

The Huantraicoan phase, that is, the inter-Senonian movements or main Patagonian phase that took place during the Campanian (74 Ma), was of high relevance in the formation of the physiography of the region. This compression reactivation locally folded the Cretaceous sedimentary cover (Panza et al. 2002). It also exhumed ample sectors of the volcanic plateau and thus generated the conditions for the erosion of a large portion of the Chubut Group sedimentary rocks, whereas other remnants were preserved in the downwarped blocks. Another consequence of these tectonic events is the inversion of the regional slope which, since that moment, tilted towards the Atlantic Ocean (Page et al. 1999). Next came deposits corresponding to the accumulation of the marine transgressions that took place during the Maastrichtian/Danian. The block located south of the Sierra Chata alignment (Fig. 2) is, according to Page (1987), a downwarped basement block covered by the Chubut Group, the Maastrichtian/Danian sedimentary rocks, and a thin veneer of the “Rodados Patagónicos” (i.e., the “Patagonian Gravels,” Pliocene-Pleistocene). The main structural features of the area have been described by several authors (Windhausen 1918; Lapido and Page 1979; Haller 1981; Lapido 1981; Cortés 1981a, b; Page 1987; Franchi et al. 2001; Panza et al. 2002; Sacomani and Panza 2007). These features are horsts and grabens, limited by fractures, fracture belts, and alignments, some of them of regional scale (for instance, the fracturing belt of Cona Niyeu and the Sierra Chata, El Moro, and Telsen alignments, Fig. 2). The blocks present, almost without exception, positive thresholds and steps, which demonstrates the complexity of the mechanical response of these large rock units during the different diastrophic events. Thus, the distinct blocks and subblocks that form the Rhyolitic Plateau presently show different dip values and directions. This is the result of not only the rising or lowering processes of each block but also tilting.

Description and Interpretation of the Rhyolitic Plateau Surface

The Rhyolitic Plateau has a great physiographic homogeneity and it is characterized by the presence of rounded hills (Fig. 5), of low elevation since the topographic amplitude in the area rarely exceeds 250 m. Only occasionally, the intense jointing generates a rough relief with acute crests and high rocky walls (Haller 1981). The hills are bounded by a drainage network that, at the present time, has an ephemeral régime. Its texture is dense, although poorly integrated. In some sections of the existing channels, this fluvial system is practically inactive and shallow; endorheic closed basins have appeared (locally called “bajos sin salida”), with depths of only 5–6 m at most, and diameters of a few hundred meters to a few kilometers, which act as local base level for a large number of tributaries (Fig. 6). These frequent depressions, whose bottoms are some meters below the thalweg of the linked fluvial channels (Fig. 7), have an essentially eolian genesis and have developed after the dismantling of the fluvial network. The landscape shows a strong structural control with adjustment of the fluvial network to the general dense fracturing of the rocks (Fig. 6). This specific aspect of the Marifil Formation outcrops shows a large contrast with those in the region which are including other younger geological units, such as the Tertiary basaltic flows (Somuncurá basaltic plateau) or the wide plains of the Tertiary/Quaternary “Rodados Patagónicos” (Figs. 2 and 3).

Several authors have discussed the origin of these surfaces. Chebli et al. (1976) mentioned that the Chubut Group unconformably overlies a marked paleolandscape eroded on the Marifil Formation. According to Codignotto et al. (1978), the sedimentary rocks of the Chubut Group accumulated over a relative relief which it is assumed was smooth to moderate. Lapido (1981) described these outcrops as an exhumed regional erosion surface and assumed that the exhumation was in times younger than the Paleocene. In the surroundings of Sierra Chata (Fig. 2), over Jurassic acid porphyritic rocks, Haller (1981) identified rock pillars of more than 2 m of local relief (Fig. 8) which he assigned to differential weathering

Fig. 5 Overview of the Sierra Colorada (Fig. 2), a small hill range of domed shape composed of the characteristic rhyolites and acid porphyritic rocks of the Marifil Formation

controlled by jointing (corestones) and concluded that the overlying weathered debris would have been eliminated by deflation and fluvial erosion. Franchi et al. (2001) found evidence that the rigid basement, which includes the Marifil volcanic rocks, was thoroughly eroded up to the degree of regional peneplanation. Panza et al. (2002) and Sacomani and Panza (2007) described the outcrops of the Marifil Formation located near the Ameghino Dam (Fig. 3) and agreed with the interpretation of other authors (Lapido 1981; Ardolino and Franchi 1996) that these surfaces correspond to an exhumed or resurrected "peneplain," concluding that such exhumation still continues today. The concept of "exhumed peneplain" was coined by González Díaz and Malagnino (1984) as they described large sectors of the province of Río Negro located in the periphery of the Northern Patagonian Massif (Fig. 1), both in the areas near the Andean Cordillera and those closer to the Atlantic Ocean coast, thus including, obviously, a good portion of the Marifil Formation outcrops (mainly those located north of 42° S) studied in this chapter (Fig. 2). These authors proposed the name "Exhumed Peneplain of Río Negro" for "a landform (eroded on granitic and volcanic rocks) which corresponds with the final stage of the evolution of the Davisian cycle and which has been exhumed later on" (free translation by the present authors). These landforms would have been developed in the period between the end of the Triassic and approximately

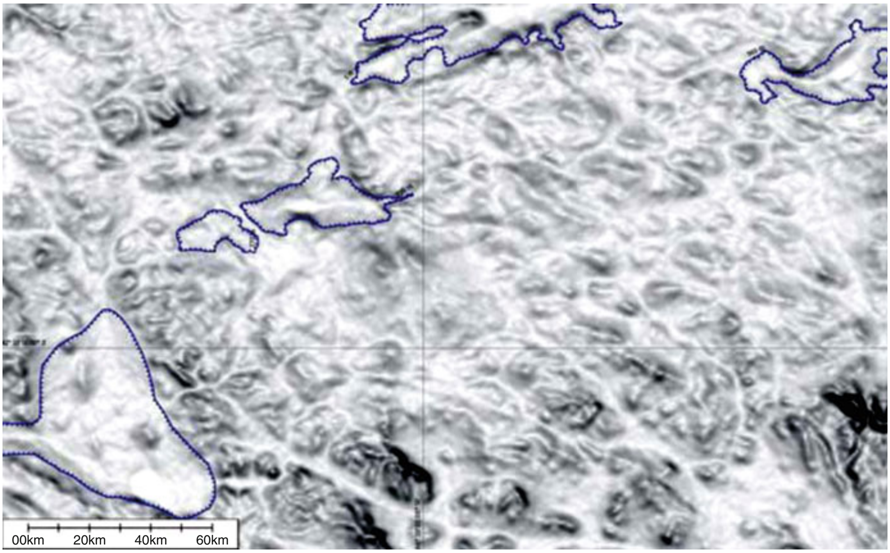

Fig. 6 Radar image (Shuttle Radar Topography Mission) of northwestern Sierra Colorada (Fig. 2), processed with the Global Mapper program. The rounded, domed shape of the Marifil Formation outcrops and the marked adjustment of the drainage network to the intense fracturing of the area are observed. Some of the larger endorheic depressions ("bajos sin salida") are indicated with a *line*, integrating the surficial drainage network

the Cretaceous-Tertiary boundary. They assigned their preservation to the large resistance of the rocks over which the erosional processes acted and the later burial by younger sediments. The geomorphology of the crystalline basement, studied by González Díaz and Malagnino (1984), in the northeastern part of the Northern Patagonian Massif, is reinterpreted by Aguilera and Rabassa (2010) who considered that this wavy landscape, with occasional rounded hills of very small relief, developed over an area of more than 20,000 km^2, is the product of deep weathering and later erosion of the regolith/saprolite levels during an extensive period of tectonic and climatic stability, which took place between the Permian-Triassic boundary and the Middle Cretaceous. Thus, this paleosurface would be an etchplain or deep weathering surface, not a peneplain in the sense of the Davisian cycle, and which would correspond to the Gondwana paleolandscape recognized in other localities of the Southern Hemisphere (for detailed references, see Rabassa (2010) and Rabassa et al. (2010)).

The preliminary character of this chapter includes a general survey of the huge extension of the Rhyolitic Plateau supported by detailed observations focused in a smaller, representative area, the Sierra Colorada (Figs. 2, 5, and 6). This range has an extension of 4 km by 1 km, with a general orientation of N 320° (Fig. 9). It presents a domed morphology (Figs. 5, 10, and 11), of thoroughly eroded aspect, although without erosion features which could be clearly correlated with the rounded shape

Fig. 7 Outcrops of the Marifil Formation rhyolites appear in the foreground, whose surface presents a typical scaly aspect and over which small basins have been developed, showing evidence of present frost weathering and deflation erosion. At the background, a hollow generated by deflation (essentially during the glacial periods) in the channel of a nonfunctional drainage line is observed

of the hills. Moreover, the cracks that act, in some cases very clearly (Fig. 11), as surficial drainage lines and are coincident with rock fractures and joints do not provide a convincing explanation the genesis of these landforms.

A relevant geometric feature of these hills is the absence of any defined pattern in orientation, shape, or inclination of their slopes (Figs. 6, 9, and 10). A consequence of this is that the observed morphologies cannot be related to the action of any particular agent, such as running water, wind, and glaciers, to establish the direction of displacement.

The occurrence of in situ weathered material represents unquestionable evidence of their origin by weathering of these landforms (Twidale 2007). In the study area, regolith accumulations in contact with these surfaces have not yet been found. However, considering the enormous extension of these outcrops and the reduced percentage of them which has actually been surveyed in detail, it may not be ruled out that such findings will be done in the future. On the other hand, the sedimentary deposits of clays and kaolin are very common in contact with the outcrops of the Marifil Formation rocks. These materials are typical products of chemical weathering. Anyhow, there are other elements that allow the suggestion

Fig. 8 Rock outcrops intensively modified by Quaternary eolian abrasion, though these ventifacts could have started even before their evolution, during the Neogene. Haller (1981) considered that these rocks correspond to a Jurassic volcanic unit, though older than the Marifil Formation, and that the landforms are in fact corestones produced by deep weathering

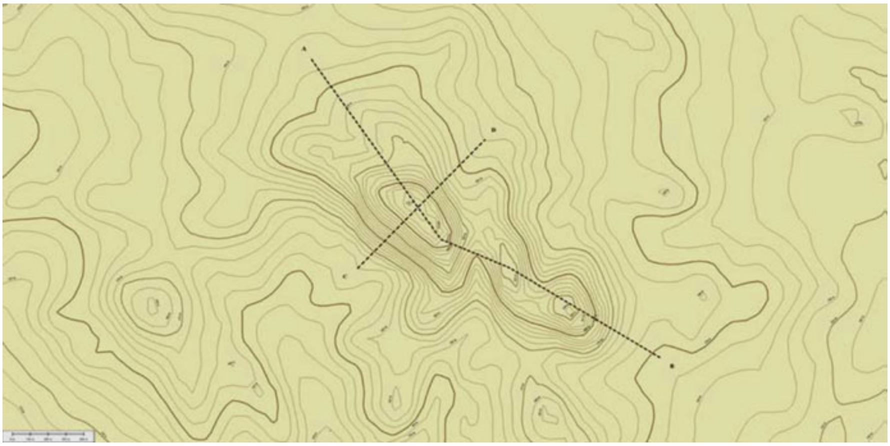

Fig. 9 Topographic map of the Sierra Colorada and longitudinal and transversal cross sections of this range, with exaggerated vertical scale

Fig. 10 Overview of the Sierra Colorada in which the domed morphology and the generally smooth surface that characterize most of the hills of the Rhyolitic Plateau are observed. Note the 3 fracture systems with vertical and subvertical inclination and the subhorizontal discontinuity planes. The latter seem to correspond with surfaces that separate the lava flow units

that the topography of the Rhyolitic Plateau actually corresponds to a paleosurface which represents an ancient deep weathering front. The domed morphologies are of high diagnostic value, many of which (including the Sierra Colorada) may be considered as similar to "bornhardts," being these landforms defined as "barren domed hills, with slopes which become steeper towards the base and which lack the development of debris cones, alluvial cones or soils, whose genesis has been controlled by the internal structure of the rock" (Thomas 1968) or as "rounded hills, usually isolated, generated under wet tropical conditions on massive rocks with fracture systems at large scale" (Allaby and Allaby 1999). These morphologies would be the result of a cycle in which two stages may be identified (Falconer 1911; Twidale 2007). A first stage took place when the compositionally homogeneous crystalline rocks (basically igneous and metamorphic rocks) underwent intense chemical weathering under conditions of extremely high moistures and moderate to high mean annual temperatures. The weathering front advances according to the cited climatic variables but also depending upon the texture, structure, and composition of the rock. The density and orientation of the fracture systems or any lithological discontinuities, such as joints, schistosity, or exfoliation, play a central role in the pattern that the weathering front developed in depth, because the front becomes progressively deeper in the sectors appearing more densely fractured. The depth achieved by the weathering front would be larger, proportionally to the

Fig. 11 Outcrops of the Marifil Formation in the southern end of the Sierra Colorada with their characteristic domed shape. A subhorizontal plane which seems to be the contact between two flow units may be observed. To the right, such a plane is intercepted by the topographic surface which indicates that the latter was generated clearly after the volcanic event

time along which the weathering agents acted. This means that a direct relationship exists between the thickness of the regolith/saprolite as a product of the epigenetic alteration and the tectonic and climatic stability of the area. The second stage of this cycle implies the mobilization of the weathered materials, thus finally leading to the exposition of the deeper unweathered rocks. This second stage starts immediately after a major tectonic and/or climatic change. The soils and vegetation cover existing up to that moment are stripped away by running water, mass movements, or wind starts as the saprolite is exposed to the agents. Finally, this stage ends with the full exhumation of the weathering front and the exposure of the etchplain. If the climatic/environmental conditions which took place after these events, usually of tectonic or epeirogenic nature, would be appropriate, as it was the case in extra-Andean Patagonia during the Late Cenozoic, these smoothly rounded landscapes would have been preserved until present times without major changes. The climatic conditions in Patagonia during the Cenozoic and particularly from the Early Oligocene onwards were never as warm and wet so as to reproduce the conditions that allowed the formation of the etchplain. Thus, all landforms and minor features associated with the etchplain must have been formed in the Late Mesozoic or, at most, in the Paleocene-Eocene, but they are never younger than this latter age.

A significant element that supports a weathering origin for the relief of the plateau is the presence of large rock boulders which clearly stand above the mean level of the surface. These boulders form, occasionally, pedestal rocks which seem to be disconnected from the bedrock but careful observations demonstrate that they are in situ and in contact with fresh rock (Fig. 8). As it was already proposed by Haller (1981), these conspicuous landforms are corestones generated by subsuperficial weathering that are later exposed when the overlying altered materials are eroded and denuded. The notable similarities existing between the landscape herein described here and those identified as Gondwana paleolandscapes studied in other regions of Patagonia and Argentina (see, for instance, Rabassa (1978), Rabassa et al. (1996, 2010), Aguilera and Rabassa (2010)) support an argument to assign a similar origin to the surface of the Rhyolitic Plateau of the provinces of Río Negro, Chubut, and a small area of eastern province of Neuquén, known as the “Sañicó Block.”

The Gondwana Paleosurfaces of Patagonia and the Occurrence of Clay Deposits

The lower valley of Río Chubut (Fig. 3) is the most important kaolin-producing area of Argentina, with more than 250 kaolin quarries distributed over an area of approximately 1,000 km^2 (Panza et al. 2002). The kaolin deposits lie exclusively over the volcanic and pyroclastic rocks of the Marifil Formation. Although they occur with a very strong topographic control (Domínguez and Murray 1995), being preferably located in the more depressed parts of the Jurassic paleorelief (Romero et al. 1974; Panza et al. 2002), they are characterized by their higher horizontal development rather than vertical, forming conspicuous levels of important and continuous lateral extent. They underlie Tertiary sedimentary rocks belonging, for instance, to the Salamanca and Roca formations (Maastrichtian to Early Tertiary in age), and occasionally, they occur underneath the Cretaceous rocks of the Chubut Group, always separated by an erosional unconformity. In general, the base of the clay units is transitional, with the degree of clay formation processes diminishing downwards, until reaching the various facies of the Marifil Formation. The thickness of the layers of white kaolinite may vary between 1 and 6 m, although the total thickness of the alteration zone is of course much greater than these values (Panza et al. 2002). With the exception of some cases in which the clays are of clearly sedimentary origin, they do not show stratification. Structural control of the alteration is not observed, with the exception of very scarce and isolated situations, in which the clay formation process is coincident with faults or it is interrupted by them (Domínguez and Murray 1995). The evidence of tectonic displacement after the generation of these deposits is relevant because they help to establish their age. The more abundant mineral components are kaolinite, quartz, plagioclase, illite, montmorillonite, halloysite, sericite, and various types of iron oxide. Organic matter is frequently present.

Different opinions have been given about the origin of these accumulations. Angelelli and Stegman (1948), Olivieri and Terrero (1952), Aliotta et al. (1977), and Domínguez and Murray (1995) have postulated that they are the product of chemical weathering. These ideas were opposed by Hayase (1969) and Maiza and

Hayase (1975) who considered that they were formed (at least some of them) by hydrothermal alteration, although they recognized deposits of sedimentary type in the area. On the other hand, Romero et al. (1974) related the genesis of these accumulations to rock alteration due to the circulation of deep underground waters. Effectively, there are kaolin deposits of primary and sedimentary origin. The primary kaolin may be a product of weathering or hydrothermal origin. Kaolin of sedimentary origin, less abundant, is formed by erosion, transport, and deposition of the primary-type ones. They may present grain-size variations in a vertical direction (Maiza and Hayase 1980), cross-bedding (Romero et al. 1974), and other sedimentary structures that depict the water environment in which they were deposited. The base of these deposits is usually flat and clean, overlying without transition the Jurassic volcanic rocks. Another aspect that confirms their sedimentary origin is their location, without exception along the depressions or paleochannels of the Jurassic paleolandscape.

With respect to the primary deposits, either they are considered supergenetic or of hydrothermal origin, it is possible to recognize the textural features of the original rock which confirms that the clay formation processes took place in situ. Both processes are characterized for the development of zoning, which in the case of the supergenetic profiles shows a clear diminution of alteration with depth, although a similar situation occurs in some deposits considered to be of hydrothermal origin (Hayase 1969). The determination of the true origin using the mineralogical composition may be challenging because, for instance, kaolinite may be formed either by hydrothermal processes or by chemical weathering and that, in some circumstances, it is impossible to decide which of these processes is responsible for the clay formation processes (Grim 1968). In this respect, the works of Maiza and Hayase (1980) and Maiza et al. (2009), in some ore deposits in the province of Chubut, present a zoning of hydrothermal origin that is composed of a level of intense silicification, then a belt of alunite formation, continuing with a kaolinization zone that grades laterally to a sericite/chlorite sector that corresponds with the zone of lesser alteration. In contrast, the zoning due to weathering of the clays in the lower valley of the Río Chubut consists of a sequence that starts, at the upper part, with a level of white kaolinite that gradually changes downwards into a brownish-reddish kaolinite, occasionally with kaolinite veins, until reaching the lower levels of the unweathered volcanic rocks (Domínguez and Murray 1995).

In any case, the predominance of kaolinite with respect to any other alteration component is very characteristic for this region. This fact is depicted by Cravero et al. (1991). These authors concluded that the presence of kaolinite as the almost only neoformed mineral indicates excellent drainage conditions and intense lixiviation, characteristics of a humid climate. In the same sense, Besoain (1985) indicated that whatever the feldspar kaolinization process would be, a large water supply is always necessary. The composition of the parent material, the Marifil Formation, is also consistent with the almost exclusive generation of kaolinite. Romero et al. (1974) summarized the average mineralogical composition of these rocks in the study area which is composed of 33.2 % quartz, 33.8 % orthoclase, and 23.1 % acid plagioclase. The results of a regional study by Domínguez and Murray

(1995) indicate that the large majority of the kaolinite and clay accumulation were generated by weathering of the rhyolitic rocks. The hydrothermal origin is ruled out by these authors because of the absence of typical minerals found in these processes (sulfur, pyrite, pyrophyllite, alunite), because of the lack of structural control of the ore deposits (the usual ascending ways of the hydrothermal fluids), and because in none of the examples increase of the clay formation processes with depth was identified. Other significant arguments in favor of the supergenic origin are the results of the isotopic analyses of deuterium and ^{18}O presented by Cravero et al. (1991), which correspond to meteoric water action.

A profile of global weathering for present times was presented by Strakhov (1967) which included five main zones ordered in order to their diminishing depth/degree of weathering: (a) a deep saprolite zone in contact with the fresh rock; (b) a zone of illite/sericite, montmorillonite, and beidellite; (c) a zone of kaolinite; (d) a zone of ochre gibbsite; and the sequence ends with (e) a laterite layer. It is possible that this general alteration sequence would have never developed on the rhyolitic outcrops of the study area in the past. Nevertheless, there is an acceptable correlation between the three lower zones, with the possibility that the level of superficial duricrust (bauxite?) would have never developed here or that it had been eroded during the process of exhumation of the plateau, which would allow the inference that the original thickness of the alteration area was much larger.

In summary, the well-known presence of accumulations of kaolinite and other clays over the Marifil Formation outcrops would be indicating intense weathering of these rocks by lixiviation of rain water (Cravero et al. 1991), perhaps for a very long period, sometime between 180 Ma (the minimum approximate age of the Marifil Formation) and 150 Ma (the approximate age of the Araucanian tectonic phase in the Andean ranges which lead towards the exhumation of the Rhyolitic Plateau). The environmental conditions of this epoch (Middle to Late Jurassic) would have been very warm and humid in Patagonia, according to the paleontological records (Volkheimer 1967), or of temperate-moderate conditions (according to Archangelsky (1967)). Cravero et al. (1991) confirmed, by means of the isotopic content analyses of the kaolinites, the need of very high precipitation conditions to generate the appropriate environments. Besides, this method allowed these authors to calculate the values of mean paleotemperature which were found to be between 10 and 12 °C. These values should be considered as a minimum, because these authors do not rule out that the climate would have been highly seasonal, with a rainy season.

The Relationship Between the Paleosurfaces and the Uranium Deposits of the Region

A significant number of uranium mineral deposits of economic value are distributed in central Chubut province, near the study area. The Sierra de Pichiñales uranium district, located 30 km north of the town of Paso de Indios, and within it, the

Los Adobes, Cerro Cóndor, and Cerro Sólo mines should be mentioned. Due to the available reserves and strategic value, the latter has been the most studied in recent years, providing some clues to understanding the relationship between the occurrence of these valuable sedimentary deposits and the processes involved in the paleolandscape development.

The Cañadón Asfalto sedimentary basin, located immediately to the west of the study area (between 42° and 44°30′ S and 68°30′ and 70° W), developed during the Mesozoic and it is composed of meso-silicic volcanic rocks assigned to the Lonco Trapial Formation (genetically related to the Marifil Formation; Page et al. 1999). These rocks were overlain by the Late Jurassic continental sedimentary rocks of the Cañadón Asfalto Formation and later by the continental sequence corresponding to the Chubut Group, Middle to Late Cretaceous. At the base of this latter unit, already described, the Arroyo del Pajarito Member (of the Los Adobes Formation) is found. These are the rocks bearing the main uranium mineralization and are composed of a series of conglomerates and sandstones deposited in a high-energy, braided fluvial environment. The descriptions of a subunit found in the Cerro Sólo mine (Benítez et al. 1993) defined a clastic fraction with very high roundness where rhyolites, ignimbrites, and multicolored acid tuffs are dominant, including quartz grains of volcanic origin and sanidine. Montmorillonite and kaolin are very abundant as well. Organic matter is frequent and of essentially clastic origin, with frequent findings of large fossil trunks and other smaller plant remains. According to Benítez et al. (1993), the mineralization is dominantly epigenic, forming tabular to lenticular bodies, parallel to the stratification. The present mineral species, originated by uranium leaching, are mainly uraninite, uranopilite, and coffinite, generally associated with organic matter. Marveggio and Llorens (2011) determined that the Arroyo del Pajarito Member occurs as a grain-size fining-up sequence, with thicknesses of up to 150 m in the Cerro Sólo mine. These same authors concluded that the deposition of such a large volume of organic matter was concomitant with the almost exclusive contribution of rhyolitic volcanic clasts transported by the large Cretaceous fluvial networks which had their heads at the Marifil Formation Rhyolitic Plateau located to the east (Figs. 2 and 3). The observations of Allard et al. (2011) and Foix et al. (2011) have been oriented in the same direction, who suggested the development of paleo-valleys that were draining from the SE to the NE, locating the source area in the Marifil Formation outcrops.

It seems pertinent to propose that at least some of the uranium mines of central Chubut province are the end product of a process that was initiated under hyper-tropical conditions in the Late Jurassic, with the development of an important level of regolith product of deep chemical weathering of the acid volcanic rocks of the Marifil Formation, which bear uranium primary minerals. Apparently, these volcanic outcrops would be comparable to those found today in the surroundings of the Florentino Ameghino Dam (Fig. 3). The regolith would have been afterwards eroded and transported towards the W and NW, to the depositional center of the Cañadón Asfalto basin. The intense fluvial erosion would have exposed the unweathered and more competent levels of the Marifil Formation at the eastern border of the basin. These surfaces have survived almost without modification up to now, representing the ancient weathering fronts, with frequent corestones and bornhardts. The assumed hyper-tropical conditions that took place during the Jurassic may also be confirmed by the immense quantities of plant and organic remains accumulated at the base of the Chubut Group (Arroyo del Pajarito Member), which later became the basic materials for the natural concentration of the uranium minerals during diagenetic processes.

Cenozoic Morphogenesis

A characteristic of the Late Cenozoic that clearly differentiates it from the preceding times is its global climatic pattern, consisting in alternating glacial (cold) and interglacial (temperate/warm) periods, approximately in 100 ka cycles. Astronomic variables, related to the Earth's orbital parameters, combined with geological processes such as tectonics and volcanism, are essentially the factors controlling the occurrence, recurrence, and intensity of the climatic events. This global atmospheric context, which started in the Late Miocene, has introduced important geomorphological modifications over all continental regions and has been especially relevant in Patagonia, due to its latitude and the presence of the Andean Cordillera as its backbone in the western border. Thus, during glacial periods and at least since the Early Pleistocene, a mountain ice sheet was emplaced in the Andes (Clapperton 1993; Rabassa et al. 2005; Rabassa 2008), whereas in extensive extra-Andean regions, periglacial conditions were established (Clapperton 1993; Trombotto Liaudat 2008). These eastern territories were even more extensive due to the lowering of sea level during the glaciations, exposing the continental shelf, roughly doubling the present surface of Patagonia. Distinctive landscape features of Patagonia are the endorheic depressions or "hollows" ("bajos sin salida"). The origin of these depressions is a problem that has been discussed by many authors in the past (for references, see Martínez (2012)). At present, most of the Argentine geomorphologists accept that these hollows are not the product of just one single process and that there are many factors which, combined or not, have taken place in their development, although hydro-eolian processes are considered as dominant, particularly deflation (Martínez 2012). The Rhyolitic Plateau shows abundant shallow depressions of this nature, which exceptionally exceed a depth of 5 m (Fig. 7) and, generally, are of small size (less than 5 km along its longest axis). These depressions have irregular shapes, though always adjusted to the superficial drainage networks which are determined by the rock fracture patterns (Fig. 6). These frequent depressions were generated by surficial physical weathering (essentially frost processes) that acted over both bedrock and structural alignments (such as joints, faults, dykes, bedding, schistosity, and foliation), which then provided the fine materials that were later removed by deflation. However, it is possible that some of the today existing depressions have, at least partly, inherited their shape characteristics from irregularities of the original weathering front, formed and active under hyper-tropical climates in the Late Mesozoic. The irregularities were probably due to differential chemical weathering

Fig. 12 Ventifacts and wind-abraded rocks, carved on the Marifil Formation outcrops, located a few kilometers S of Sierra Colorada. These eolian erosion features are overprinted on the original morphology of the paleolandscape, during the glacial cycles of the Late Cenozoic. Simultaneously, during these cold and dry events, the numerous hollows found in this area were generated and later expanded

on varying rock types or fracturing patterns. Thus, at least some of these shallow and relatively small features are in fact relicts from the Late Jurassic, ancient etchplain and have been reactivated by Tertiary denudation and remodeled by a set of totally different processes.

Another unquestionable indication of the great influence of eolian erosion in the area is the size and abundance of ventifacts (Figs. 8, 12, and 13). Ventifacts are rock fragments, boulders, or gravels, and wind-abraded rocks are outcrops which show evidence of eolian abrasion, characterized by their shape and surficial features (Laity 1994). The shape of ventifacts and wind-abraded associated features, such as facets, keels, flutes, striation, grooves, scallops, and pits, depend upon the size of the rock, its density and hardness, primary texture, characteristics of the impacting particles (density, diameter, and roundness), wind characteristics and régime, and time length of exposition to abrasion. The fine-grained, hard rocks tend to generate facets, as more or less smooth, abraded surfaces, and a few surficial irregularities. Poorly homogeneous rocks, mostly coarse grained, are more limited in the possibilities for development of facets, with more surficial features. The sand particles are the main, if not the only agent with capacity to produce eolian abrasion, and other materials such as air, dust (clay/silt), ice, or snow should be definitively ruled out (Laity and Bridges 2009). This abrasion capability of sand with respect to other materials is due not only to the size but to the fact that the majority of these particles are made of quartz. The development of landforms due to eolian abrasion implies

Fig. 13 Overview of a surface modeled by eolian erosion, located a few kilometers S of Sierra Colorada. The grooving in these ventifacts and wind-abraded rocks has a general W-E orientation, thus indicating the dominant wind paleo-direction during glacial episodes

not only the presence of strong and frequent winds but also the availability of loose sand in the surroundings (Laity 1995). Another aspect that should be considered is the maximum elevation at which eolian abrasion loses efficiency. In general, it is assumed that on a flat topography, the sand particles lose their erosion capacity at 1 m high (Hobbs 1917). Some authors have argued that sand has no abrasion power above 40 cm (Schlyter 1994). Laity and Bridges (2009) demonstrated that several factors, such as the topographic accidents, may increase the erosion power by saltation, elevating the sand grains above 1 m high and producing erosion at upper levels. In the study area, near Sierra Chata (Fig. 2), outcrops of igneous rocks as corestones have been deeply eroded by the wind, with abraded features above 2 m high (Fig. 5). The ventifacts are excellent paleoenvironmental indicators because they are related to arid, in this case cold, conditions, with lack of vegetation and strong winds capable of transporting sand grains. The eolian abrasion is concentrated exclusively in the upwind side of the affected rocks, which is a valuable element to establish the dominant wind direction. In any case, ventifacts should not be interpreted as indicators of mean wind velocity, or when the wind pattern is or has been bidirectional or multidirectional, these erosion features do not allow the approximation to the strongest wind directions (Laity and Bridges 2009). The sense of the dominant wind in the study area, measured from the linear features on ventifacts (basically grooves), is coincident with that established by other authors (Haller 1981) and tends to be oriented according to a W/SW (upwind)-E/NE (downwind), roughly parallel to the present wind directions. However, although

Fig. 14 Weathering basin on outcrops of the Marifil Formation in the study area. Physical weathering processes and deflation are presently the main morphogenetic processes in the area and they were significantly more intense during Late Cenozoic glacial periods

Patagonia is well known for the frequency and intensity of the winds, the present environmental conditions do not match those needed for the development of such features.

The origin of the “bajos sin salida” and other wind erosion features of this region should be correlated with environmental conditions much drier and colder than today. Physical weathering (particularly, frost processes; Figs. 7 and 14) provides important quantities of sand (quartz, feldspar) to the wind, mostly obtained from the outcrops of the Marifil Formation but also from the Chubut Group exposures and other younger sedimentary rocks, which favors rock abrasion and simultaneously, associated to deflation, contributes to the development of the endorheic depressions. These rigorous climatic conditions should be placed in time during glacial periods, which were represented in extra-Andean Patagonia as periglacial environments, mostly with permafrost conditions south of 42° S.

Final Remarks

The Rhyolitic Plateau, located in the eastern portion of the Northern Patagonian Massif, is a very large geological/geomorphological unit, extending over more than 50,000 km^2, and composed of volcanic/pyroclastic rocks extruded during a roughly

10 Ma period, between the Early and Middle Jurassic ("a" in Fig. 15). Today, this plateau is noted for its homogeneous physiography with low, rounded, and domed hills, and a scarcely integrated drainage network, of ephemeral nature, on which the "bajos sin salida" have been developed, suggesting a prolonged inactivity of these fluvial systems. This mega-landform presents a general "erosive" aspect, with exposure of a rocky substrate with rounded hills and absence of depositional landforms. This has been interpreted by several authors as a "peneplain," corresponding to the final stage of the Davisian fluvial cycle. However, there are sufficient and solid arguments to consider a different genesis for these landforms, comparable to that described in other cratonic areas of Argentina and the Southern Hemisphere (see Rabassa (2010) for further references). These features would be related to (a) deep chemical weathering during a long period of tectonic and climatic stability, under warm and wet environmental conditions ("b" in Fig. 15), and (b) later remobilization of the regolith/saprolite due to erosion enforced by tectonic or epeirogenic reactivation ("c" and "e" in Fig. 15). The surface generated by these mechanisms is a deep-weathering plain or etchplain. The domed shape of the hills and the unweathered corestones derived from the volcanic bedrock are related to an ancient weathering front, exhumed today. Although ignimbrites are the most frequent rocks found in this plateau, it is also true that the rest of lithological types that integrate the Marifil Formation (rhyolites, porphyritic rhyolites, breccias) outcrop in all areas under study, thus suggesting that lithological composition has not played the most relevant role during the development of this homogeneous surface. It is more likely that structural features, such as fracture and joint density, have controlled the efficiency of weathering processes being more intense and, therefore, deeper where bedrock occurs with a higher degree of fracturing ("b" in Fig. 15). According to Twidale (2007), the combination of orthogonal fractures and laminar structures (sheet structures) favors the development of bornhardts and bornhardt-like features. A similar or even identical situation to that described by Twidale (2007) may be observed in many localities of the study area, including Sierra Colorada (Figs. 5, 10, and 11).

The abundant accumulations of epigenetic clays, which appear in contact and overlying rocks of the Marifil Formation, are a modest relict of the huge volumes of weathered rocks that covered a good portion of the plateau in the Jurassic ("b" in Fig. 15). A significant portion of the materials composing these weathering profiles, some of them several hundreds of meters thick, were removed and denudated when the Late Jurassic landscape was reactivated by the Tertiary Araucanian movements ("c" in Fig. 15), to become incorporated as clastic sediments in the Chubut Group basin ("d" in Fig. 15). It should not be ruled out that these weathered materials are also genetically linked to the formation of secondary uranium minerals which are abundant at the base of the lithostratigraphic unit. It is highly probable that, at least partially, the mostly nonfunctional, present drainage network found in the area would have started its development during such tectonic reactivation.

Apparently, the diastrophic events that forced the exhumation of the plateau were the inter-Senonian movements ("e" in Fig. 15), which not only provoked the differential dislocation of the rocky blocks but exposed them to erosion. The

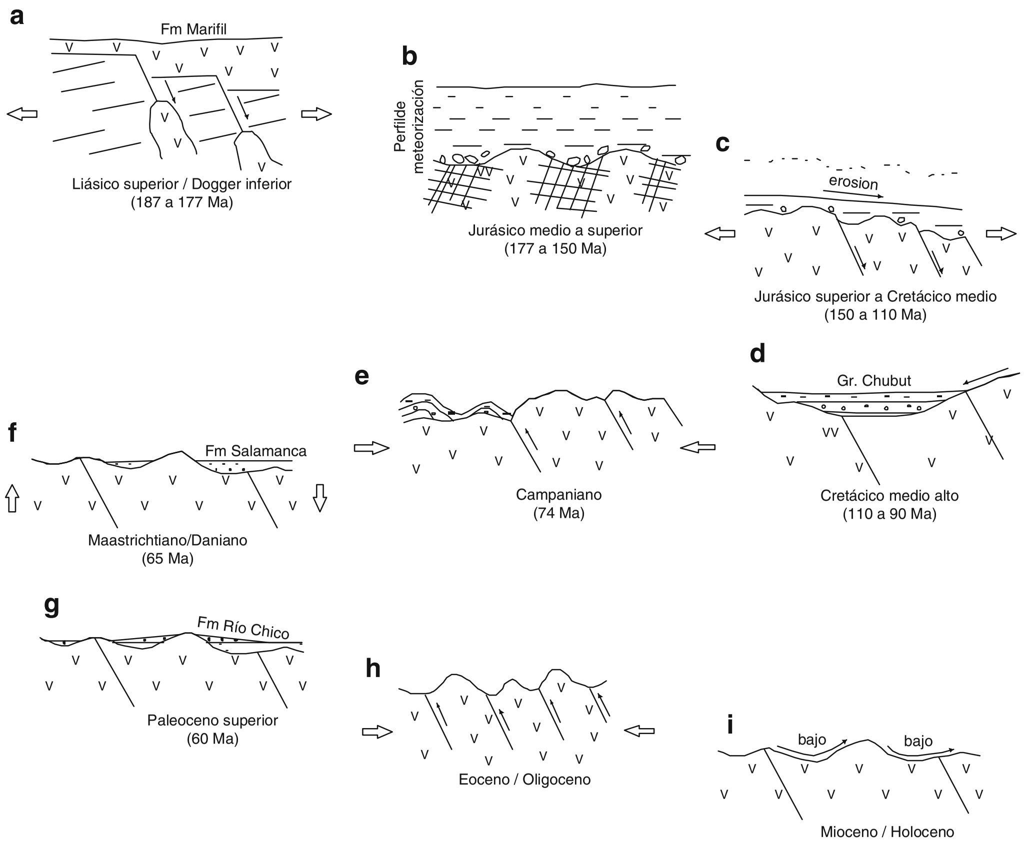
a
Fm Marifil
Liásico superior / Dogger inferior
(187 a 177 Ma)
b
Perfilde meteorización
Jurásico medio a superior
(177 a 150 Ma)
c
erosion
Jurásico superior a Cretácico medio
(150 a 110 Ma)
d
Gr. Chubut
Cretácico medio alto
(110 a 90 Ma)
e
Campaniano
(74 Ma)
f
Fm Salamanca
Maastrichtiano/Daniano
(65 Ma)
g
Fm Río Chico
Paleoceno superior
(60 Ma)
h
Eoceno / Oligoceno
i
bajo
bajo
Mioceno / Holoceno

Fig. 15 (**a**) Extrusion of lavas and pyroclastic flows of the Marifil Formation during the initial phases of the South Atlantic Ocean rifting. (**b**) Phase of tectonic stability with intense chemical weathering in which most of the clay deposits of the region were formed. (**c**) The Araucanian movements initiated an erosion phase of essentially fluvial nature. (**d**) Associated with the uplifting of the Northern Patagonian Massif, the continental sedimentary rocks of the Chubut Group are irregularly accumulated over the ancient surfaces. (**e**) The inter-Senonian movements exhumed the Marifil Formation outcrops. (**f**) Eustatic and/or epeirogenic events favored the marine transgressions coming from the newly born South Atlantic Ocean. (**g**) The regional uplift forced the lowering of sea level and the accumulation of continental deposits. (**h)** The Andean orogeny reactivated the structures producing a new exhumation of some of the regional tectonic blocks and final denudation of the paleosurfaces. (**i**) The evolution of the landscape is controlled by the glacial cycles with a marked predominance of wind erosion, which completed the denudation and modeled the volcanic rock outcrops by abrasion and deepened the existing depressions by deflation and generating the endorheic depressions. At least some of these hollows probably correspond to original depressions of the weathering front, formed during the Late Mesozoic and controlled by differential erosion and/or fracturing. Thus, some of the present depressions are in fact landforms which inherited their basic shapes from the original Gondwana paleolandscape fluvial network was initiated in the Late Jurassic. Reactivation of the landscape took place in this region during the different phases of the Andean orogeny in the Early Tertiary ("h" in Fig. 15). This would have been an essentially erosive period, and possibly, the drainage network was very active. The tectonic or epeirogenic events after the Middle Jurassic which took place forced the different blocks of the plateau up, down, or tilted in different directions. This should have imposed a permanent adjustment on the fluvial network. Thus, the stream channels, strongly controlled by weakness zones and coincident with extensive and abundant alignments present in the area, slowly developed subsequent valleys. This is a relevant aspect because it could be accepted that erosion would have been concentrated through time in the same sectors, essentially those of more intense fracturing allowing a better conservation of the domed hills and bornhardts.

Finally, the present landscape of the study area has clear signals of intense and prolonged chemical weathering under environmental conditions of extremely high temperature and moisture, hyper-tropical climates which took place in the Mesozoic and which did not occur again later in geological history. Remobilization of alteration products and unweathered bedrock erosion was controlled by the degree of exhumation of each of the rocky blocks affected by different tectonic and/or epeirogenic events. During the Late Cenozoic, episodic, extreme environmental conditions also developed by these were exactly opposite to those which allowed the formation of the paleosurfaces. Especially during the Pliocene and the Pleistocene, during glacial periods, the region underwent very cold and dry conditions which favored denudation and wind erosion. This had a very marked geomorphological impact since deflation excavated sections of the nonfunctional fluvial channels, generating the characteristic Patagonian "bajos sin salida," endorheic depressions ("i" in Fig. 15). However, it should not be ruled out that at least some of the hollows are in fact relicts of the Late Jurassic etchplain, deeper portions of the weathering front denudated in the Tertiary, characterized by irregularities due to differential weathering based on different rock types or degree of fracturing.

Eolian abrasion features have been carved on the Marifil Formation outcrops as well as on isolated boulders such as corestones. These provide a good indicator of the morphodynamic impact of the wind during glacial epochs. These features may be generated only under intense and constant wind action associated with a large sand supply.

In summary, the Rhyolitic Plateau of the Marifil Formation in eastern Chubut province provides a perfect scenario to understand the deep chemical weathering environmental conditions under hyper-tropical climates in the Late Mesozoic, which produced an etchplain and a unique set of landforms at different scales on a Jurassic volcanic/pyroclastic complex. The chemical weathering of these rocks generated an enormous amount of regolith/saprolite which is related to the accumulation of kaolinite deposits and uranium secondary minerals of high economic interest. Future work in the region with detailed surveys in selected areas will undoubtedly provide a much clearer insight to understand the Gondwana paleolandscapes in Northern Patagonia.

Acknowledgments The authors are greatly indebted to Professor Cliff Ollier for his careful and most valued reviewing of a previous draft of this contribution. His comments and suggestions over the whole text and his personal discussion of some of the topics considered here are very much appreciated, as well as his colossal and indefatigable efforts to bring this manuscript into some sort of more readable English language.

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