Landscapes Developed on Ignimbrites

Emilia Y. Aguilera, Irene Hernando and Jorge Rabassa

Abstract This paper analyses the landforms and landscapes developed on ignimbrites outcropping in different regions of Argentina: Portezuelo (province of Mendoza), Lihuel Calel (province of La Pampa), Pilcaniyeu (province of Río Negro), Barda Colorada (province of Chubut) and Chon Aike (province of Santa Cruz). Some of these localities show clear resemblance to landforms which are typical of sedimentary rock landscapes, whereas others expose landforms typical of granitic rock landscapes. Systems of macro- and micro-landforms have been observed, such as inselbergs, bornhardts, nubbins, castle koppies, tors, crests and pinnacles, low cliffs, whale backs, and many other, associated minor features. Landforms of micro-modelling are shown at the base of vertical slopes, as cavities of the alveolar hollows and tafoni types, with subsequent evolution to caves, caverns and rock shelters. Besides, sometimes peculiar landforms such as yardangs, mushrooms and hoodoos are observed. The dominant agents that are responsible for these features are chemical and physical weathering and aeolian erosion. The micro-modelling affecting the different ignimbrite units is a direct consequence of their particular textural and structural conditions, on which a varied set of processes and erosion mechanisms have acted and defined their shape. In other cases, the orientation of the prevailing winds and the exposure of the ignimbrite flows have a decisive contribution to their genesis and ensuing development. It is herein concluded that the heterogeneity of these rocks, mostly due to changes in the welding degree, generates diverse types of macro- and micro-landforms.

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1 Introduction

The landforms and landscapes developed on ignimbrites have been described and studied in five different areas of Argentina, in the provinces of Mendoza (western Argentina) and La Pampa (central Argentina) and the provinces of Río Negro, Neuquén, Chubut and Santa Cruz, in Patagonia. The geomorphological criteria applied to the five study areas have taken into consideration the morphological types, geological structure, lithology and petrology in terms of fabric and texture, palaeoclimate and tectonic stability. The combined application of these concepts allows establishing the classification of the different environments in which they were formed and the dominant processes, as well as the landform types which have been generated.

From the lithological and petrologic point of view, the ignimbrite rocks are the product of explosive volcanic eruptions and their deposits are formed from pyroclastic flows. At a large scale, they may be considered as homogeneous bodies, but at more detailed scales, they exhibit significant heterogeneity which is a consequence of the depositional regimes within the pyroclastic flow. These rocks are composed of a matrix of glassy shards, crystalline clasts, lithoclasts and vitroclasts. Their emplacement at high temperatures is reflected in the degree of welding, designating as high-degree ignimbrites those which are densely welded and as low-grade ignimbrites those which are not so welded. Differential erosion is a characteristic of the different types of ignimbrites (Ollier 1988).

Concerning tectonic stability, planation surfaces are common in the landscapes developed in cratonic areas. Several erosion processes have acted upon them. The extensive and prolonged crustal stability of these cratonic massifs, in which the planation surfaces generated by deep chemical weathering are found, is the cause of the formation of very thick weathering mantles (or their remains), partially exposing the remnants of the weathering front.

It is very important to consider also palaeoclimates, because the climate changes that have taken place since the Mesozoic have produced important modifications in the landscapes that permit to recognize formation environments and acting processes.

Contrasting landscapes are distinguished in the studied outcrops, with landforms very similar to those described in the typical “granitic landscapes” (Aguilera et al. 2014), even those developed in sandstones (Bruthans et al. 2014).

Many of the micro-modelling landforms are developed in igneous and sedimentary rocks, commonly in sandstones, but rarely in conglomerates, gneisses and porphyritic rocks (Gutiérrez Elorza 2001). Of the five studied areas, three of them include very ancient, relict and partially exhumed landforms. Among the younger units, such as the Pilcaniyeu Ignimbrite (Middle to Late Miocene: Rabassa 1974, 1975, 1978a, b) and the "Tobas del Portezuelo" (Quaternary; Llambías 1966), similar landforms have also been described. In all cases, caves, taffoni and even yardangs have been carved over these ignimbrites.

The development of rocky arcs and natural bridges is conditioned by the combination of erosion processes, by "piping" or "tunnelling". In the genesis of yardangs, the aeolian erosion acts by means of high velocity winds blowing in a constant, permanent direction.

Although many landforms have been explained starting from sub-superficial etching processes, once these landforms have been exhumed, the differential weathering and erosion rates would have continued acting along existing fractures and specific places of less resistance in the bedrock.

2 Materials and Methods

The methodology applied consisted of field work at both regional and detailed scales, with the support of satellite imagery and aerial photographs, and the petrographic studies of thin sections in the different outcrops.

Appropriate zones were selected for grain size, clastic components, distribution, lithology, welding degree and small-scale structures. Systematic identification of flow units was completed, including different welding facies and areal distribution of the ignimbrite components.

Likewise, landforms were recognized related to the fabric and jointing of the ignimbrites.

3 Location and Description of the Study Areas

The various studied areas are five, distributed in ample regions of western and southern Argentina (Fig. 1):

(a) The Payunia volcanic district, between 36°–37°S and 68°30′–70°W. The Portezuelo de los Payunes is located near the town of Malargüe, province of Mendoza, Argentina, where the yardang landscape developed over the Portezuelo Ignimbrite has been described.
(b) The Sierra de Lihuel Calel, 38°00′S, 65°36′W, province of La Pampa, Argentina, occupies approximately 40 km2 and stands as a giant inselberg above the surrounding planation surfaces, with a maximum elevation of 590 m a.s.l.
(c) The volcanic–pyroclastic complex of the middle Río Chubut valley is located in the province of Chubut, Argentina, between the localities of Paso del Sapo and Piedra Parada (69°47′–70°32′W and 42°13′–43°00′S).
(d) The Deseado Massif, north-eastern Santa Cruz Province, Argentina, is a morphostructural unit where the pyroclastic–volcanic complex of the Bahía Laura Group is located. This group is composed of the Chon Aike and La Matilde

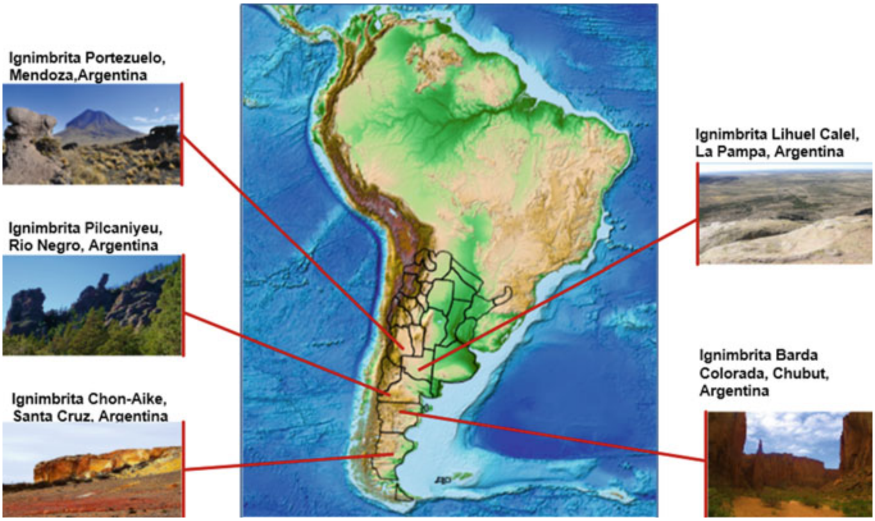

Fig. 1 Location map

formations, both merging laterally. These units are widely distributed in the Massif, and most of the observations were made in its central and eastern portions.

(e) In western Río Negro Province, Argentina, the region between the Río Pichileufu and the town of Comallo, at the western edge of the Northern Patagonian Massif, where the Pilcaniyeu Ignimbrite has been studied.

3.1 The Portezuelo Ignimbrite

The Payunia volcanic district is a volcanic region covering more than 25,000 km^2, located in the province of Mendoza, Argentina, at the foot of the Andean ranges. The building up of the Payún Matrú volcanic complex was initiated in the Early Pleistocene. The evolution of these volcanic vents extends up to the Pleistocene–Holocene boundary, with pyroclastic flow deposits and trachyte layers interbedded with basaltic lava flows. Since the Pleistocene until Holocene, pre-historic times, the region has been a subject of extensional events, generating enormous volumes of volcanic products which are located in a retro-arc position with respect to the presently active arc (Bermúdez and Delpino 1989).

The landscape is characterized by volcanic landforms of huge dimensions, such as the El Nevado, Payún Matrú, Payún Liso and Chachahuen volcanoes, which are composed of alternating explosive and lava flow eruptions. Small and numerous volcanic cones, lava flows with a great diversity of landforms, cinder flows, volcanic bomb fields and pumice rocks are identified. In the Payunia volcanic district, the El Nevado, Payún Matrú and Payún Liso volcanoes have generated explosive eruptions with a scale of super-eruptions (Llambías 2009). The Payún Matrú volcano is a composed shield volcano with an 8-km-diameter caldera at its summit. The ignimbrites related with the caldera formation cover a surface of approximately 4000 km2, whose mantles have variable thicknesses related to the topography that has been buried, and they may be followed up to 30 km away from the eruptive vent. These ignimbrites have been given different names such as “Tobas de explosión” (Groeber 1937), “Tobas del Portezuelo” (Llambías 1966), El Portezuelo Formation (González Díaz 1972) and Portezuelo Ignimbrite (Hernando 2012). The name corresponds to the extensive outcrops found at Portezuelo de los Payunes, that is, the area between the Payún Matru and the Payún Liso volcanoes. These pyroclastic deposits are related with the formation of the Payún Matrú caldera (Groeber 1937; Llambías 1966). Hernando (2012) obtained radiometric dates on pre- and post-caldera lavas, pointing out that the explosive eruption took place in the Late Pleistocene, between 148 and 82 ka. He also noted the impossibility of dating the Portezuelo Ignimbrite.

The ignimbrite mantles are deposits formed from pyroclastic flows, which at a large scale are considered as homogeneous bodies. However, at detailed scale, these rocks present a certain heterogeneity, as a consequence of different depositional regimes within the same pyroclastic flow.

The Portezuelo Ignimbrite is in general described as poorly welded, although it presents local variations in the welding degree, which depict a behaviour ranging from coherent rocks to mostly friable sediments, in different sectors. Hernando (2012), due to the frequent lateral and vertical changes detected, performed a differentiation of a facies series in this ignimbrite formation. In the study area, only two of these facies have been recognized.

3.1.1 Lithological Description of the Studied Section at the Portezuelo

At the lower portion of the section, a massive ignimbrite is found, with pinkish and reddish colours, pumice fragments without a substantial compaction, with crystals of feldspars, biotite, clinopyroxene and olivine and angular lithic fragments of a variety of volcanic rocks, though those of trachytic–trachyandesitic types are dominant. These trachytic facies are the most common, occupy a larger surface and integrate most of the section. In the upper portion of the profile, a massive, pinkish-reddish ignimbrite is found, highly rich in matrix, with scarce pumice fragments of up to 2 mm long. It also includes crystals of feldspars, biotite, clinopyroxene and olivine, and rare volcanic lithoclasts of 1–2 mm in diameter.

3.1.2 Yardangs

Yardangs are elongated, keel-like mounds, showing grooves and unstable sides. Their shape resembles an inverted boat, although some yardangs have instead a flat top. These features may occur in a wide variety of lithological types (Goudie 1989, 2004). The outcrops of the Portezuelo Ignimbrite are eroded by the wind, forming yardangs of a depth of 3–6 m. In these sections, these two facies may be observed, in a neat, straight contact. These landforms were described by Llambías (1966) and Inbar and Risso (2001).

At a regional level, morphology of sand-covered crests and corridors or depressions is distinguished. In some areas, the amount of accumulated sand is so large that it gradually buried the yardangs. As it may be observed in the satellite imagery, they are thin, elongated landforms, of great areal extension which integrate large yardang fields, where the landforms occur aligned due to the dominant wind abrasion (Fig. 2a–c).

At the Portezuelo de los Payunes, the area comprised between the Payún Matrú and the Payún Liso volcanoes, the appropriate topographic conditions are met to produce the channelization of the strong, dominant winds, with a prevailing WNW-ESE direction. The intensive wind action, loaded with sand particles, impacts upon the ignimbrite sheets, deeply modelling them (Fig. 3). Their size varies between 30 and 120 m in length, and they are up to 2–6 m tall.

Yardangs are carved as elongated grooves, separated by vertical walls. In the upper part, the roof is slightly expanded as rock shelters. In addition to the observation of the neat contact between the two recognized facies of the Portezuelo Ignimbrite, the abrasion power of the wind is noted in the lower facies up to an elevation of 1.80–4.0 m, where the exposed surface has frequent rills, channels, tafoni and micro-yardangs. Contrarily, the upper portion occurs as a massive and polished surface (Fig. 4). This unit is dissected by vertical joints, which are related to the cooling conditions of the individual pyroclastic flows.

Some yardangs expose a flat top, and the groovy channel previously described is modified by strangling and thinning in certain levels of the profile, thus acquiring a more rounded morphology with tendency to mushroom shapes (Fig. 5).

The differential response of the two facies of the Portezuelo Ignimbrite to aeolian erosion may be due to the relative abundance of pumice fragments and sub-angular lithoclasts in the lower section, which is more profoundly affected by erosion. These fragments do not show intense compaction. These components are easily degraded out of the friable and scarce matrix, leaving hollows which are expanded by abrasion and deflation, thus favouring the mobilization of the eroded clasts and their subsequent removal. The upper portion of the unit is more resistant to wind erosion. This part is differentiated from the lower section because it has a greater proportion of matrix and a lower content of pumice fragments and lithoclasts, which are smaller and rarer, characteristics that confer it a much higher toughness. As most of the particles are deflated up to a certain elevation above the soil surface, the more intense erosion action takes place at the basal portion of the flow, thus originating thinner landforms at the base and more exposed ones in the upper zone.

Aeolian erosion is favoured by the scarce vegetation cover and the general aridity of the zone. Although precipitation is not frequent, they may be very intense in time and of a torrential nature, providing great erosion capacity to running

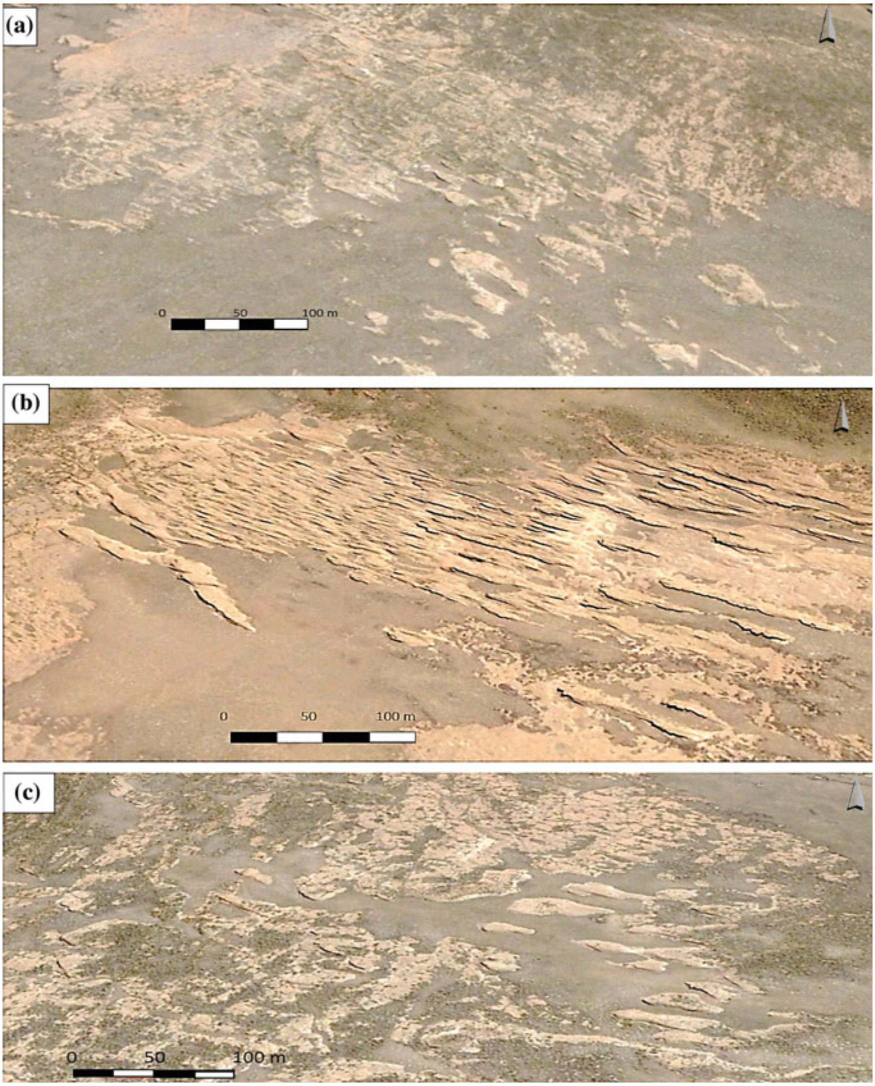

Fig. 2 Views at a regional scale of the yardang field at Portezuelo de los Payunes, province of Mendoza. Google Earth image. **a** Sand-covered crest and corridor morphology is observed. **b** Note the prevailing orientation of the landforms as WNW-ESE. The projected shadows suggest a positive relief. **c** Sand deposits gradually cover the yardang field

waters. The joints cutting the yardangs produce water migration with the development of rills and small channels in those surfaces which lack vegetation.

Another intervening process, though of lesser proportions and totally subordinated to aeolian action, is the physical weathering, which may be exposed as a

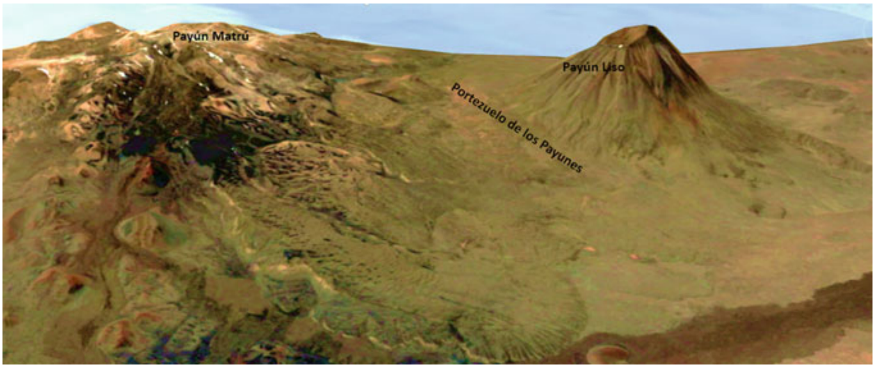

Fig. 3 3D view of the Portezuelo de los Payunes. The yardang field extends at the pass in between both volcanoes

Fig. 4 Yardangs carved as elongated channels, bounded by vertical walls. Micro-yardangs have developed along the lateral wall. At the background, one person for scale. At the foreground, a fracture with snow and ice

cryoclastic product and may be observed as wedges in which freezing water exerts powerful pressure.

It is possible that the natural wind tunnel generated at Portezuelo de los Payunes facilitates and magnifies the debris-loaded, wind erosion activity. Wind produces corrosion or abrasion on the ignimbrite surfaces, as they are permanently hammered by the coarser particles (normally, middle to coarse sands) which the wind transports, grabbing the angular clasts and excavating the surface, generating bowls, furrows and grooves, which are progressively enlarged by the constant, endless erosion of wind action (Fig. 6).

Generally, the coarser particles move by saltation between 0.45 and 1.00 m above the soil surface. However, favoured by the local topography at Portezuelo de los Payunes, the maximum elevation of the trajectory of the particles would have

Fig. 5 Flat topped yardangs near the Volcán Payén Liso. A strangled level that reflects a faster erosion rate

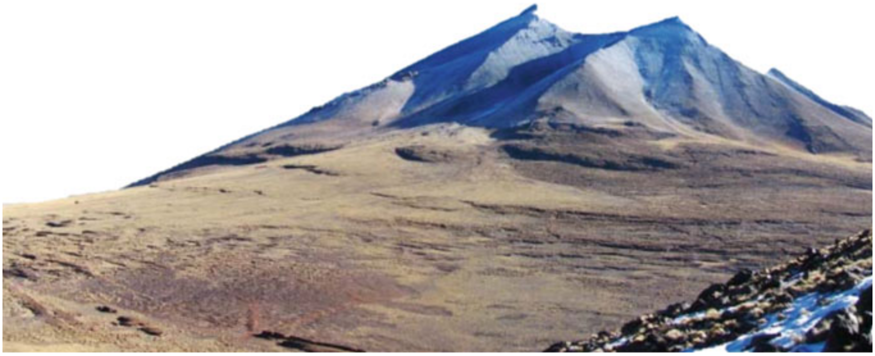

Fig. 6 Portezuelo de los Payunes: at the foreground, aligned yardangs are observed, following the prevailing wind direction

necessarily been of at least 2 m and even more. That is, the aeolian flux would have been greater than usual, as suggested by the yardang dimensions (Figs. 7, 8, 9 and 10). Additionally, as the wind velocity increased and generated ascending turbulence, exfoliation and particle releasing from the base of the landforms upwards, these landforms show evidence of progressive dismantling. Towards the roof of the landforms, a flux of finer materials (silt and clays) would have acted, thus producing polished surfaces, although in this portion the ignimbrite is more agglutinated and coherent, lacking large sized pumice fragments and lithoclasts which could be extracted by abrasion. It is undisputable that velocity and turbulence of the aeolian agent was more intense at the base than in the roof, but heavier particles would have acted at lower elevations because the wind was unable to rise them further up, and they were transported close to the ground by rolling. In this way, additional

Fig. 7 Falt topped yardangs with rock shelters limited by fractures

Fig. 8 Yardangs of large dimensions and varying height; a person for scale

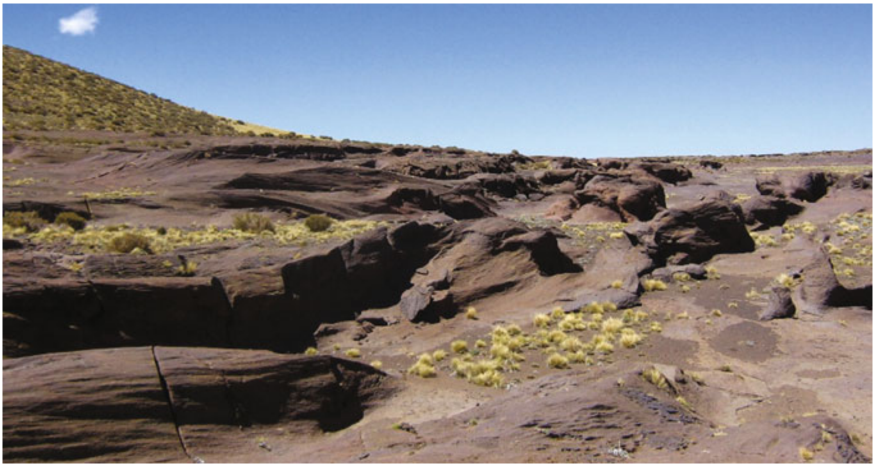

Fig. 9 Keel roofed yardangs, transversally cut by fractures

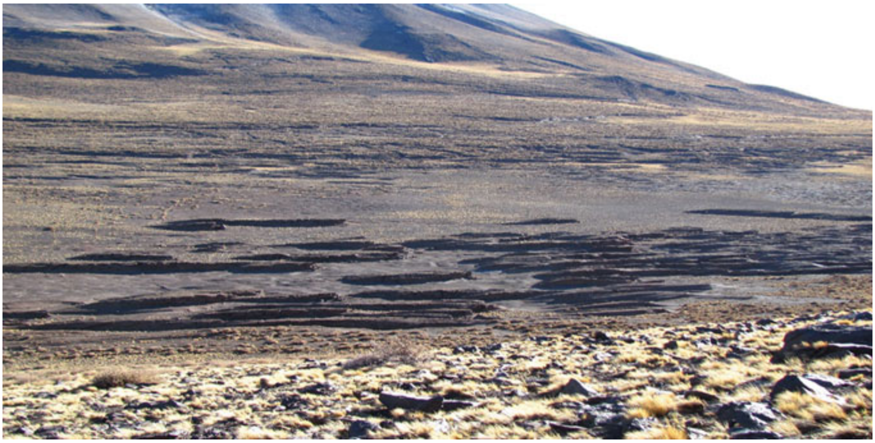

Fig. 10 Panoramic view of the yardang field at the base of the Volcán Payén Liso

erosional effects were generated due to impacts between clasts and the interaction of wind-blown particles driven by saltation.

Based upon the radiometric dating of the Payún Matrú eruptions, it is assumed that this landscape has a post-Late Pleistocene age. Concerning the concept of landscape genesis and evolution, the resulting landforms reveal that the dominant modelling process has been aeolian erosion, indicating that these are simple landscapes. From a morphoclimatic point of view, no relevant climate oscillations have taken place since their formation. Due to the fact that these landforms have been modelled by a unique morphogenetic system, this is a monogenetic landscape.

3.2 The Barda Colorada Ignimbrite

The volcanic–pyroclastic complex of the middle valley of the Río Chubut (province of Chubut; Aragón and Mazzoni 1997) developed over igneous and metamorphic rocks ranging in age from the Proterozoic to the Late Palaeozoic and volcanic and sedimentary rocks emplaced between the Jurassic and the Early Tertiary (Maastrichtian-Danian). Their more important deposits correspond to ignimbrite and lava flows, domes and smaller sub-volcanic intrusive bodies, ash falls and reworked pyroclastic rocks, which are related to igneous activity of a great caldera of about 25 km in diameter and two stratovolcanoes of lesser size, located on the northern and southern flanks of the caldera. The magmatic activity, essentially of acidic composition, was developed between the Palaeocene and the Middle Eocene (Aragón and Mazzoni 1997).

The deposits of pyroclastic flows erupted from the outburst of the Piedra Parada Caldera, in the middle valley of the Río Chubut, are distributed in an area of

Fig. 11 Volcanic landscape in the Piedra Parada region, province of Chubut. At the foreground, the ignimbrite plateau; at the background, the Río Chubut and the Piedra Parada inselberg within the valley of such name

200 km3 and comprise an extensive plateau of rhyolitic ignimbrites recognized as the Barda Colorada Ignimbrite Formation—BCIF—(Aragón and Mazzoni 1997; Fig. 11). Mazzoni et al. (1989) recognized in the BCIF two varieties which were informally named as Lower Member and Upper Member. The Lower Member of the BCIF is of light yellowish, tuffaceous nature, with abundant lithoclasts and rounded pumice pebbles, whose size reach up to 10 cm in diameter. This unit is slightly welded, and both pumice fragments and lithoclasts are easily separated from the tuff mass. In some areas, the unit exceeds 80 m in thickness. The Upper Member of the BCIF has yellowish to brownish colour, dark "fiammes" and blackish vitrophyric colour. The more important feature of this unit is the abundance of lithoclasts and the high degree of welding.

In most cases, the exposures of the Lower Member of the BCIF are discontinuous and incomplete, due to their highly friable character, whereas the Upper Member of the formation forms structural terraces, among other features, due to its higher resistance to erosion. These deposits are characterized by different degrees of welding, from welded to highly welded, with abundance of pumice fragments and lithoclasts.

Due to the marked differences pointed out for both members, it should be noted that each member presents particular heterogeneity concerning fabric and structures. This anisotropy plays an important role concerning the erosion processes involved and the relief modelling. The fabric of the ignimbrites, with more welded zones in contact with other lesser welded ones, levels with abundant pumice fragments and lithoclasts, contacts between different cooling units, interbedded conglomerate layers, etc., and the structural characteristics, such as joints, fractures and pseudo-stratification planar surfaces, set conditions for their massive behaviour against the morphogenetic agent action.

3.2.1 Landforms

At the regional level, the ignimbrite flows buried the previous landscape, levelled the topography, and the pre-existing fluvial valleys were fully drowned by the pyroclastic deposits (Figs. 12 and 13). Once the ignimbrite plateau was formed, new drainage networks developed, with channels which were partially different compared to the pre-existing ones. One of the more relevant effects of the coalescent pyroclastic flows forming the plateau was the change in the hydrological conditions of this region.

In general, the BCIF is situated at high elevations, around 1000 m a.s.l. Field observations performed in several localities of the plateau show that the Upper Member of the Barda Colorada Formation has columnar jointing. In these vertical cliffs, the processes of physical weathering are quite active. Weakness surfaces are developed in preferential directions, marked by the jointing. When the fractures are widened, the cliffs are affected by breaking up processes that produce collapsing and dislodging of hexagonal columns (Fig. 14) leaving new fronts with walls very close to vertical positions. Through this process, an important reduction in the relief starts, due to erosion and gravitational slumping. These erosion processes have developed an irregular landscape, dissected by deep, narrow and elongated gullies, with predominant straight channels, such as the La Buitrera, El Loro and La Horqueta canyons.

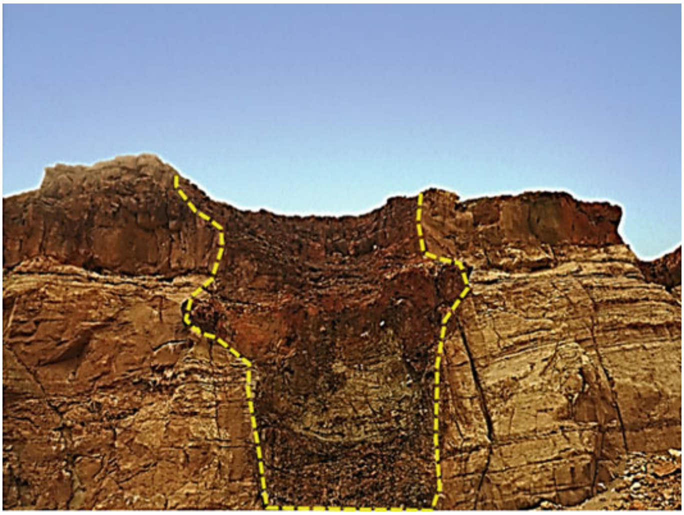

Fig. 12 Ignimbrite in-filling a fluvial valley, depicted in *yellow*

Fig. 13 Ignimbrite deposit burying a Cretaceous landscape

3.2.2 Arches, Rock Bridges, Tunnels and Corridors

Thick layers of welded ignimbrites are overlying lesser welded beds, being the latter eroded faster. This anisotropy contributes to make unstable the structure and the hard rock layers preserve their continuity, whereas the more friable strata are more easily eroded and mobilized by running water generated by high energy, intermittent rain storms.

In the rock wall fronts, at more vulnerable points, depressions generate which become deeper, forming hollows, bowls, caves, caverns and tunnels, sided by columnar structures, from which other galleries depart (Fig. 14). Due to the fracture network and in the interception of surface planes of different cooling units and cracks, water penetrates to sub-superficial levels, eroding and excavating the ground, generating tunnels and corridors, producing slumping and developing rock cliffs. The channelization of sporadic water currents at the base of the tunnels and corridors contributes to their deepening, weathering the rocks and transporting the altered and loosened materials (Fig. 15).

Concerning its morphogenesis, this landform could be explained by the process of “tunnelling” or “piping”, due to the development of a selective, sub-superficial drainage in friable materials such as these volcanoclastic rocks, whose components are mobilized in suspension with the hydrological flow.

Although the ignimbrites of the Upper Member are highly welded and tenacious, they are cut by plentiful cracks and fractures. These fractures represent weakness zones which are occupied by rainwater or even snow and ice. This structural feature affects its behaviour related to the action of the same morphogenetic process, where the nature and position of these materials play an important role in their modelling.

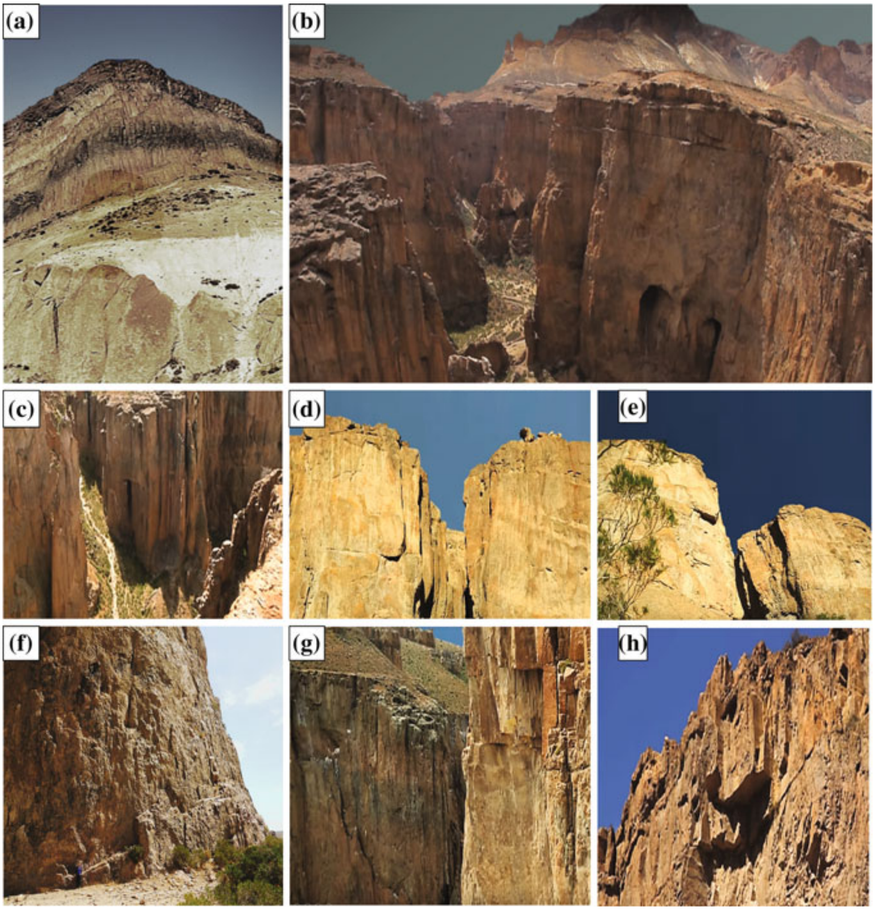

Fig. 14 Different views of columnar and pseudo-columnar structures in the Upper Member of the Barda Colorada Ignimbrite, with erosional features in vertical walls. **a** Hexagonal jointing in the upper part and the tuff-like, friable, Lower Member at the base. **b** Columnar fracturing, slumping and sliding that started at the roof. **c** Talus whose angles are close to a vertical position. **d** and **e** Massive aspect zone, with horizontal fractures that bound blocks. **f** Massive aspect zone with horizontal and oblique jointing; a person for scale. **g** and **h** Orthogonal fractures that favour the weathering processes

Another primary features in the structure of the ignimbrites are the pipes or degasification tubes which are the product of escaping gas during cooling. They represent a discontinuity in the outcrop whose dimensions make progress due to differential erosion, favouring tunnelling and piping processes.

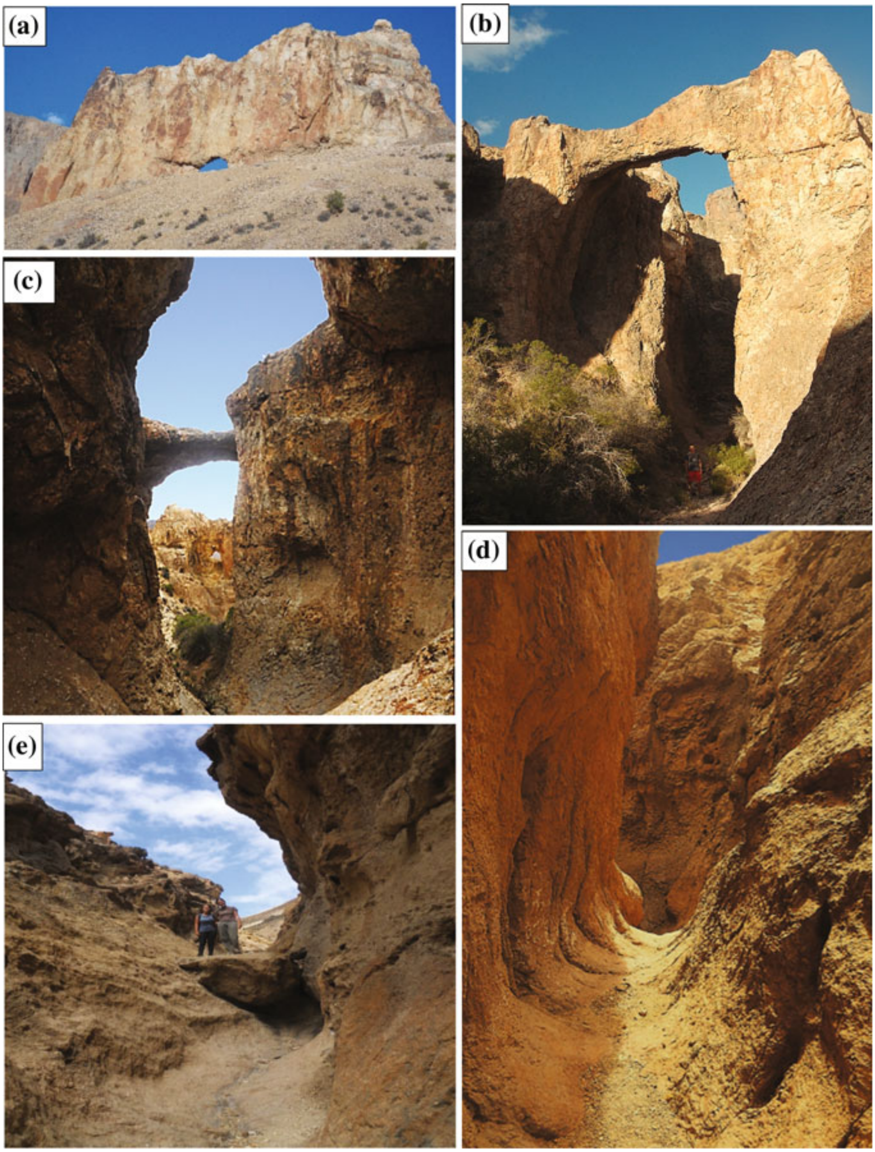

Fig. 15 Arches, rock bridges, tunnels and corridors. **a** Rocky front with generation of caves. **b** Rock arch flanked by columnar structures known as “pillars”. **c** Evolution of a rocky front into hollows, chambers and galleries flanked by columnar structures, from which subsequent galleries start. **d** Corridors generated by erosion and bedrock carving. **e** Tunnel with channelization of ephemeral streams in down-cutting processes, abraded and altered materials

3.2.3 Demoiselles and Badlands

In certain sectors, erosion landforms of slightly conical shape known as “demoiselles” are found, in which the tallness is clearly dominant with respect to the width (Fig. 16). These are elongated landforms with vertical flanks and, seldom, a more resistant level at the top befalls, perhaps due to stronger welding that resembles a hat (“demoiselles coiffées”; Godefroy 1940) (Fig. 17). These landforms are usually not isolated but forming groups instead. An orthogonal jointing is typically developed. These joint sets facilitate the erosional incision due to the channelling of the rainwater with the development of very steep slopes. These landforms may be observed at Cañadón de la Buitrera, in levels of the Upper Member of the BCIF. An important factor in the erosion process is that even though the environment has semiarid characteristics, the scarce rain events may reach prodigious intensity.

At the Lower Member of the BCIF, slopes with dissection modelling at the metric scale may be observed, in the shape of gorges, gullies and rills. By means of sub-superficial erosion, ravine-concentrated rainwater excavates the surface and drags materials developing a “badland” landscape, with tunnelling and piping as dominant processes. A very friable ignimbrite, with abundant clayey materials due to weathering of the primary minerals (basically feldspars and volcanic glass

Fig. 16 “Demoiselles”: erosion landforms of a roughly defined cone shape morphology, where the height is significantly prevailing with respect to the width. The contact between cooling units is depicted by tafoni and caves

Fig. 17 At the foreground, slender forms with vertical flanks. At the top, a more resistant level, resembling a hat, is observed ("demoiselles coiffées")

shards), correlates with this landscape. These features may be observed at the sites of Cañadón del Loro and the Barda de los Perros.

3.2.4 Smaller Scale Features

These smaller size features are the product of a set of erosion processes that lead to the granular disintegration of the rocks. Such micro-modelling landforms are exposed in vertical walls, forming holes and hollows such as alveolar cavities and tafoni, later evolving to caves, caverns and rock shelters.

3.2.5 Alveolar Cavities, Tafoni, Caves, Caverns and Rock Shelters

These minor landforms are localized in vertical and sub-vertical joints associated with oblique orthogonal, joint networks. Coincidently, in the areas with alveolar hollows, the rocks present a blackish to dark reddish colour, compatible with the presence of desert varnish generated by Fe and Mn precipitation.

Layers marked by pseudo-stratification seen in vertical walls exist, where sub-circular cavities with sizes between centimetres to metres in diameter dominate. It may be observed that these landforms are started in an isolated distribution, but they coalesce during growth and form larger size cavities. These cavities are located at the base of the vertical walls and along the pseudo-stratification layers, where textural and structural changes are found (Fig. 18). They may be due to

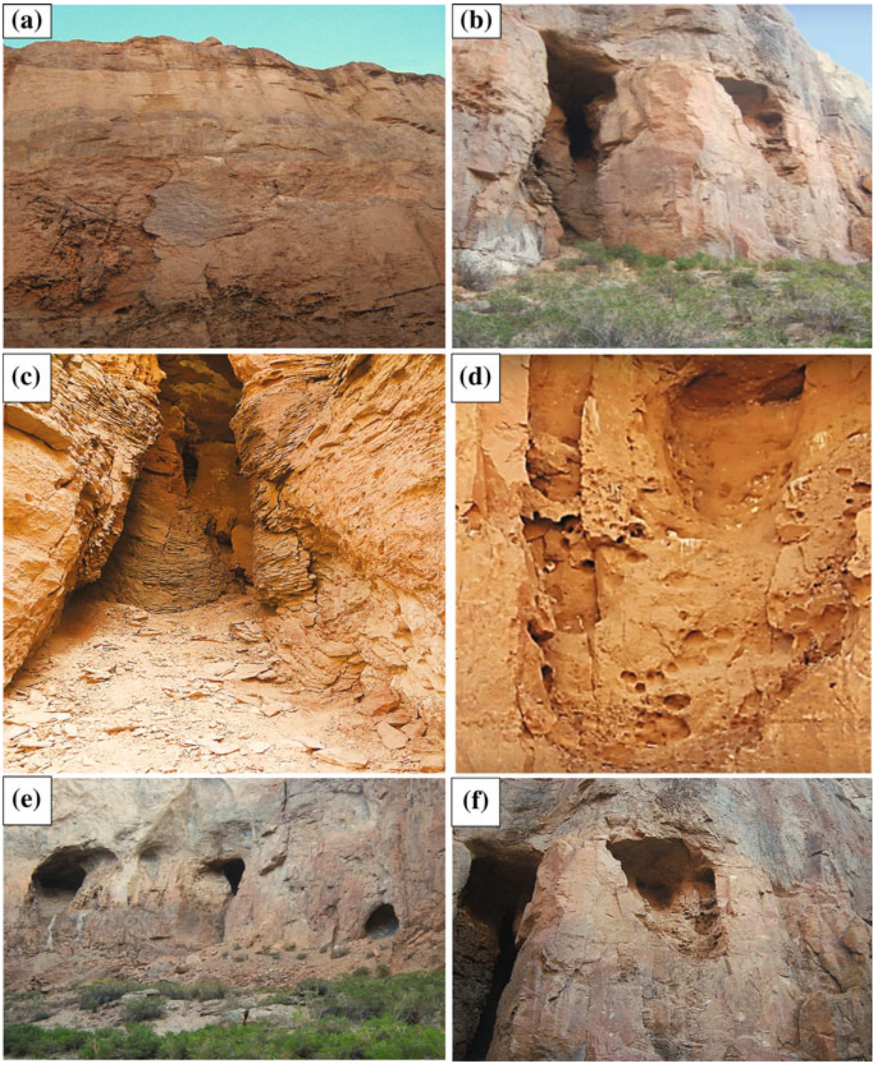

Fig. 18 Alveolar hollows, tafoni, caves, caverns and rock shelters. **a** Alveolar hollows and tafoni in vertical walls, associated with joints and descaling processes. **b** and **c** A cave developed from degassing tubes which make progress in size due to differential erosion. **d** Vertical rock wall with development of tafoni and tunnels. **e** and **f** Lenses of poorer welding degree, bearing tafoni and caves, are depicted

heterogeneous welding, levels of abundant pumice fragments and lithoclasts, convergence of joint planes or, simply, joint surfaces. These cavities evolve into caves at the Cañadón de la Buitrera, where cavern levels may be followed along discontinuity zones representing the contact between two pyroclastic flows.

3.2.6 Remarks

The igneous activity of this volcanic complex ended in the Middle Eocene, covering a Cretaceous planation surface. Since then, these units remained exposed and the modelling of these deposits started (Aguilera et al. 2010).

This morphogenetic processes, in which chemical weathering has had a dominant role compared to other external morphogenetic agents, would represent the first cycle of this landscape formation, favoured by contrasting climatic scenarios from temperate/warm, sub-humid seasonal climate. Starting in the Late Eocene, these scenarios were related to a warm/humid event towards the end of the Palaeocene and the beginning of the Eocene. Towards the end of the Eocene, the climatic conditions became temperate and dry, as a consequence of the global cooling that took place at the Eocene–Oligocene boundary. This cooler event culminated in the Late Oligocene with a warm/temperate, sub-humid seasonal climate (the Late Oligocene warming event), with permanent, meandering streams. Although during the Miocene a warm/humid event also occurs, related to the Middle Miocene climatic optimum, likewise indicating a global warming period.

The preponderance of warmer and wetter conditions favoured deep chemical weathering, with the development of weathering mantles that were later denudated and mobilized. Finally, the weathering front became exposed. Later on, during the Quaternary, another cycle under drier climate evolved, with episodic, fast run-off and aeolian action. The weathering front remained exposed to other morphogenetic agents, with the capacity of obtaining and transporting materials, thus contributing, directly or indirectly, to the creation and evolution of new landforms. Deflation became the dominant process, caused by the powerful, permanent winds, responsible for the detaching, flaking, uplifting and subsequent elimination of the finer sediments.

From the morphoclimatic point of view, this could be considered a polygenetic landscape, depicting features of different morphogenetic systems, each with its characteristics landforms.

3.3 Sierra de Lihuel Calel

The Sierra de Lihuel Calel, located at around 38°00′S and 65°36′W, covers approximately 40 km2, and it rises as a giant inselberg from a surrounding planation surface, with maximum elevation at 590 m a.s.l. It is composed of a sequence of rhyolitic ignimbrites (Llambías 1975; Sruoga and Llambías 1992) which are part of an extensive rhyolitic plateau of Permian–Early Triassic age (Llambías and Leveratto 1975). The bedrock basement on which the ignimbrites are lying on is composed of igneous/metamorphic units of Late Proterozoic to Early Palaeozoic age (Linares et al. 1980; Tickyj et al. 1999; Sato et al. 2000).

The thickness of the Sierra de Lihuel Calel ignimbrites exceeds over 950 m, with no base or top identified. Beds are inclined towards the WNW, as part of a

Fig. 19 N-S view of the Sierra de Lihuel Calel, where beds with homocline dipping towards the WNW are shown

homocline structure, with values close to 25° in the basal levels and values closer to 15° in the coarse stratification noticed in the upper layers (Fig. 19). The sequence is composed of two cooling units, both of them of rhyolitic composition: the lowermost unit, 440 m thick, and the upper one, more than 450 m thick (Sruoga and Llambías 1992). The lower unit is composed of highly welded rhyolitic ignimbrites, partly vitrophyric or with spherulitic crystallization, with participation of volcanic breccias. The upper cooling unit is separated from the lowest one by a relatively thin cooling unit of 50 m in thickness, composed of a highly welded dacitic ignimbrite. Certain levels of the ignimbrites at Lihuel Calel were affected by marked recrystallization, being transformed in rocks of apparent porphyritic texture with micro-grained groundmass, due to the high proportion of gas components and to the slowness of the cooling during the welding of the glass shards (Llambías 1973). The age of the Lihuel Calel ignimbrites has been established by means of Rb-Sr isochrones in 238 ± 5 Ma (Linares et al. 1980) and 240 ± 2 (Rapela et al. 1996). After the intense volcanism of the Permian and Triassic periods, no more magmatic activity took place in the region and the accumulated ignimbrites were never buried again.

3.3.1 The Lihuel Calel Ignimbrite

The modelling of the more massive rocks of this unit exposes fractures by sheet development or by intersection of orthogonal joints. Both types of fractures are recognized in the Sierra de Lihuel Calel where the layering modelled the landscape basically in dome landforms. The best example is the Sierra de Lihuel Calel itself that rises from the surrounding plain as an enormous inselberg, that is, a large dimension dome. This “mega-inselberg” would be the product of the denudation of the weathering profiles, developed since the Triassic in humid, tropical climate conditions, followed by the denudation of the weathered products in these profiles and the subsequent exhumation of an ancient etchplain.

The mega-inselberg of the Sierra de Lihuel Calel is recognized for several topographic steps, defined by the differential resistance to erosion of the ignimbrite flows. In the analysed levels, step-like slopes with landforms assigned to granitic landscapes are noted (Aguilera et al. 2014), as well as slopes resulting from the pseudo-stratification depicted by several ignimbrite layers. The Sierra de Lihuel Calel has a N-S orientation, and its outcrops show a WNW-ESE orientation, with gorges and rocky valleys similarly oriented.

A large plain develops surrounding the rock elevations, whose pediments are differentiated by a reduced areal extent compared to the regional plain. They are generally covered by regolith, thus receiving the name of "regolith pediments". Towards the east, the regolith got to lower elevations, following the regional slope, and the landscape became monotonous. This is a planation surface or erosion surface, in the sense of Ollier (1991).

The types of inselbergs recognized here are denuded domes (bornhardts) and by evolution of some of them other residual landforms occur, such as "nubbins", "castle koppies", "boulders" and "tors" (Figs. 20, 21 and 22). These landforms and other smaller ones have a sub-superficial origin and are usually developed at the weathering front (Mabbutt 1961).

Fig. 20 Very degraded domes with orthogonal fractures and varied dissection degree, with stepped and convex slopes

Fig. 21 Dome landforms of the "whale back" type, with curved jointing and partially degraded to nubbins and a diversity of smaller forms

In the stratigraphic profile of the Sierra de Lihuel Calel, several units are recognized, such as rhyolitic flows, glassy layers and ignimbrite flows with varied degree of welding, which become zones more or less favourable for erosion. In addition to the lithological differences, it should be noted the important role that the joint systems play, acting as weakness planes. Following them, corridors of higher moisture content are excavated, where the weathering processes generate convex landforms, with down-wasting of sides and corners.

In the middle and upper sections of the lower cooling unit, these rocks have a similar behaviour to granitic rocks. These are massive rocks which do not preserve

Fig. 22 Curved jointing in dome shapes, associated with a vertical system with progressive development of nubbins of different scales and convex slopes

primary textures and, not without difficulties, the contacts between the different flow units may be identified. Structural and textural changes have modified the properties of the rocks, increasing their resistance to erosion, thus developing a sort of “granitic landscape”, as it can be seen in the Cerro de la Sociedad Científica. The same landscape develops in the upper cooling unit, in the Valle de las Pinturas, where rock art in caves and rock shelters are plentiful, with alveolar hollows and tafoni as secondary components.

Panoramic views of the mountain ranges show their convex slopes, highlighted by the dipping layers of the ignimbrite. Run-off takes place under surficial flow conditions, with the formation of rills and creeks following smaller topographic irregularities. The morphology of the slopes is conditioned by the spacing of the joint systems. In some sectors with large spacing, the landscape resolves in stepped profiles (Fig. 20). Contrarily, when the jointing is closer, the morphology of the slopes is much more gentle.

Different sectors of the weathering front have been recognized in relation to the landforms present. The zone with a larger depth of the weathering front, the Valle de las Pinturas (Arroyo de las Sierras), is revealed with landforms that preserve the orthogonal jointing sets, with blocks in which it is still possible to identify corners, edges and sides. The orthogonal jointing bounds landforms of the castle koppies type (castle-like forms) (Fig. 22).

The uppermost levels, recognized in other sectors of the range, show landforms such as boulders, tors and nubbins, in the area of the Cerro de la Sociedad Científica. Landforms such as the whaleback type predominate, limited by horizontal fracturing of ample curvature radius, which is also depicted by the convexity of slopes and hills (Fig. 22). In this succession of layers of different resistance to erosion along the main slopes, a series of steps is seen, a product of differential erosion.

The landforms of the granitic landscape have been classified according to the criteria exposed by Twidale (1982), Vidal Romaní and Twidale (1998) and Migoń (2006).

It is clear that the weathering and dismantling of the regolith has been incomplete. The landscape is characterized by flat sections interrupted by block accumulations, outcrops, nubbins and castle koppies. The regolith is preserved in the lowest areas, where residual nuclei outcrop (Fig. 23). In those sectors where the sierras preserve pseudo-stratification, due to the disposition in thick strata of

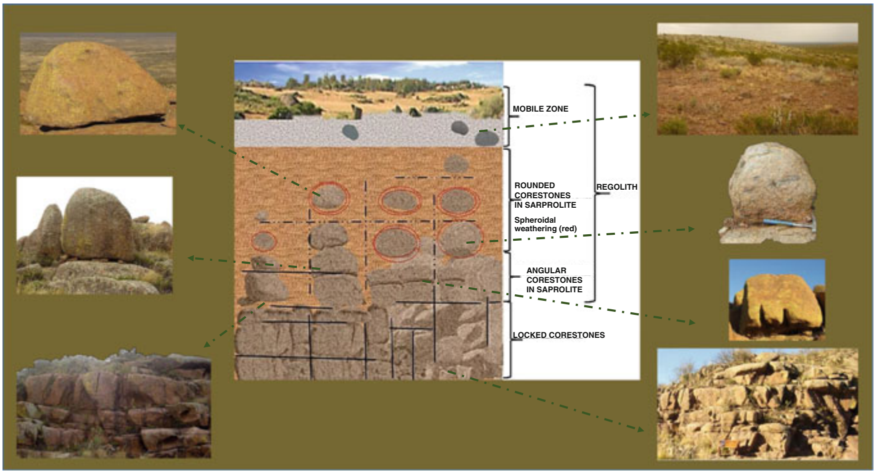

Fig. 23 Analogy between the granite landforms identified in the Lihuel Calel Ignimbrite with the typical weathering profile in granites, where the joint systems and the weathering processes generate this characteristic landscape (based upon ideas and a diagram by Ollier 1991).

the ignimbrite, and the spacing of the jointing is closer, the slopes are very gentle. Likewise, the homocline inclination of the flows generates such landforms as “mesas” or “cuestas”.

At a larger, detailed scale, the horizontal jointing is dominant with respect to the vertical one. The basal undercutting process is active where the running water erodes the slope and it weathers the bedrock, developing shelters, alveolar hollows, tafoni and gnammas. The alveolar hollows are rounded or ellipsoidal holes of centimetre size. They have developed in surfaces of medium to strong inclination (Fig. 24). Tafoni are hollows of larger size than the alveolar depressions, and they may get up to cave size. They may occur grouped with circular or elliptical geometry, and some of them with the bottom covered by debris. In some occasions, they occur oriented according to weakness planes of the ignimbrite mantles (usually, boundaries between flow units), and generally in vertical slopes (Fig. 25). The blocks or rounded boulders occur in tors, where the horizontal jointing is dominant. Blocks may preserve equilibrium position on a pedestal. On the slopes of Cerro de la Sociedad Científica, many boulders and blocks are found.

Gnammas are weathering closed depressions, which are developed on horizontal or semi-horizontal surfaces. Their size is in the order of metres. Their shapes are

Fig. 24 Alveolar hollows, reaching 50 cm in diameter. They have been developed in sheltered surfaces

Fig. 25 Tafoni somewhat larger than the alveolar hollows, oriented according to weakness planes in vertical walls of the ignimbrite sheets

circular and elliptical, and in some of them, a spillway channel may be observed or they may occur as forming sequences or chains of depressions (Fig. 26). In the landscape of the Sierra de Lihuel Calel, all types of gnammas have been recognized following the ordering provided by Twidale and Corbin (1963), who classified them according to their transversal section: gnammas in rock bottoms or pits, basin gnammas, and armchair-shaped gnammas. Descaling and scraping is generalized elsewhere, as granular disintegration and lichen colonization take place.

The study of Cerro Cortado shows that, in its slopes, the upper portion is slightly convex to flat, where highly welded ignimbrite beds form as bench that is receding due to different erosion processes. The materials that are removed from the crest are removed by hydrological erosion towards the debris slope, until they reach the pediment, which merges with the plain. The slopes depict a concave profile (Fig. 27). In these sectors, the rocks do not achieve the development of a "granitic landscape".

Fig. 26 Gnammas: closed depressions in horizontal surfaces or gently inclined

Fig. 27 Cerro Cortado: primary structures of the ignimbrite flows, with the development of crests, cuestas and debris slopes, are shown. Concave slope merging the pediment with the plains

3.3.2 Remarks

Most of the landforms in this landscape suggest that they have been formed sub-superficially and they are recognized in the weathering front where they were generated. Thus, they correspond to corrosion and etching processes, in the sense of Wayland (1934) and Willis (1936). Due to deep weathering processes that started perhaps even during the Late Triassic, these landforms evolved in two periods, starting with the sub-superficially modelling of the weathering front and later dismantling of the regolith, thus exposing the fresh bedrock front. Mineral and textural transformations due to devitrification and/or assisted crystallization by vapour phase provide to the rock an even stronger cohesion, typical of a coherent igneous rock. This feature allows the explanation of the development process of the herein described landforms, otherwise typical of granite environments.

3.4 The Chon Aike Ignimbrites

3.4.1 Geology of the Deseado Massif, Province of Santa Cruz, Argentina

The oldest rocks in the Deseado Massif are of Neoproterozoic to Palaeozoic age. They are metamorphic rocks and are covered by Permian and Triassic sedimentary rocks. These ancient rocks occur only in very small and sparse outcrops. A significant volcanic episode took place in the Middle Jurassic, related to deep fractures in the crust, coeval with the efforts that preceded the fracturing and separation of Gondwana. These rocks are andesites, basalts and pyroclastic rocks, a product of fissure volcanic eruptions, included in Bajo Pobre Formation. Later on, during the Middle to Late Jurassic, another volcanic event occurred in the Massif, with the extrusion of volcanic and volcanoclastic rocks of the Bahía Laura Group, covering most of the Massif surface and building up an enormous, extensive plateau. This magmatic episode is related with the dismembering of the Gondwana continent, which produced the separation of South America and Africa and the opening of the South Atlantic Ocean. This volcanic event was mostly explosive, generating important volumes of pyroclastic flows, whose coalescence generated the large ignimbrite plateau. These ignimbrites and lava flows comprised by the Chon Aike Formation are associated with intense ash fall, with the subsequent tuff genesis (La Matilde Formation). During the Cretaceous and the Neogene, the Deseado Massif was a positive element of the regional landscape, and, along its margins, sedimentary rocks of continental environments were deposited, with the limited transgression of marine deposits of Atlantic provenance that accumulated from the Palaeocene to the Miocene.

3.4.2 Landforms and Landscapes

Bluffs, crests, needles, cliffs, nubbins, castle koppies and badlands

The ignimbrite sedimentary packages are the more irregular and discontinuous landscape of the Deseado Massif. Thick beds appear in the local relief, forming an extensive plateau with sub-vertical bluffs that exceed 20 m in height. They show abrupt crests and pinnacles marked with intensive vertical jointing that form prismatic columns (Fig. 28a).

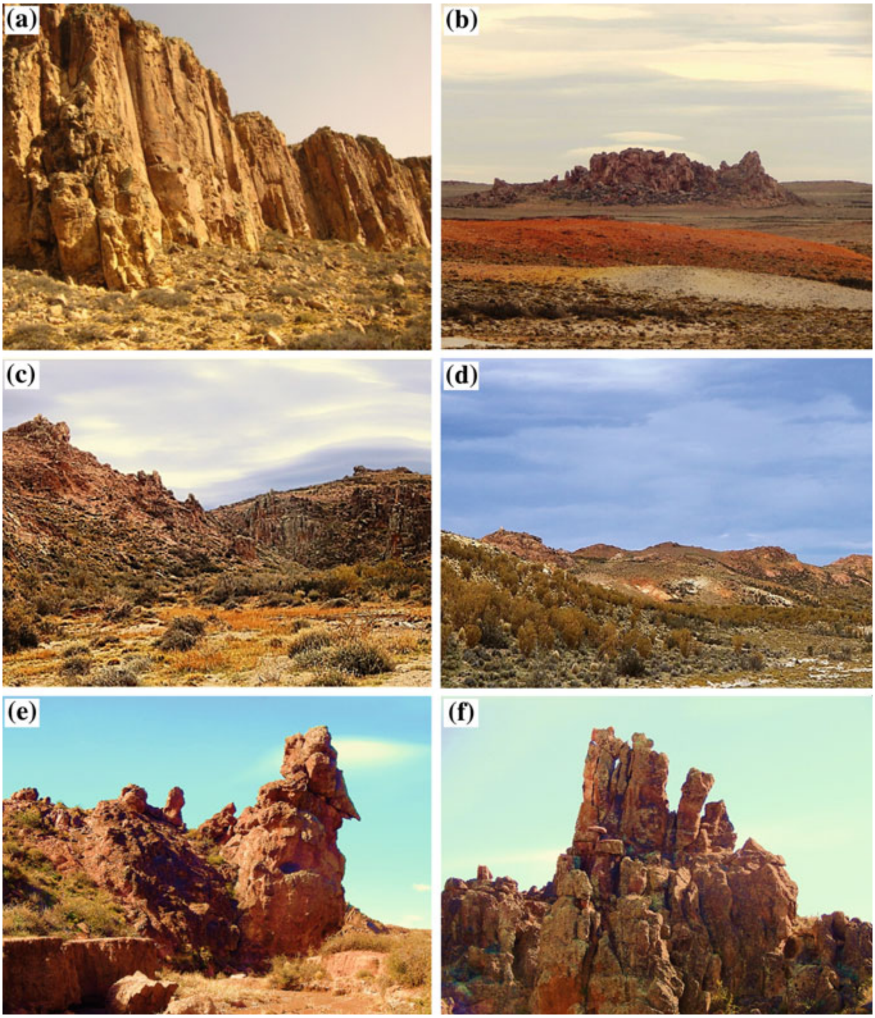

Fig. 28 **a** Sub-vertical walls with vertical jointing that bounds prismatic columns. **b** Nubbins, dome landform later fractured and degraded. **c** and **d** Low and rounded hills. **e** Abrupt crests and needles, bound by jointing. **f** castle-like landforms: "castle koppie"

The dominant landforms in terms of their abundance are outcrops of small cliffs with heights between 4 and 8 m high. Low hills and rounded outcrops occur as well with different steps of outcrops, generally covered by their own regolith. Landforms of the nubbin (dome-like landforms) and castle koppies (castle wall like landforms) occur as well (Fig. 28b–d, f).

Weathering mantles

In depressed topographies, weathering mantles have been preserved, a by-product of the chemical disintegration of ignimbrites. These weathering mantles have thicknesses in the order or metres to tens of metres, where "corestones" may be observed, immerse in the regolith. The regolith is composed of multi-coloured clayey materials, with clayey packages of reddish, brownish and whitish colours. These levels are distributed in several sectors of the Massif. They basically differ in the preserved thicknesses, and they include outcrops in depressed areas, with badland morphology (Fig. 29). They occur generally in the same topographic level where more resistant, overlying layers protect them from erosion. They are overlain by Tertiary sedimentary rocks or glaciofluvial deposits.

The ignimbrite expositions have reddish colours, due to the oxidation of the iron-bearing minerals present in the original rocks, and also whitish, yellowish, light brownish and pinkish grey sediments. The ignimbrites exposed in the area have a variable degree of compaction and welding, from poorly welded to and very altered due to their high porosity, to those highly welded and massive.

Caves, caverns, tafoni and alveolar hollows

At a regional scale, the ignimbrite mantles integrate bluffs, abrupt crests and cliffs. These major structures present lesser features as caves, caverns and needles (Fig. 30). They are usually localized in levels with lesser degree of welding and compaction, or levels of a larger concentration of pumice fragments and/or lithoclasts which have been displaced from the pyroclastic matrix of the ignimbrite, due to erosion processes. In some cases, the alveolar hollows are very common and they occur so close to each other that they confer to the rock the aspect of a sponge (Fig. 31a). Textural and structural control is evident in terms of their development, genesis and later evolution, which becomes favoured by the existence of orthogonal joint networks. Another factor that contributes in this sense is that during the deposition and cooling of the pyroclastic flows, the escaping gases generate tubes and chambers (known as degasification tubes) that are afterwards enhanced by differential erosion.

Corridors, galleries and tunnels

Thick layers of welded ignimbrites overlie other lesser welded ignimbrites which become eroded by processes such as "tunnelling" and/or "piping" faster than the welded sections and the hard rock strata which contribute to the formation of corridors, galleries and tunnels (Fig. 31b, c).

The drainage network is of angular–rectangular pattern as a consequence of the structural control that the frequent joint and fracture systems exert. Water channels have an ephemeral character, and they are incised in vertical wall gorges. In interbedded locations with the Chon Aike ignimbrites, tuffs and water-lain tuffs of the La Matilde Formation are present, and when the water channels cross these

Fig. 29 Weathering mantles in badland landscape; the regolith is the product of "in situ" weathering of the ignimbrites and it shows *reddish*, *brownish*, *whitish* and *yellowish* colours

formations, alluvial plains traverse these formations developing alluvial plains and acquiring braided patterns.

Mushroom rocks/Hoodoos

In the direction of the valleys, slopes or depressed areas such as endorheic basins, different levels of degradation of the ignimbrite sheets may be observed. Relict landforms are identified due to their conspicuous morphological expression. Vertical jointing is noted, as it gradually dissected sections of irregular columns, in which corners and crests are present. These landforms are localized in the proximity of the ground, within the valley or depression. They continue to reduce their

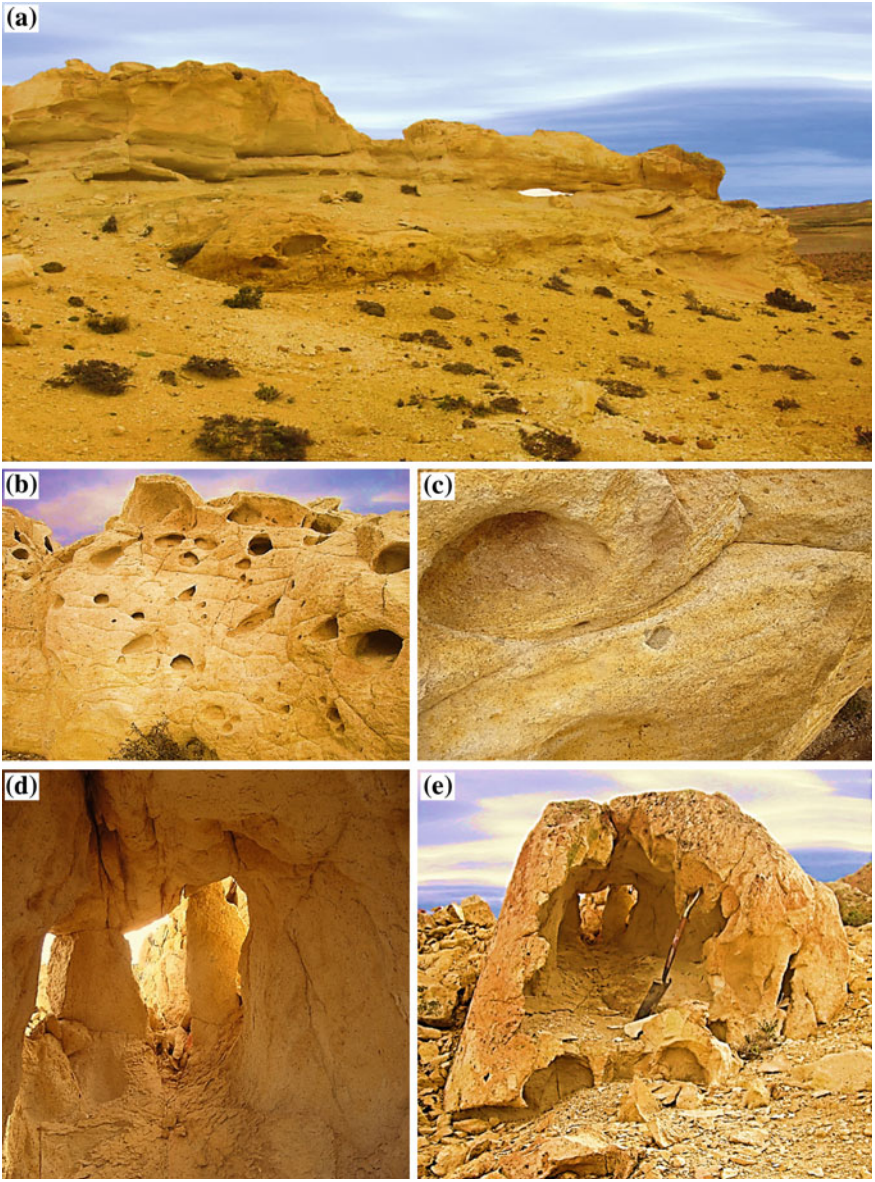

Fig. 30 Different degrees of tafoni formation. **a** Incipient arch, in formation. **b** Tafone with shelter at the *top*. **c** Detail of tafoni with Liesegang rings. **d** Grooves, pillars, cavities, arches and rock bridges. **e** Tafone with evolution towards cave or tunnel

Fig. 31 **a** Alveolar hollows of the honeybee type. **b** and **c** Corridors, galleries and tunnels favoured by the joint systems and the degassing tubes

volume and, due to differential erosion, they achieve the shape of a pedestal or a mushroom with bases smaller than the diameter of the upper portion above it.

In geomorphological literature, there are other terms that are used as equivalent to those cited here, such as mushroom rocks, pedestal rocks, chimney rocks, earth pillars, yardangs, demoiselles, and hoodoos, among others. In general, these names are applied according to specific geographical regions; for instance, in Utah (USA), the term “hoodoo” (Goudie 2004) is used to describe landforms of the chimney type, which in France they are known as “demoiselles”. These terms point out mostly anthropomorphic shapes than their true genesis. It is shown in several examples that the lower portion of the landform is smaller in diameter than the upper one, and it describes a concave profile. This aspect is related with slopes of the “flared slope” type. Some of these landforms may show more than one level of flared slopes. Another characteristic is that the concave slopes may present the genesis of tafoni. They rise over a platform of up to 4–5 m high and laterally surrounded by flares slopes. The upper portion is varied in shape, since some of them have indurated porous surfaces, as a duricrust, exposing tafoni and other alveolar hollows resembling bee hives. In some occasions, the upper portion develops shelters or spiral forms (Figs. 32 and 33).

The surface of the ignimbrite is rugged and presents grains of quartz in micro-relief, with spots of clayey materials which are the product of weathering of

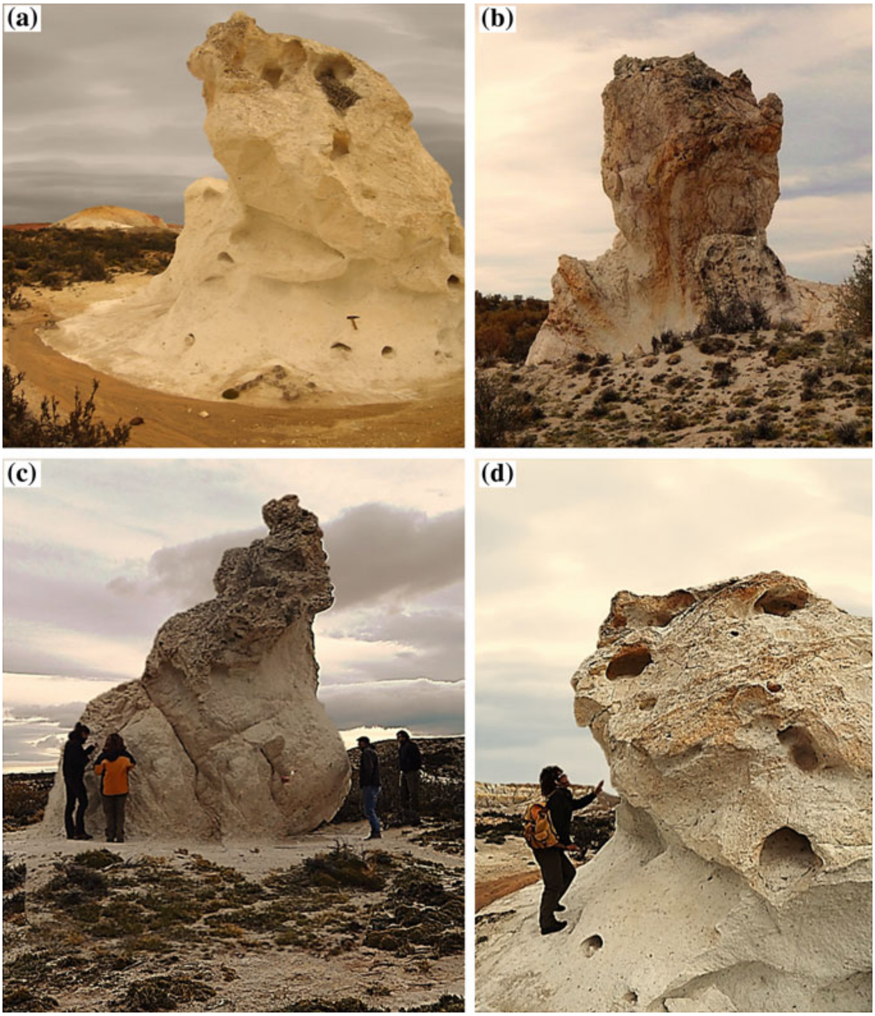

Fig. 32 Landforms in poorly welded ignimbrites. **a** Flared slopes in the periphery and tafoni formation from the base to the roof. A bird nest at the shelter. **b** Evolution to mushroom rocks with two levels of flared slopes. **c** Rounded landforms bound by fractures in the upper zone with alveolar hollows of the honeybee type. **d** Tafoni and carving in the middle zone, with a wide flared slope

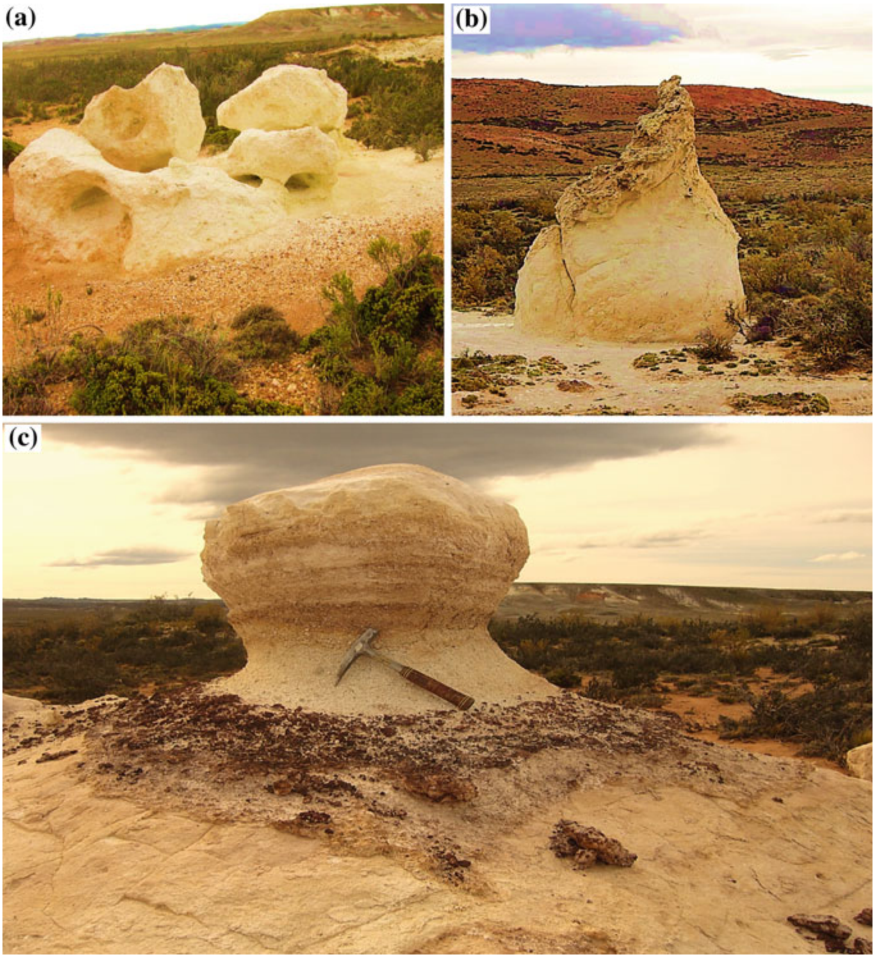

Fig. 33 Landforms developed on platforms or pedestals. **a** High erosion and relicts of a tunnel. **b** Bulb-like landform with endurated surficial duricrust, with alveolar hollows of the honeybee type. **c** Differential erosion of the soft sediments of the intermediate zone. Flared slopes merge with the platform

feldspar crystals and pumice fragments, which is an expression of differential erosion and expansion of the hollows as the result of lithoclasts.

“Pseudo-pillow” landforms

In the badland landscape, outcrops with morphology of sub-rounded hills as piled-up pillows, somewhat deformed, are observed. These landforms are pressed one against the other, with size reaching 1 m in diameter. These structures remind “pillow lavas” to the observer. They have a reddish-violet colour (Fig. 34). Thin sections analysed with a petrographic microscope permitted to recognize breccias of the peperite type, a product of the interaction between water-saturated sediments

Fig. 34 An outcrop whose morphology is noted for its piling up of cushions, somewhat deformed, which get compressed against each other, reaching sizes of 1 m in diameter. The larger structures look like valley walls

(White et al. 2000) with pyroclastic flow deposits. Peperites are of the globular type because the clasts present similar forms to those of the pillow-lava flows, surrounded by sedimentary materials (Busby-Spera and White 1987). This outcrop is interpreted as the interaction of a pyroclastic flow with a water body, most likely a lake.

3.4.3 Remarks

Due to its field relationships, fabric continuity and in situ, mineralogical composition/transformation, the alteration mantles are interpreted as fundamental components of the Late Jurassic weathering surfaces, in this case palaeoweathering surfaces and corrosion/etching plains. Over the Jurassic rocks of the Bahía Laura Group, a palaeosurface developed (Rabassa 2010; Bétard et al. 2014), a product of deep chemical weathering, under very hot and humid conditions. This landscape evolved in two phases: the first one included sub-superficial modelling of the weathering front and comprises the gradual transformation of the fresh rock into a regolith, which is the final product. The second phase involves the regolith denudation and the exhumation of the weathering front.

These landforms have been explained as due to sub-superficial etching and once they have been exhumed, differential rates of weathering and erosion would have continued acting along the existing fractures and the spots where rocks were less resistant.

Concerning the pedestal rocks and mushroom/hoodoos, it is interpreted that these landforms are the result of differential erosion rates, which have operated along the existing blocks as defined by fracture systems in the rock. The landforms that occur in the slopes were probably initiated under an ancient regolith mantle, which was later eroded and mobilized, leaving these landforms exposed perhaps to other dominant erosion processes in present climate conditions. Thus, it is very important to consider the climatic changes which have functioned since the Late Mesozoic to present times, which have imprinted important modifications to the landscape.

3.5 Pilcaniyeu Ignimbrite, Collón Curá Formation (Middle to Late Miocene)

3.5.1 Geology, Petrography and Stratigraphy

The stratigraphy of the Pilcaniyeu-Comallo region in western Río Negro Province, northern Patagonia, is related to the westernmost section of the Northern Patagonian Massif. It is composed of the following: (1) a lithological-structural complex known as the “Crystalline Basement”, gneisses, schists, migmatites and granitic rocks, probably of Early Palaeozoic age, metamorphosed in the Middle to Late Palaeozoic times; (2) Permian granites; (3) volcanic and sedimentary rocks probably of Late Triassic to Jurassic age; (4) Late Cretaceous sedimentary rocks; (5) the Ventana Formation, volcanic, pyroclastic and sedimentary rocks of Late Palaeocene and Eocene age; (6) the Collón Curá Formation, ashfall tuffs, ignimbrites, and conglomerates and sandstones of Middle to Late Miocene age; (7) Late Miocene and Early Pliocene basalts; (8) Pliocene piedmont deposits; (9) Quaternary glacial sediments; and (10) Quaternary alluvial, aeolian and colluvial deposits (Rabassa 1974, 1975, 1978a). The landscapes and landforms described in this section correspond to those related to the Pilcaniyeu Ignimbrite, Middle to Late Miocene (Rolleri et al. 1975; Rabassa 1978b; Mazzoni 1993; Mazzoni and Benvenuto 1990; Mazzoni and Stura 1990). The palaeoclimatic and palaeoenvironmental conditions of this region during these times were investigated by Bondesio et al. (1978) and Vucetich et al. (1993) among many others.

The Collón Curá Formation is a set of ashfall tuffs, ignimbrites, sandstones, conglomerates and water-lain tuffs, of about 200 m in thickness, which extends for most of the western part of northern Patagonia. The outcrops of the type section are located in the Collón Curá River Valley and are laterally connected to those units described here. The petrographic description of this formation recognizes four basic lithologic types: (a) well-stratified, brownish, lithic tuffs, which are bearing insect nests and other concretions, usually with interbedded intra-formational breccias; these rocks are interpreted as regional palaeosols; (b) dacitic and rhyodacitic ignimbrites, in various welding degrees; (c) greyish, cinder ashfall tuffs, partly of a sandy nature, of very coarse stratification and usually bearing abundant land mammal fossil remains (see Bondesio et al. 1978, among many others); and (d) conglomerates, sandstones and sandy tuffs, usually well stratified and cemented by calcium carbonate. The three first types represent a continuous and clearly organized sequence and were named as Caruhué Tuff Member, Pilcaniyeu Ignimbrite Member and Las Bayas Tuff Member, respectively. The (d) type comprises a thick epiclastic sequence which has been named as the Río Chico Conglomerate Member, interpreted as a direct signal of the uplift of the adjacent Andean Cordillera to the west. The ignimbrite member rocks have developed peculiar landscapes and landforms and will be described in greater detail.

The Pilcaniyeu Ignimbrite Member (Fig. 35) is exclusively composed of dacitic to rhyodacitic ignimbrites. The term "ignimbrite" is used here in the sense of Sparks et al. (1974, p. 115). This ignimbrite occurs in sheets of up to 40–60 m thickness, generally exhibiting various degrees in their welding. In most cases, three zones may be described: a lower one, poorly welded, which appears as a whitish cineritic tuff (Fig. 36); a middle one, of incipient welding which shows well-defined columnar jointing; and an upper one, deeply welded, which fractures in small, equidimensional blocks, usually characterized by tafoni, the result of aeolian abrasion (Fig. 37). It has not been possible to identify remnants of other uppermost zones, of lesser welding which originally were found above the deeply welded portion. These uppermost zones have been probably removed by denudation. From a petrographic point of view, there seems to be no major differences between these units. In all cases, these are dacitic to rhyodacitic ignimbrites, of vitroclastic, porphyritic texture, with quartz, intermediate plagioclase, potash feldspar (sanidine, anortoclase) and biotite in a cinder matrix of very angular, acidic glass shards. The eruptive vents that generated these rocks have not been identified in the study area. These vents have perhaps been eroded or they were fissures, which were later sealed by the eruption products. The great extension of the outcrops of this unit and the presence of these rocks in many different, intermontane drainage basins,

Fig. 35 Pilcaniyeu Ignimbrite Member, welded zone with columnar jointing. Pichileufu River Valley, Río Negro Province

physiographically not connected, favour the hypothesis of multiple eruption vents. In most of the studied area, this ignimbrite is integrated by only one cooling unit. In only one site two superposed, welded ignimbrites are present, with an unwelded layer in between (Rolleri et al. 1975; Rabassa 1978a). It is important to note that the dispersal area of this unit is at least of 15,000 km2, thus involving a huge mass of volcanic ejecta. Many fossil mammal bones and teeth and plant remains have been found in layers of this formation, usually forming part of calcareous concretions (see Bondesio et al. 1978). The identified fossils correspond to the “Santacrucense-Friasense” stage, widely represented in Patagonia, which has been assigned to the Middle to Late Miocene. A concentrate of biotite crystals obtained from the ignimbrite member was dated in 15 Ma, confirming the Middle to Late Miocene age of the unit (Rabassa 1974, 1975, 1978a).

3.5.2 Landscape Evolution

This region has been emerged and exposed in a continental environment since, at least, the Triassic, as it is shown by exposures of sedimentary and volcanic rocks rocks of Triassic and Jurassic age (Rolleri et al. 1975). Probably since the Late Jurassic and perhaps up to the Middle Cretaceous, planation surfaces developed due to deep chemical weathering, forming etchplains (Fig. 38). The regional planation surface is covered by Late Cretaceous continental sediments. Since then, the region

Fig. 36 Pilcaniyeu Ignimbrite Member, poorly welded zone with original deformation of tephra layers during the ash-flow movement. Pichileufu River Valley, Río Negro Province

has undergone successive periods of fluvial erosion, with the development of a complex fluvial network which was partially buried by Early Miocene basalts and deeply incised later during the Middle Miocene (Rolleri et al. 1975; Rabassa 1978b). The ignimbrite flows closely followed this stream network, totally burying the network and, partly, also the divides. The orogenic movements towards the end of the Oligocene started to uplift the Andean Cordillera, gradually leading to the inversion of the regional slope from the Pacific towards the Atlantic Ocean. Erosion, essentially of a fluvial nature, carved in the latest Oligocene and earliest Miocene a very well integrated, deep landscape, which had achieved a maturity stage (in a Davisian sense) when the sedimentation of the Collón Curá Formation concealed it in the Middle Miocene. Palaeosols which follow bedrock landforms are perfect witnesses of the existence of such landscape. This formation rapidly submerged the pre-existing landscape, including the outcrops of its own Lower Tuffaceous Member, when the ignimbrite flows occupied the existing drainage network and the ashfall tuffs in-filled all depressions and covered most of the

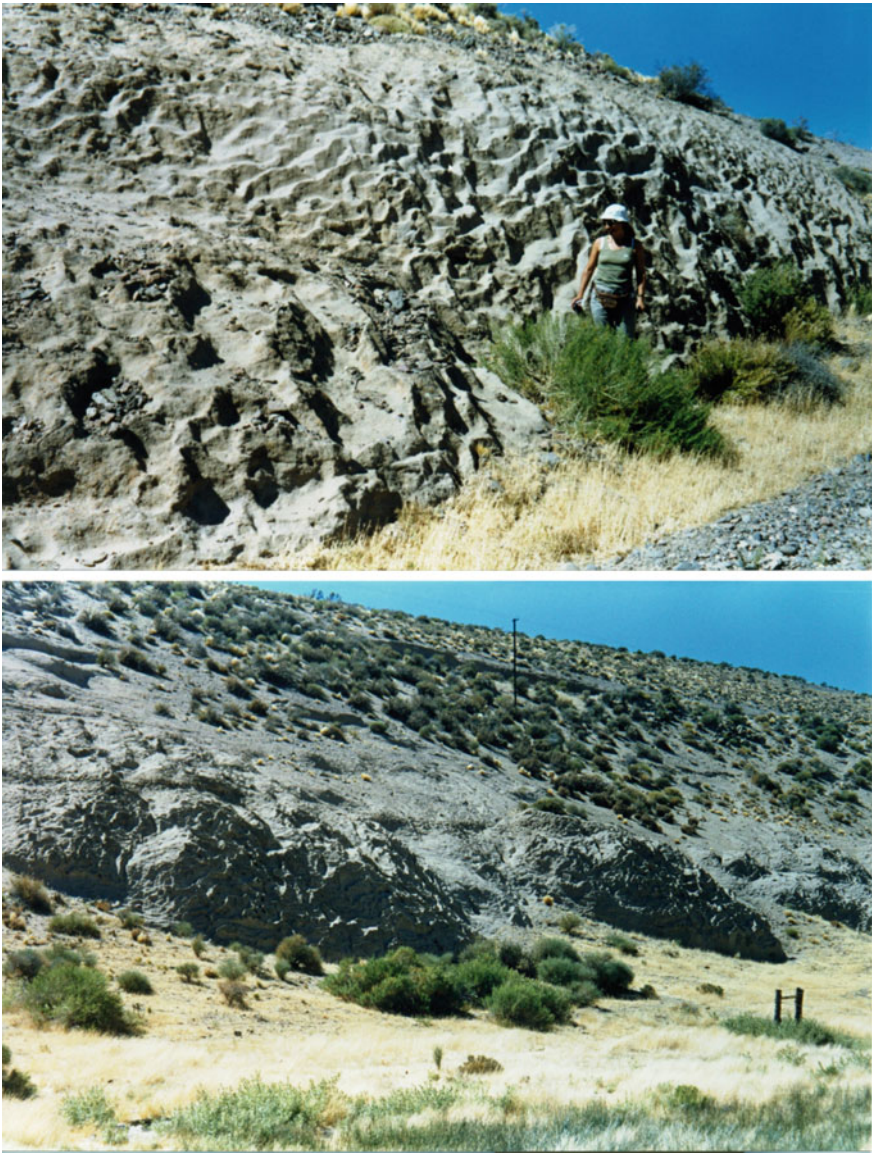

Fig. 37 Pilcaniyeu Ignimbrite Member, tafoni and block disintegration in heavily o zone. Pilcaniyeu, Río Negro Province

ancient divides. Only a few summits of the pre-Miocene, hilly, bedrock outcrops emerged from the ash mantles.

The in-filling of the basins and the rising of the first ranges of the Andean Cordillera built up a new positive area in the westernmost portion of northern

Fig. 38 Late Mesozoic planation surface developed on Crystalline Basement rocks, Comallo creek valley, Río Negro Province. This surface is unconformably covered by Late Cretaceous sedimentary rocks and the Collón Curá Formation (Middle to Late Miocene tuffs)

Patagonia, including the inversion of the drainage networks, from a Pacific to an Atlantic slope. Groeber (1929, p. 66, 1941) assigned this regional elevation to orogenic movements which he called the "First Phase of the Andean Movements". The landscape developed as a consequence of these processes was rapidly in-filled by the pyroclastic sediments of the Collón Curá Formation. This accumulation was very fast and accompanied by substantial climatic changes, stopping the erosion process of the stream networks, allowing the in-filling of the landscape depressions and the preservation of the palaeolandforms. The identification and study of these landforms are strongly favoured by the deep lithologic contrast between the Collón Curá Formation and the pre-existing lithostratigraphic units.

On the central, palaeopositive block of the Northern Patagonian Massif, the pre-Collón Curá Formation landscape is characterized by the carving of integrated drainage systems in state of "maturity". The fluvial systems where the present drainage network is located existed already in pre-Collón Curá times, as main valleys of the consequent type and smaller valleys of subsequent nature existed, adjusted to main fractures and joint systems. Ample, merging valleys generated depressions which were rapidly filled up by the Miocene tuffs. The sources of the valleys were usually found on the ancient surface of the Crystalline Basement massif. Towards the west, the palaeovalleys developed over the Palaeogene volcanic rocks. The sides of the valleys may have been as steep as 25°, as shown by the original dip of the basal lithic tuffs. In some cases, the former palaeosols cover rounded hills with peripherical dip around the buried palaeohills (Rabassa 1978b).

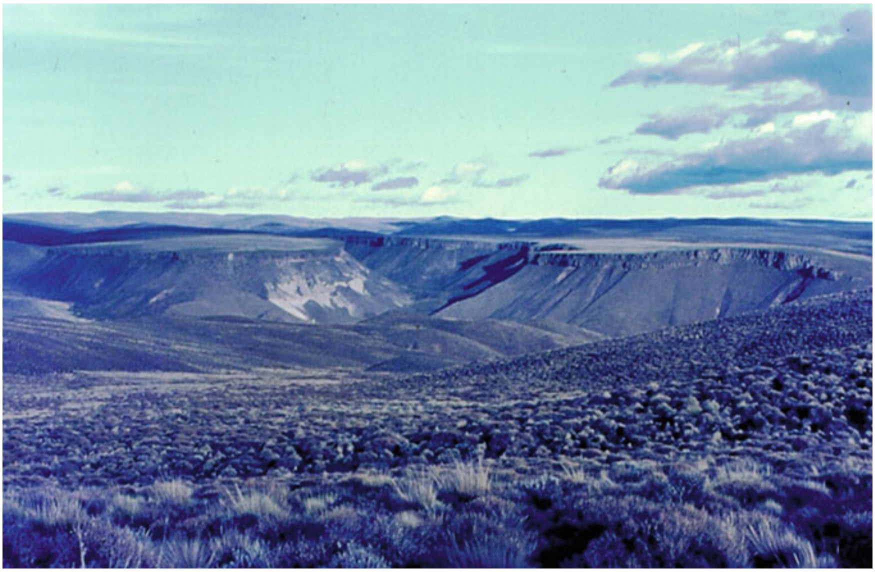

Fig. 39 Well-stratified ashfall tuffs of the Collón Curá Formation, in steep outcrops covered by Pliocene basalts. Río Pichileufu valley, Río Negro Province

Some of the valleys were up to 2 km wide. The valleys within the Northern Patagonian Massif were deep and elongated depressions, which augmented sharply their gradient when reaching the large tectonic basins located one to the north, the Collón Curá Graben, and another to the south, the Ñirihuau marine basin. Perhaps a rapid deepening of the network took place just before the eruption of the ignimbrites, as the Andean Cordillera was being elevated towards the west and the graben was being enlarged. In the western basins and grabens, very few sites exposed the base of the Collón Curá Formation and, therefore, little information is available about the pre-existing landscape. However, the sedimentary deposits suggest large, powerful streams with ample flooding plains of braided drainage pattern, consequently developed over the tectonically down-warped blocks.

The Collón Curá ashfall tuffs generated large mesetas and highplains, favoured by their friability and large inner friction of their clasts, mostly very angular glass shards. These landforms present abrupt walls, rock towers, and steep and sharp crests (Fig. 39). Micro-relief landforms of the “volcano-karst” type (Fairbridge 1968, p. 1205) are very frequent along the sides of these landforms. In these deposits, the slopes receed in a parallel manner, partly due to slumping of blocks, whereas at the foot of the slope, the removal of the materials generated as a result of the slumping process, and particularly the calcareous concretions, developed rounded landforms of gentle slopes. If the outcrops of the Pilcaniyeu Ignimbrite are involved, the erosion landforms are very similar, but in this case, the differential degree of welding controls the genesis of these features. Therefore, very gentle slopes are formed at the base of the outcrops (the poorly welded zone), whereas the upper portions (deeply welded zone) show usually almost vertical rock walls, rock monuments and cliffs, displaying columnar jointing, needles, tafoni and steep cliffs.

4 Discussion and Final Remarks

In the studied ignimbrite outcrops, contrasting landscapes are frequently observed, from features related to "granite landscapes" and easily taken for such rocks, and other landforms that resemble landscapes developed in sandstones. Several further questions arise from our observations.

(1) Why is it possible that rocks with so different lithology and texture may generate comparable landscapes?
(2) Is it relevant to consider the age of the ignimbrite plateaus when dealing with the geomorphological analysis or is it sufficient to indicate their fabric characteristics?
(3) Have the morphogenetic agents responsible for the generation and evolution of the landforms acted independently or are these features the result of multiple actions or even converging activities?
(4) What is the relationship between the similarities on landform development of some ignimbrite flows and the modelling of sandstones?
(5) Are there also similarities between ignimbrite modelling and granite rock landforms?
(6) From a morphoclimatic point of view, are they monogenetic or polygenetic landscapes?

To answer these questions, emerging from our own field work observations, it is necessary to support the research activities with elements provided by other geological studies. The observed characteristics require the explanation of the landscape starting from structural analysis, determination of lithology and stratigraphic position of the deposits, considering the information related to the age of the outcrops and their fabric characteristics. In this sense, it should be highlighted the role of the chronology and, subsequently, the climatic changes that have taken place since the eruption of the ignimbrite flows until present times.

Since the morphogenetic agents are directly related to the climatic conditions, in the case of the Portezuelo ignimbrite only one agent would have acted in an isolated form, whereas other landscapes would have been the result of multiple processes and even several morphogenetic agents could have operated simultaneously with one of them prevailing over the others.

Concerning the fabric, it demands detailed analyses, because within even one individual flow, many fabric variations may coexist, both laterally and vertically. Moreover, these outcrops may be composed of several pyroclastic flows, superposed within one single cooling unit, each of them with their peculiar characteristics. This information allowed the definition and interpretation of landforms according to the observation of structures and morphogenetic systems. In this manner, the generational stages of the various landforms were reconstructed, their consequence being the organization of the present landscape.

Concerning the geomorphological analysis, the landforms were defined and explained, searching for the differential resistance to erosion in specific points of the various outcrops, adding to this the identification of the successive climatic cycles that occurred since their eruption, thus becoming responsible for the present configuration of the vast majority of the ignimbrite landscapes.

The landscape of the Portezuelo de los Payunes would have started to develop sometime after the Late Pleistocene. The yardangs found in the landscape reveal that the dominant geomorphic process today is aeolian erosion and that the landscape is a simple one. From a morphoclimatic point of view, these landforms were modelled by a unique morphogenetic system, thus forming a monogenetic landscape.

The Barda Colorada and Chon Aike ignimbrites present similarities with sedimentary rocks concerning the existing set of landforms, such as rock arches, rock bridges, galleries, tunnels, corridors, demoiselles and badlands, mushroom rocks, hoodoos and minor features such as alveolar hollows, tafoni, caves, caverns and rock shelters. The integration of these landscapes results from multiple processes, sometimes acting simultaneously.

Both areas were affected by severe climatic changes since the Jurassic (the Chon Aike Formation) and the Middle Eocene (the Barda Colorada Formation), where the presence of erosion landforms was conditioned by different morphogenetic agents. The action of these agents in the creation and evolution of the landforms was eased by orthogonal jointing. These landscapes include slopes with dissection modelling, sub-superficial water erosion with “tunnelling” or “piping” processes, affecting ignimbrites with levels marked by pseudo-stratification and/or very friable deposits with abundant clayey materials as in friable sedimentary rocks.

Other sections of these ignimbrites show deeper, thorough welding, which enables the development of a specific set of landforms such as rock walls, crests, needles, pyramids, cliffs, nubbins, rowars and castle koppies, where the first ones are typical of welded ignimbrites and are positive elements of the landscape, whereas nubbins, rowars and castle koppies compare much better with granite landscapes, since these are rocks of higher cohesion.

To explain the modelling of the Lihuel Calel Ignimbrite with the development of granite landscape, it should be taken into consideration that this is a primary process, that is, mineral and textural transformations due to devitrification and/or vapour-phase, assisted crystallization, during the cooling of the unit. These transformations provided an even higher cohesion to the ignimbrite, which is typical of coherent igneous rocks. This feature permitted the explanation of the development of the landforms herein described, which are typical of granite environments.

Due to deep weathering processes which may have started as early as the Late Triassic, these landforms evolved in two stages, beginning with the sub-superficial modelling of the weathering front and posterior dismantling and denudation of the regolith and the surface exposure of the ancient weathering front.

Concerning the Pilcaniyeu Ignimbrite, the differences between the deeply welded and the poorly welded zones are so relevant that these welding facies occur as if they were totally different rocks. Welding defines large-scale features, as well as minor landforms, sometimes with strong gradation between the two end types. Future studies may allow the identification of micro-landforms which occur only in each of these welding types.

The landscapes developed on the ignimbrites cited in this work, concerning a morphoclimatic approach, correspond to a polygenetic relief bearing features of different morphogenetic systems which are defined by diagnostic landforms.

Ignimbrites are very common in volcanic landscapes of a varied scope of geological ages, thus deserving carefully dedicated geomorphological studies.

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