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GRANITIC LANDSCAPE IN THE MUNRO PLUTON (TAPERA DE BURGOS), PROVINCE OF CHUBUT, PATAGONIA, ARGENTINA

PAISAJE GRANÍTICO EN EL MUNRO PLUTON (TAPERA DE BURGOS), PROVINCIA DE CHUBUT, PATAGONIA, ARGENTINA

PAISAGEM GRANÍTICA NO PLÚTON MUNRO (TAPERA DE BURGOS), PROVÍNCIA DE CHUBUT, PATAGÔNIA, ARGENTINA

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ABSTRACT
The Munro Pluton is located in the extra-Andean region of the province of Chubut, Argentina, in northern Patagonia, northeast of the Sierra de Tecka and northwest of the Sierra de Languineo. It is a sub-volcanic pluton with a SHRIMP age of 60 Ma (Paleocene?). Studies of fission tracks on apatites of the studied region suggest that the exhumation of the region took place during the Paleogene, indicating that the lapse since its emplacement until its exhumation, took less than 35 Ma, and that the pluton has been exposed to weathering at least since the Miocene until present times. This pluton has ellipsoidal shape and a surface of 25 km2 and it is intruded by two dyke systems. The Munro Pluton develops a landscape whose weathering front exposes fresh rocks, regolith zones and boulders immersed in regolith. Granitic landforms have been recognized at different scales. Among the bigger landforms of the granitic landscape, the following have been identified: domes (bornhardts), nubbins, koppies and smaller landforms such as boulders, flared slopes, gnammas, rills/gutters/gullies, tafoni and pseudo-bedding. Structural and textural observations allowed the inference that many of the identified landforms are generated in the sub-soil, being followed by the regolith mobilization thus exposing the paleo-weathering front. Other landforms have a tectonic component associated for their development, such as pseudo-bedding, as well as the endogenous deformations, related to the emplacement type of the Munro pluton. In general, most of the landforms are convergent as they evolve along different pathways.
Key words: Munro Pluton. Patagonia. Argentina. Granitic landscape. Fractures. Weathering.

RESUMEN
El Plutón Munro se ubica en la región extrandina de Chubut, al noreste de la Sierra de Tecka y al noroeste de la de la Sierra de Languineo. Es un plutón sub-volcánico con una edad SHRIMP de 60 Ma (Paleoceno?). Estudios de trazas de fisión en apatitas de la región de estudio sugieren que la exhumación de la región tuvo lugar durante el Paleógeno, indicando que desde su emplazamiento hasta la exhumación transcurrieron menos de 35 Ma, y que ha estado expuesto a la meteorización por lo menos desde el Mioceno a la actualidad. Tiene forma elipsoidal, con una superficie de 25 km2 y está intrusado por dos sistemas de diques. El Plutón Munro desarrolla un paisaje cuyo frente de meteorización expone rocas frescas, zonas de regolito y bloques inmersos en regolito. Se han reconocido geoformas a distinta escala. Entre las formas mayores del paisaje granítico se reconocieron: domos (bornhardt), nubbins, koppies y formas menores como: bloques (boulders), laderas acampanadas (flared slopes), gnammas, cárcavas (rills/gutters/gullies), tafonis y pseudo-estratificación (pseudo-bedding). Observaciones estructurales y texturales permiten inferir que muchas de las geoformas identificadas se inician en el subsuelo seguido de la movilización del regolito para exponer el antiguo frente de meteorización. Otras formas tienen asociado un componente tectónico para su desarrollo (pseudo-estratificación) así como las deformaciones endógenas vinculadas al tipo de emplazamiento del Plutón Munro. En general, la mayoría de las geoformas son convergentes a medida que evolucionan por diferentes vías.
Palabras clave: Plutón Munro. Patagonia. Argentina. Paisaje granítico. Fracturas. Meteorización.

RESUMO
O Plúton Munro está localizado na região extra-andina da província de Chubut, Argentina, no norte da Patagônia, a nordeste da Sierra de Tecka e a noroeste da Sierra de Languineo. É um plúton subvulcânico com uma idade SHRIMP de 60 Ma (Paleoceno?). Estudos de traços de fissão em apatitas da região estudada sugerem que a exumação da região ocorreu durante o Paleógeno, indicando que o lapso desde sua localização até sua exumação, levou menos de 35 Ma, e que o plúton foi exposto ao intemperismo em pelo menos desde o Mioceno até os tempos atuais. Este plúton tem forma elipsoidal e superfície de 25 km2 e é intrudido por dois sistemas de diques. O Plútón Munro desenvolve uma paisagem cuja frente de intemperismo expõe rochas frescas, zonas de regolito e blocos imersos em regolito. Os acidentes geográficos graníticos foram reconhecidos em diferentes escalas. Entre os maiores acidentes geográficos da paisagem granítica, foram identificados os seguintes: domos (bornhardts), nubbins, koppies e pequenos acidentes geográficos, como blocos, taludes alargados, gnammas (riachos/calhas/ravinas), tafonis e pseudo-estratificação. Observações estruturais e texturais permitiram inferir que muitas das formas de relevo identificadas são geradas no subsolo, sendo acompanhadas pela mobilização do regolito, expondo assim a frente de paleo-intemperismo. Outras formas de relevo apresentam um componente tectônico associado ao seu desenvolvimento, como a pseudo-estratificação, bem como as deformações endógenas, relacionadas ao tipo de localização do plúton de Munro. Em geral, a maioria das formas de relevo éconvergente embora evoluam por diferentes caminhos.
Palavras-chave: Plútón Munro. Patagônia. Argentina. Paisagem granítica. Fraturas. Intemperismo..

INTRODUÇÃO

The geomorphology of granitic outcrops is the field of studies of undoubted great interest for magmatic rocks. The granitic landscape is developed on magmatic rocks emplaced and consolidated at great depths and later exposed at the surface due to the denudation of overlying materials of varied origin. Along their elevation towards the Earth surface, these rocks are exposed to lithostatic and tectonic forces that contribute to the final morphology developed on the granitic rock outcrops, highlighting the importance of the systems of rocky discontinuities and the active weathering processes. Differential weathering is the main process in the evolution of granitic landscapes, alteration that is produced by atmospheric agents, the hydrosphere and the biosphere.

The transformations experimented by the rocks at the surface impact upon the mineral composition, morphology, grain size, and mineral fabric. Their intensity is depending upon the climatic conditions and time. The weathering processes produce physical and chemical transformations on the rocks. Weathering implies the in situ decomposition and disintegration of the masses of rocks and minerals.

The mechanic or physical weathering is related to the disintegration of the rocks and depends upon the characteristics of the rocks themselves.

The chemical weathering consists in a set of changes in the mineral structure (decomposition). The active process are hydrolysis, hydration, dissolution, oxidation, etc. The separation between physical and chemical weathering is arbitrary, because in general both sets of processes act together.

The differential alteration is the consequence of the heterogeneity typical of the rocky massifs, in which the density of fracturing and the spatial orientation (i.e., vertical, inclined, horizontal) intervene, offering different exposition to the weathering agents; mineral composition, texture and grain size also take part in this processes. The highly fractured rocks are more susceptible to weathering and erosion than those in which fractures are absent, widely spaced or locked.

In the development of the granitic landscape the weathering patterns are important. Granites are important also in the interaction with the atmosphere and the hydrosphere that leads towards the erosion of the mineral components and the formation of the regolith. The contact between the un-weathered, fresh rocks and the weathered rocks (the regolith) is a clean surface known as the weathering front (MABBUTT, 1961). The differential alteration is the product of the fracture density at different scales and the action of the erosion processes that mobilize the regolith and expose the weathering front. The result is the peculiar relief of the rocky outcrops, or irregular morphology and the relict presence of the regolith, in a typical association for granitic landscapes.

GEOLOGICAL FRAMEWORK

The igneous rocks that compose the basement of the region are schists and phyllites of Precambrian-Early Paleozoic age (the Cushamen Formation) and they are intruded by Early Paleozoic acid plutonic rocks, covered in erosional unconformity by the sedimentary rocks of the Tepuel Group (Carboniferous to Permian). These rocks are then covered with angular unconformity by Jurassic sedimentary rocks, and both rock groups are the country rocks of a set of gabbro intrusive rocks of Early Cretaceous age, which reach very large dimensions (POMA, 1986). During the Early Jurassic, intense volcanism of andesitic-basaltic composition (the Lonco Trapial Formation) took place. These volcanic rocks are followed by a sequence of lacustrine sedimentary rocks with interbedded basaltic rocks of the Cañadón Asfalto Formation. Acid and intermediate volcanic rocks characterize the Early Cretaceous, together with a succession of continental sedimentary rocks of the Chubut Group that overlies them with angular unconformity, and then the fluvial and marine sedimentary sequences of the Paso del Sapo and Lefipán formations of Late Cretaceous age. Simultaneously, an acid, igneous event took place, with a series of intrusive bodies, the granites of the Aleusco Formation, which intrude Carboniferous and Liassic sedimentary rocks, with basalts and tuffs of the Tres Picos Prieto Formation.

During the Paleogene, an intense volcanic activity occurred, of markedly meso-silicic composition (the La Cautiva Formation) and sub-volcanic, alkaline bodies of the El Buitre Formation (Late Paleocene-Eocene), together with the pyroclastic sedimentation of the Sarmiento Group (Late Eocene-Early Oligocene). A set of conglomerates, sandstones and tuffs, known as the Cañadón Pelado Formation, is assigned to the Oligocene. Granites of the igneous complex of Tapera de Burgos intruded the sedimentary rocks of the Tepuel Group. Their radiometric age is Oligocene (SPIKERMANN, 1978), together with alkaline lavas of the Mesa Chata Formation and basalts of the La Vasconia Formation. The basalts of the El Mirador Formation (Late Miocene) and the Epulef Formation (Pliocene) are assigned to the Neogene. Extensive aggradation deposits and psephitic ridges of the Laguna Agnia have been assigned to the Pleistocene, and more modern basaltic flows, saline, alluvial and colluvial sediments complete the sequence into the Holocene (MÁRQUEZ; NIETO, 2005).

THE IGNEOUS COMPLEX OF TAPERA DE BURGOS

The Munro Pluton is a sub-volcanic body located in the extra-Andean region of the province of Chubut, Central Patagonia, Argentina, between the Sierras of Tecka and Languineo. It has an ellipsoidal shape, a surface of 25 km^2. It is intruded by radial and longitudinal dykes (Figure 1). A SHRIMP age of 60 Ma (earliest Paleocene) has been assigned to this pluton (RODRÍGUEZ *et al*., 2017). Regional studies of fission tracks on apatites (SAVIGNANO *et al*., 2016) suggest that the general exhumation of this area occurred during the Paleogene.

This magmatic complex has been studied by Suero (1953), Spikermann (1978), López de Luchi *et al*. (1992), Rodríguez *et al*. (2017) and Aragón *et al*. (2017). The Munro Batholith is composed of small, tonalithic-granodioritic, epizonal plutons, that intrude Carboniferous and Jurassic sedimentary rocks, and which are at a time intruded by volcanic rocks of the La Cautiva Formation (Tertiary). The Munro Batholith includes a group of plutons circumscribed with neat and regular contacts that cut across the older structures, with elliptical shapes in map view, in most cases. It includes the Munro Pluton (also known as the Tapera de Burgos Pluton), Estancia

Los Menucos, Cerro Kanquel and Sierra de Tepuel, with K-Ar ages corresponding to either the Late Cretaceous or the Early Tertiary (ARAGÓN *et al*., 2017).

The Munro Pluton presents variations or facies corresponding to a pinkish granodiorite in the southeastern portion of the area (SPIKERMANN, 1976). The main body is composed of different rock types such as quartzose diorite, monzodiorite, tonalite and granodiorite. Darker inclusions of more or less spheroidal shape are common, with varying sizes ranging up to 50 cm), with microgranular texture and dioritic composition (SPIKERMANN *et al*., 1993).

It presents hipidiomorph granular texture, composed of plagioclase, potash feldspar, quarts, amphibole, opaque minerals and zircon. The relative mode proportions of the essentially felsic minerals vary according to the facies of the pluton since, as it was mentioned by Spikermann (1993), and this pluton shall be considered of the zonal type in lithological terms.

Figure 1. Location of the study area. To the right, map of Argentina, showing the political division in provinces (i.e., states). In the lower right corner, map of the province of Chubut indicating the location of the Munro Granite.

Location of the study area

The Munro Pluton is a sub-volcanic body, located in the extra-Andean region of the province of Chubut, central Patagonia, Argentina, in an area that extends between the Sierras de Tecka and Languineo.

Figure 1 - Location of the study area.

Source: the authors.

METHODOLOGY

Field reconnaissance to determine the morphological characteristics of the massif and its bedrock, as well as the most relevant aspects by means of regional and detailed observations were performed. Google Earth satellite imagery was used for this study.

The different landforms of the granitic landscape and the associated processes were classified. Samples were obtained for the identification and recognition of the lithological facies of the pluton and the visualization of the textural and structural characteristics. The intrusive contact with the sedimentary rocks was clearly established. The longitudinal and radial dykes were measured as well as their orientation and lithology. The analysis of the fracture systems was performed and the patterns of weathering were recognized.

The mineralogical and textural analysis was completed, together with the study of the most relevant structures using hand lenses and thin sections in petrographic microscope to identify the various facies, the characterization of discontinuities and the degree of weathering of the primary minerals.

RESULTS

The Munro Pluton is a rocky massif related to a more or less elliptical shape, which is in clear contact with the bedrock. It is topographically located within a depression with respect to the surrounding bedrock outcrops, which reach up to 985 m a.s.l., comprising a depression limited by the flanks of the Carboniferous, hornfels and sedimentary rocks, which form the topographic wall in coincidence with the largest topographic steps, representing the contact of the pluton with the surrounding sedimentary rocks.

At the regional scale, a series of inner hills within the depression composed of the segmented igneous body are observed. This igneous unit exhibits several joint and dyke systems that form these elevations and small valleys following fractures. The igneous body is intruded by a system of mafic dykes of radial and sub-vertical geometry. It is also traversed by longitudinal, leucocratic dykes of N-S bearing which cross through the body.

The bottom of the depression descends in a SW direction, with a local elevation difference of 315 meters. Its inclination is clearly exhibited due to the drainage design of the crossing streams. The régime of the water channels is temporary and the drainage follows two major directions, clearly controlled by the structure (LÓPEZ DE LUCHI *et al*., 1992).

The drainage directions of the northern and central sectors of the pluton are oriented with slopes towards the W and NW, to reach a major stream that flows into the Laguna Aleusco-Las Salinas system.

The drainage directions of the southern sector exceed the boundaries of the body and they flow into the basin from the South, in the same Laguna Aleusco-Las Salinas system as well.

The water divide between both directions is determined by a system of dykes of E-W bearing that comprises a topographic high.

In the northern and eastern margins, within the plutonic body, topographic highs are noted, expressed in the sites with the following coordinates: 43°10´37´´/70°16´56´´; 43°10´73´´/70°16´35´´. These boundaries are compatible with more resistant lithology, such as granodiorite, compared with those that dominate other portions of the pluton (diorites-tonalites). In the interior of the body, gradual changes are observed, both of grain size and lithology nature. The diorite facies is greyish, of medium to fine grain size, and are composed by plagioclase, rare quartz and diminution of the mafic mineral content, in order of abundance. As quartz becomes more common and the mafic minerals tend to diminish, the lithology gradually enters into the tonalithic facies. This sector of the plutonic body is markedly weathered at the surface, to the point that, in general, the areas occupied by these facies compose a denudated, low landscape associated to smooth topographic depressions.

In contrast with the granodiorite facies, located in the central portion of the body and pinkish grey in color and middle to coarse grain size, they are part of a local hilly relief with development of a granitic landscape.

Microscopically, the granodiorites have ipidiomorphic granular texture, composed of plagioclase, potash feldspar, quartz, amphibole, biotite, and opaque and accessory minerals.

Plagioclase is the more abundant mineral, with respect to the potash feldspar. Its crystalline morphology is euhedral, with polysynthetic and Carlsbad twinning, where a few crystalline individuals show zonation. It shows marked alteration to clay minerals and, to a minor proportion, to calcite. The potash feldspar is subhedral with Carlsbad twinning, altered to clay minerals and sericite. Quartz is anhedral and abundant, of interstitial character or with intergrowth with potash feldspar.

The amphibole is hornblende which occurs as subhedral, with long prismatic habit, in longitudinal sections and euhedral bases, with marked pleochroism around yellowish brown tones, and altered to calcite, epidote and chlorite.

The subhedral to euhedral biotite show segregation of iron oxides through their cleavage planes (deferrization) or chlorite alteration.

Granules and small crystals of opaque minerals are observed. Rare apatite and zircon crystals, of accessory nature, are also found.

The characteristic features of the granite domes are the “sheet structures”, which respond to the direction of fractures, sub-parallel to the topographic surface. They are also known as curved joints and exfoliation fractures, among other terms.

The dense network of sub-vertical joints combined with the “sheet structure” provokes the degradation of the rocky massifs in castle-like forms.

Among the larger landforms, with scale of tens to hundreds of meters, the following are recorded: domes (bornhardts), nubbins, castle koppies and boulders, and smaller forms at one meter scale or even smaller, such as boulders, rock platforms, flared slopes, tafoni, gnammas, rills, gutters, gullies, and pseudo-bedding.

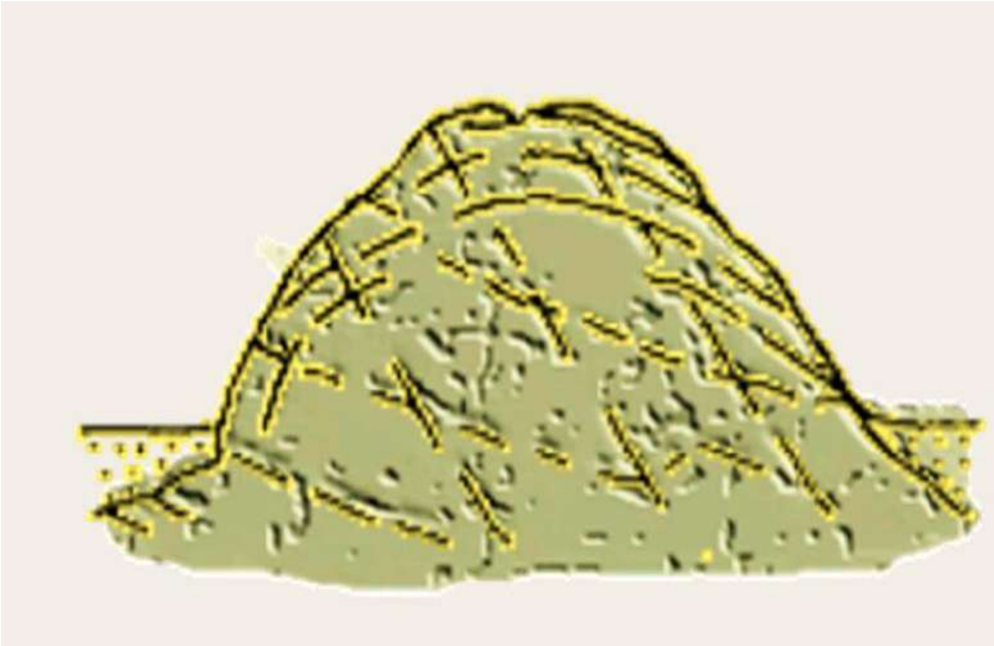
LARGER LANDFORMS OF GRANITIC LANDSCAPE IDENTIFIED IN THE MUNRO PLUTON

Domes or bornhardts

The Munro Pluton has a morphology of a dome or bornhardt (TWIDALE, 2007), developing a set of dome landforms. The characteristic fractures of the granitic domes are the “sheet structures”, which correspond to directions of fractures, sub-parallel to the topographic surface. They are also called as curved joints and exfoliation fractures. They usually have a wide curve angle (Fig. 2).

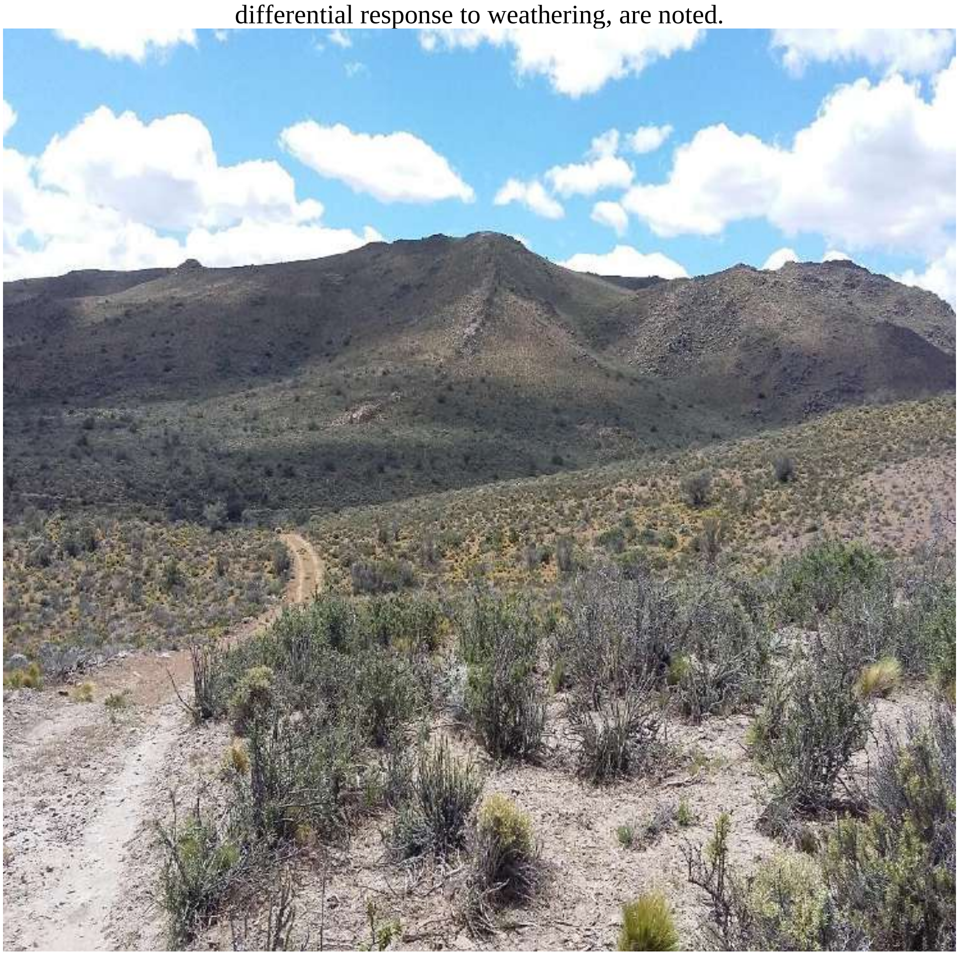
The domes or bornhardts form individual and sub-rounded hills composed of massive rock, limited by orthogonal fractures (Fig. 3). Vertical fracturing shows tendencies in relationship to the horizontal fracturing, with respect to the axial relationships (longest axis vs. shorter axis) of the pluton. The fractures parallel to the surface provide a dome-like profile (Figs. 4 and 5). They appear as convex masses that remain as high points in the landscape, from where water flows, that become channelized in minor features called gutters, towards lower zones where weathering advances rapidly. From the bornhardts, nubbins and castle koppies are derived. In these domical landforms it is common at the surface that a set of morphological features of smaller size is found. Gnammas and tafoni (plural of tafone), cave-like holes that are open at the base and curved at the top, are placed. “Flared slopes” or reversed slopes, and other smaller forms also occur here, which will be described later on.

Figure 2 - Schematic view of a dome (bornhardt), with diagonal jointing and predominance of sheet structures (curved jointing) due to decompression.



Source: the authors.

Figure 3 - Association of cupuliform and bell-form features, where radial rhyolithic dykes as ribs, product of a differential response to weathering, are noted.



Source: the authors.

Figure 4 - Different views of whaleback domes.

Source: the authors.

Figure 5 - Conjugated joint systems. At the front, a set of gnammas that merge into channels (rills/gutters/gullies).

Source: the authors.

Domes or bornhardts form rounded, individual hills, carved in massive rocks, bounded by orthogonal fractures (Fig. 3). The vertical fracturing shows tendency related to horizontal fracturing, with respect to the axial relationships (larger axis vs. shorter axis) of the pluton. The fractures which are parallel to the surface give as a result a dome profile (Figs. 4 and 5). They occur as convex rock masses and they remain as high points in the landscape, from where drainage is established, which become channelized in smaller landforms such as gutters towards lower levels where weathering makes very fast progress. From bornhardts, nubbins and "castle koppies" are derived. In these domical landforms it is common that a large set of smaller landforms takes place at their surface. Gnammas, tafone (cave type hollows, open at the bottom, vault like shapes at the top), "flared slopes" or reversed slopes and other small landforms are found, together with other minor features described elsewhere in this paper.

Nubbins

Nubbins (also known as knolls or boulder inselbergs) are conical hills, composed of "in situ" blocks, a product of the partial breaking below the surface. These are essentially hills covered by dispersed rocky blocks, with oblique scarp walls. They are formed as a result of the disintegration of the rocks into blocks of different shapes and forms. They originate in sub-aerial conditions and they evolve after exhumation, what is known as the two-step phase. They are produced, preferentially at the slopes of domes or bornhardts and they assume a major evolutionary state. The arrangement of the blocks reflects the superficial disintegration of the external rock layers, as they became denudated from the regolith.

Weathering is improved by the system of fractures of the blocks that exhibit the shape of a solid with parallel walls. In this way, the weathering fluids are more active and efficient at corners and edges than on the flat sides. For these reason, the rounding of the blocks takes place under sub-aerial conditions.

Figure 6 - Evolutionary stages in the formation of nubbins (modified from Vidal Romaní and Twidale 1998).

Source: the authors.

Figure 7 - Nubbins in bornhardt slopes, of conical shape, "in situ" blocks product of the partial breakage below the surface. Systems of vertical, conjugated joints (oblique) (curved jointing).

Source: the authors.

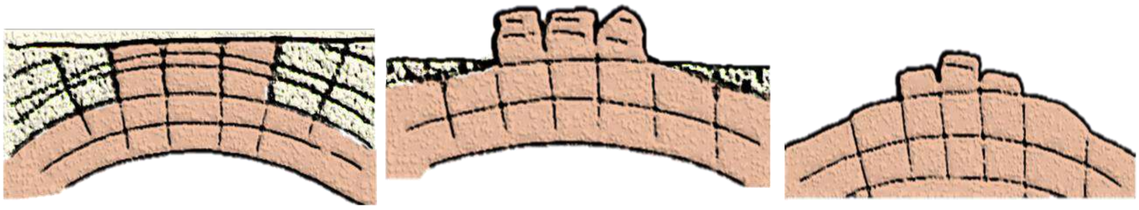
Rocky domes or nubbins are macro-landforms in transit, as a result of the disintegration in blocks of different shapes and sizes, partly in sub-superficial conditions, partly after the exhumation (the two-step or two-phase hypothesis). They are produced at the edges of the massif and they are interpreted as a higher evolutionary stage compared to the previous examples (Figs. 6 and 7).

"Castle koppies" or tors

Other landforms of steep sides are the "castle-koppies", with almost vertical joints that are continuous in depth. Although they have dome-like residual landforms, they are modified with a pronounced marginal weathering along the vertical fractures and the sub-soil. They are landforms where the vertical jointing and the curved jointing interfere with each other, providing forms as towers (Fig. 8 and 9). The granitoids have very low primary permeability, but the secondary permeability. Due to the presence of joints and cracks, the permeability may be potentially very high due to the fracturing systems, and as a consequence, they may exhibit very well developed differential weathering.

The genesis of these forms requires three well defined steps:

Figure 8 - Evolutionary stages in the formation of castle koppies (modified from Vidal Romaní and Twidale, 1998).



Source: the authors.

(a) In subaerial conditions, fresh rock and weathered rock (regolith), impacted by normal to the surface, vertical jointing where they are intercepted by curved joints (sheet structures), determining rock blocks with angular edges;
c) Partial mobilization of the regolith and incipient exhumation of fresh rock with rounded edges in the blocks:
d) Complete exhumation, revealing blocks which have been differentially weathered.

Granitic boulders

Taking the granitic domes as the largest forms, from which nubbins and "castle koppies" occur as intermediate forms within the evolutionary sequence, the final forms of less magnitude and greatness, of transitional kind, are of smaller size or they are landforms in transit. These are the granitic boulders (Figs. 10, 11 and 12).

Figure 9 - Degradation forms of domes, castle koppies or tors), with steep boundaries associated to the development of almost vertical joints.

Source: the authors.

Figure 10 - Boulders that reflect the continued disintegration of nubbins, whose arched fractures dominate the bounding vaults.

Source: the authors.

Figure 11 - Degraded boulders bounded by "sheet structures" (curved and orthogonal jointing), from which smaller boulders and channels of various sizes.

Source: the authors.

Figure 12 - Sector with degraded nubbins, with "in situ" regolith and fracturing system that bounds blocks with advanced rounding.

Source: the authors.

Minor landforms of the granite landscape recognized in the Munro Pluton

There are many smaller landforms that have been recognized in the regional environment of the Munro Pluton. This is a simplified list of minor landforms of these granitic landscapes:

a) Boulders or corestones
b) Rock platforms
c) Rills / gullies /gutters

d) Flared slopes
e) Gnammas
f) Tafoni
g) Pseudobedding: the landforms of the pseudobedding type are structures developed from horizontal joints that follow the regional slope.

Figure 13 - Boulders with tendency towards spherical and ellipsoidal shapes of intrinsically fresh rock immersed in a matrix of weathered material (regolith).

Source: the authors.

(a) Boulders or corestones

The morphology of boulders or corestones shows a tendency towards spherical and ellipsoidal shapes, intrinsically fresh, immersed in a matrix of weathered material (the regolith). As the weathered surface is being lowered down, the friable degraded material is eliminated, leaving the nuclear rocks exposed (Fig.13).Some of these boulders or corestones are found associated to minor landforms, related to the continuous disintegration of the nubbins, whose arcuate or bow-shaped structures dominate the characteristics vaults that are bounding and the material that underlies with the later external displacement of the boulders. In other cases, they are associated to the advanced disintegration of the "castle koppies", where some remains are left as "boulder towers". In general, the boulders are distributed in several sectors, although a certain distribution in terms of size takes place, with those of larger size located at the topographic highs and the smaller ones are placed instead in the lower zones. In those places where they are concentrated, they conform boulder fields (Fig.14).

Figure 14 - "In situ" Boulder field, residual blocks where erosion has re-mobilized the regolith.

Source: the authors.

(b) Rock platforms

These are flat and smoothly inclined landforms of varied morphology, essentially nude rock surfaces at the foot of elevations that cover extensive areas within the pluton (Fig.15). In some sectors they retain remnants of a thin "in situ" regolith bed. These landforms are related to horizontal fractures, markedly parallel to the edges of the intrusive body.

Figure 15 - Rock platform, slightly inclined at the foot of higher elevations, where weathering advances rapidly.

Source: the authors.

(c) Rills, gullies and gutters

These are minor landforms of lineal weathering that are produced at the surface of granitic rocks. Their morphology is basically small channels developed along the rocky walls with a certain inclination. Rills are lineal, erosion forms as grooves of sub-parallel orientation following the direction of maximum slope. Due to the coalescence of several rills, structures of greater dimensions are formed, which are named as gullies (PEDRAZA GILSANZ, 1996) (Figures 16 and 17), whereas the gutters are more evolved channels, of higher hierarchy, which act as collecting channels; both types are found in surfaces with slight inclination. Equivalent terms to grooves that are frequently used are channels, runnels, flutings and striations (VIDAL ROMANÍ, 1989). From the slopes of major forms, water flows. This water is channelized in these minor landforms (rills, gullies and gutters) towards lower zones where weathering advances rapidly.

Figure 16 - Gutters, channeled drainage lines of higher hierarchy that act as collector channel in surfaces of slight inclination.

Source: the authors.

Figure 17 - Rills are noted as lineal erosional forms that have a bearing sub-parallel orientation, following the direction of maximum slope.

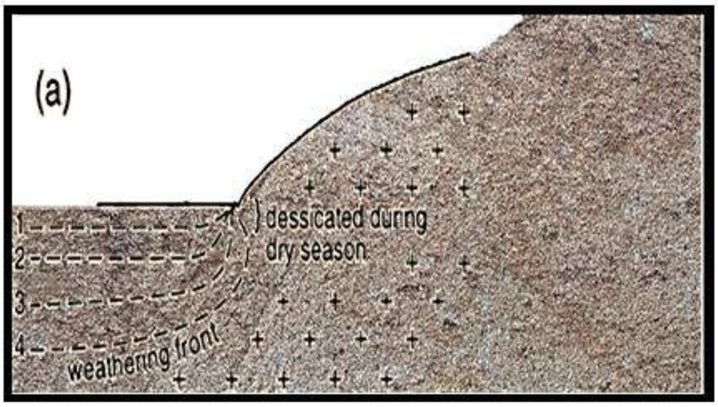
Source: the authors.

(d) Flared Slopes

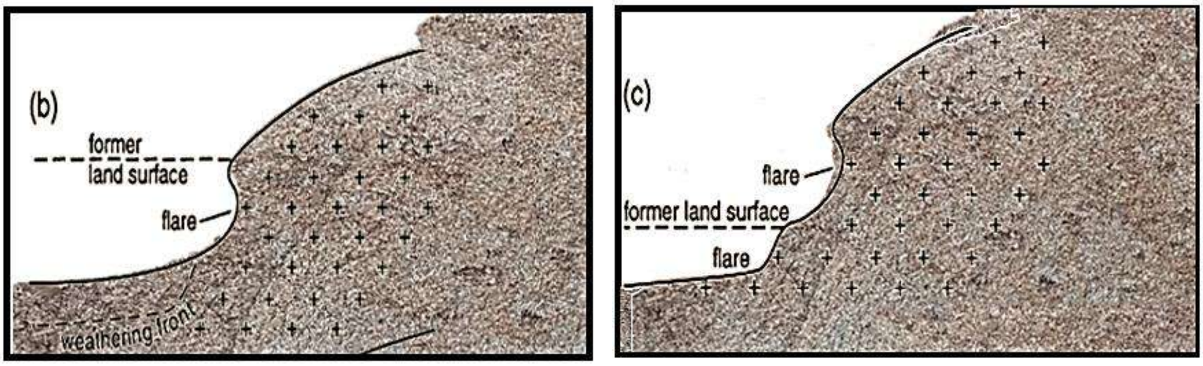
At the foot of certain slopes, acting as transitional cavities and occurring in some type of boulders, flared slopes (also called reversed slopes) have developed. These slopes represent a special form of the weathering front, developed in the piedmont zone of hills and rock blocks, due to the exposition of residual materials contained in the "in situ" regolith (TWIDALE, 1962). Basal cavities are developed as a result of the chemical attack of water and moisture in massive rocks. The cavity is due to the relative drying at the surface and close to it by weathering, whereas in depth, the moisture is persistent. The diminution of the flat surface is generated as a result of the exposition of the slopes (Fig. 18). These morphologies reflect the faster erosion-mobilization of the bedrock at the base of the slope, where water is more abundant than in other places of the system. They are produced "in situ", before the erosion of the topographic surface, and they are characterized because they present a visor, a sort of scree, at the upper part that indicates the level of stabilization of the soil previously to the erosion process. The origin of these visors starts at the interphase soil-air, before they appear totally exposed to sub-aerial conditions (TWIDALE; BOURNE, 1975).

The formation process of flared slopes is as follows:

Figure 18 - Stages of formation of the flare slopes at the foot of the scarp, with weathering and subsequent differential erosion (modified from Twidale 1976).



(a) sub-soil infiltration of moisture at the foot of the slope foot and reduction of the weathering front.



(b) and (c) lowering of the base level and denudation of the weathered material, with the consequent exposition of the weathering front as an inverted slope (flare).
Source: the authors.

The flared slopes identified at the Munro Pluton provide the boulders with a concave, inverted profile in all directions. The depth of the cavity thus formed oscillates from between a few centimeters in some boulders, to up to 1.0 meter in others. The platform over which this landform is based has a variable width of a few centimeters, and it is raised over the present soil level between 5 and 10 centimeters, bounded by a surface with a certain step development (Fig. 19). The surface of the rock is especially rugged at the walls, due to the differential weathering of the rock forming minerals (Fig. 19). At the upper part of some blocks, processes of tafoni formation and pseudobedding may also be observed (Figs. 20 and 21).

Figure 19 - Flared slope developed on a block, sitting upon a slightly stepped platform.

Source: the authors.

Figure 20 - The concave slopes in all directions may be observed. The rugged surface of the block is the product of differential mineralogical alteration. At the fractures, vegetation can be noted and lichen colonization in the cavities. The process of tafonizati

Source: the authors.

Figure 21 - Flare slopes, developed at the foot of the slope, in the mode of transitional concavities. At the visor, pseudobedding structures in transit to curved jointing (sheet structures) may be noted.

Source: the authors.

Many, abundant blocks have development of flared slopes, defined along the entire perimeter, which should allow for the evolution to fungiform types, known as mushroom rocks (Fig. 20). Due to their size and their relationship with the present soil, at least two groups of flared slopes are identified at different topographic levels. In the first group it reaches a height of 2.0 m. They may escalate from a platform of up to 5.0 m in width, or from a flat expansion, as a sort of a foot. The second group, of smaller size since it does not exceeds 1.0 meter, is developed on the aforementioned basal platforms and they may be totally or partially exposed. In this case, they show rounded edges, with a slope slightly concave that emerges from the soil, where it is common that it would be buried in the regolith (disintegrated and weathered granitoid rocks) (Fig. 22).

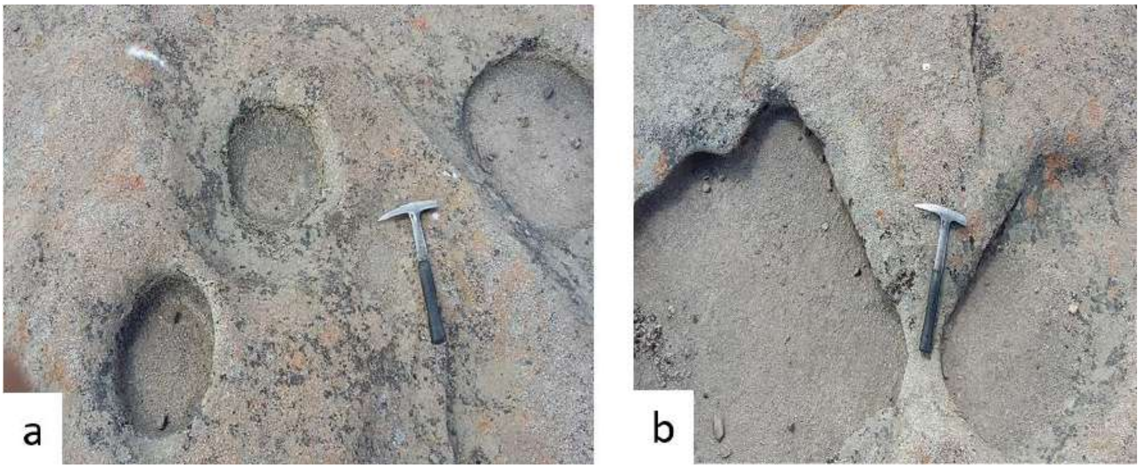
Figure 22 - Flare slopes of smaller size developed in the basal platforms with partial exposition within the regolith in which they are still immersed. They expose rounded edges, with a slightly concave slope that emerges from the soil. At the concavity, the sepa

Source: the authors.

(e) Gnammas

Gnammas (or pías, in Spanish) are weathering cavities that are developed in horizontal surfaces. They have a varied gradation of sizes and morphologies, and they are spatially associated to rills, gullies and gutters of different magnitude (Figures 25 and 26). These are microforms, excavated in massive rocks. Some of them have a flat bottom and others are concave (Fig. 23). They temporarily retain rain or melting water in colder climates. Several gnammas increase their development by collapsing into other neighboring gnammas, creating lobate and interconnected forms (Fig. 24) that are good indicators of a profound degree of evolution and an advanced phase of degradation. Some of them show well defined discharge channels.

Figure 23 - Gnammas with circular morphology and concave floor.



Source: the authors.

Figure 24 - Coalescence of a larger gnamma with a smaller gnamma, achieving a lobate morphology.

Source: the authors.

Figure 25 - Aligned gnammas (shown with red broken line) along channels and grooves through the sub-stratum with slight local slope that improves drainage (see arrows).

Source: the authors.

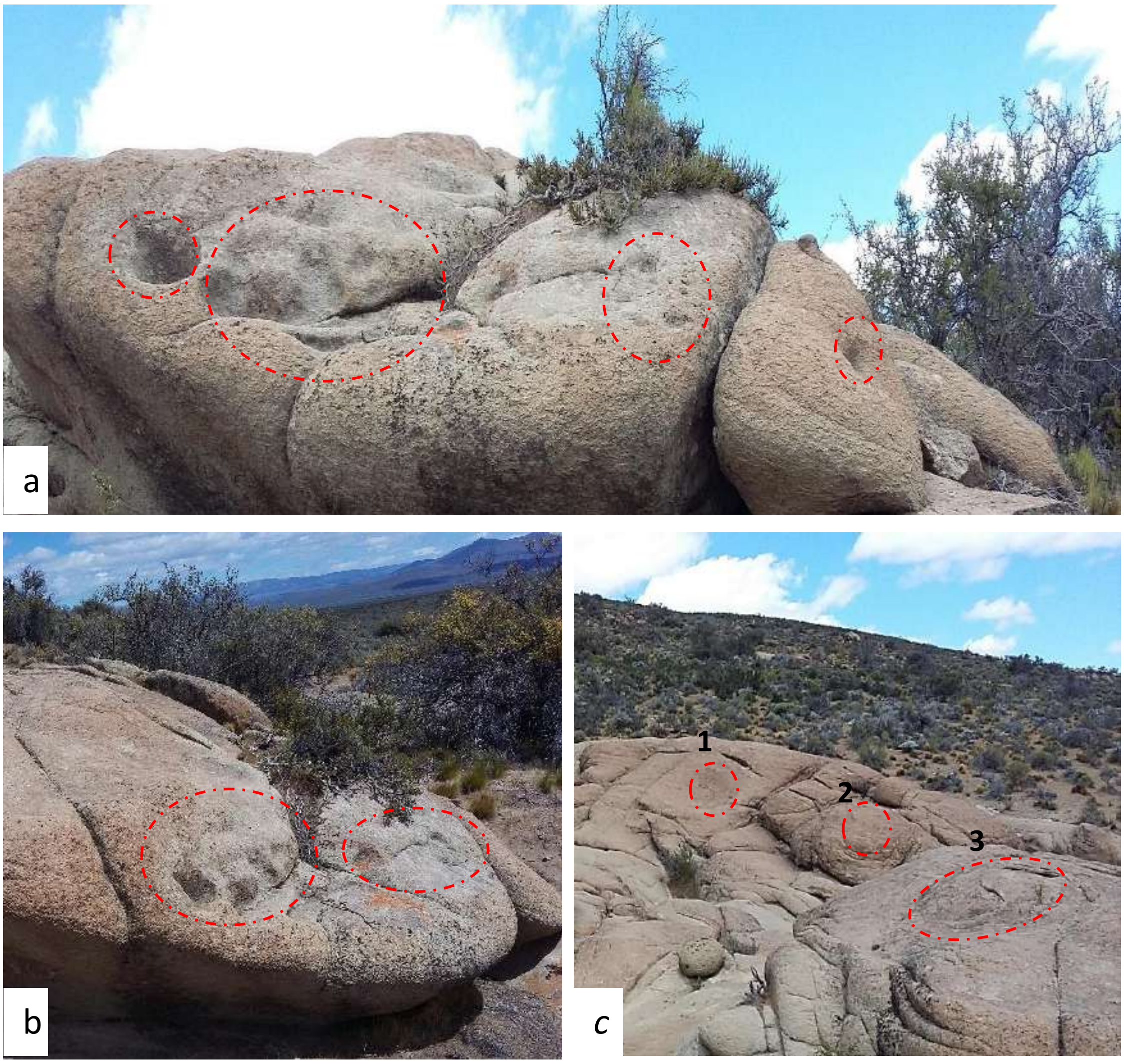
Figure 26 - Coalescence of adjacent gnammas, with high degradation, making an intricate morphological design, following gnammas and drainage channels.

Source: the authors.

(f) Tafoni (plural for tafone)

In the vertical and sub-vertical walls of slopes and blocks, cavities of the tafoni type are recognized. It is a type of cavity that it is subaerially developed in blocks or granitic walls, of gradual growth, by granular disaggregation and/or in plates (flaking or negative exfoliation), from the interior towards the exterior, progressing in those points where the weathering processes are more effective, enlarging in an anti-gravity sense, that is, from the bottom to the top (Fig. 27) (VIDAL ROMANÍ; TWIDALE 1998).

Figure 27 - a) and b). Tafoni developed on isolated boulders defined by orthogonal fracturing systems in massive outcrops. It is noted that the starting horizontal plane is a joint that constitutes the basal plane. c) Incipient tafonization process: the indicator



Source: the authors.

(g) Pseudobedding

The landforms of the pseudobedding type include morphologies related to structures developed from horizontal joints that follow the regional slope. These planar morphologies are recognized because the rock appears in thin slabs or plates of a few centimeters in thickness, simulating a stratification (pseudo-stratification). When the degree of weathering is advanced, the rock separates following these planes and slabs. These morphologies have received different denominations, among them, sheet structure, flat-lying, pseudobedding, exfoliation, curved jointing, deflaking slabs or false stratification (Figs. 29 and 30). According to their origin, they are related with the fracture cleavage in a flat fabric, or also by fragmentation induced by shearing in contact with bedrock. Pseudobedding is considered as a transitional state to sheet structure (VIDAL ROMANÍ; TWIDALE, 1998).

Basically, they are fractures, joints more or less parallel to the topographic surface, or they are cracks that cut the surface with a very low angle, following the flow lines of the magmatic rocks (Fig. 27). Massive and homogeneous slabs, of very large curving, are observed.

Massive and homogeneous slabs of great curvature are noted. Between the slabs, openings remain in the rocks, which will be the starting of cavities such as gnammas (Fig. 28).

Figure 28 - Pseudobedding determined by fractures parallel to the topographic surface, following the lines of magmatic flow. Geoforms of the pseudobedding type are structures developed from horizontal joints that follow the regional slope.

Source: the authors.

Figure 29 - Different relationships between pseudobedding and fractures, with incipient development of cavities in the convergence of the rock slabs.

Source: the authors.

Figure 30 - Pseudobedding, circular joints of the sheet type, exfoliation, curved joints, deflaking sheets or false stratification.

Source: the authors.

FINAL CONSIDERATIONS

The landscape of the Munro Pluton integrates a degradational environment that includes geoforms whose morphological expression is defined by the combined action of moderate to intense weathering and erosion processes that model these features and leave their remnants at or near the surface.

Field evidence revealed that the domes or bornhardts are complex structural forms developed in environments of resistant rocks with very few open fractures, in contrast with the highly fractured surrounding rocks, which are subject of weathering. At the Munro Pluton, the different landforms reflect a strong structural control in their genesis. In addition, the lithological control is very significant, considering the differences between the varied lithological facies that become obvious due to their distinct topographic expressions. The result is a dome landscape, where these large features are gathered one to each other, affected by characteristic curved fracture systems (sheeting). Starting from these domes, other forms are developed, such as “castle koppies” and nubbins and, due to degradation, boulders.

Tafoni are preferably located at the foot of scarps of the domes, sometimes interrelated to flared slopes, at the boundaries of sheet structures or in the blocks that result from the dismantling of those structures. In this sense, it is concluded that the fracture zones are favorable places for the tafoni development.

Concerning gnammas of different sizes that were recognized, it is estimated that those of larger size and also more degraded, are located in higher topographic levels and are also the older ones, compared to those of smaller size that are located in the lower zones.

Structural and textural observations permitted to infer that many of the identified landforms are initiated at the sub-soil, followed by the mobilization of the regolith to expose the weathering front. Other forms have association to a tectonic component that induces their development, such as pseudobedding, as well as the endogenous deformations related to the type of emplacement of the Munro Pluton. An estimated evolution of these forms would start from the magmatic consolidation and freezing, where the primary fabrics, that will generate the pseudobedding and the sheet structures, would become the preferential directions for the development of tafoni and gnammas. In general, most of the geoforms are convergent as they evolve following different pathways.

Many of the granitic landforms have an underground origin and have been exposed later on following the dismantling of the loose debris, grus or granitic lehm after a climate change or isostatic uplifting.

It could be assumed as the result of a two-step process, where the first one would be the formation of a jointing system present since very ancient times, where the water would circulate, and a second phase that would expose the weathered material as it was evacuated in the past.

Macroforms in transit are the rocky domes and nubbins, the result of the disintegration of different shapes and sizes, partly in sub-superficial conditions, partly after the exhumation (the two-step hypothesis). These forms preferably take place at the edges of the massifs and they assume a higher evolutionary stage compared to the previously mentioned forms.

Weathering brings as a consequence the loss of cohesion and erosion evacuates the regolith. Nuclear rocks or boulders would provide block fields (which are endogenous primary forms that are attributed to the protoclastic break up; PEDRAZA GILSANZ, 1996), that are preserved almost intact because they need much energy to mobilize them, as it has been noted to the “compayrés”, which should be considered as residual forms and not as accumulation forms (VIDAL ROMANÍ, 1989). These formations may generate caves or irregular cavities.

Structures of smaller size that are “opened” in this phase are polygonal cracking and pseudobedding, the latter considered as a state of transition to sheet structures. The cavities in those zones where the granite was more sensitive to weathering by granular disaggregation or in plates are also “opened” here, liberating the gnammas and the tafoni.

Some of these examples are epigenetic, formed by sub-aerial agents, particularly running water. Embossed forms, as in the palins around Meekatharra, Western Australia, are developed as a result of weathering and the formation of a regular weathering front, followed by the denudation of the regolith up to the weathering front.

This outstanding aggregation of erosional and weathering landforms, in quite different scales, origin and sizes, represent a spectacular set of geoforms which are very unusual and attractive for tourists. Besides, the Munro Pluton is located near the city of Esquel, province of Chubut, Argentina, a very important touristic center of Northern Patagonia for its natural touristic resources, either unique landscapes, impressive glaciers, pristine forests and abundant wildlife. The Munro Pluton is a valuable natural resource for its untouched environment and its unusual scenic views. This area should be considered in the future for the development of a Geopark for its unusual geomorphology, or even a Natural Reserve for the treasured junction of landforms and wildlife, that would perhaps expand the already valuable touristic offer of the city of Esquel.

REFERENCES

ARAGÓN, E.; CASTRO, A.; GIACOSA, C.; RODRÍGUEZ, C.; D´ERAMO, F.; PINOTTI, L.; DÍAZ-ALVARADO, J.; AGUILERA, E. Y.; CAVAROZZI, C.; DEMARTIS, M.; HERNANDO, I. R.; FUENTES, T.; RIBOT, A. The Palaeocene Cerro Munro tonalite intrusion (Chubut Province, Argentina). **XX Congreso Geológico Argentino. Simposio Tectónica de los Andes argentino-chilenos**. San Miguel de Tucumán, Argentina, 2017.

GOLDICH, S. S. A study in rock weathering. **Journal of Geology, 46**, p. 17-58, 1938.

LÓPEZ DE LUCHI, M. G.; SPIKERMANN, J. P.; STRELIN, J. A; MORELLI, J. Geología y petrología de los plutones de la Tapera de Burgos, Arroyo El Rápido y Cerro Caquel, Departamento Languiñeo, Provincia del Chubut. **Revista de la Asociación Geológica Argentina, 47** (1): 87-98. Buenos Aires, 1992.

MABBUT, J. A. "Basal surface" or "weathering front". **Proceedings of the Geologists Association**, London, 72, p. 357-358, 1961.

PEDRAZA GILSANZ, J. de. **Geomorfología: principios, métodos y aplicaciones.** Editorial Rueda. Madrid: 414 pp., 1996.

POMA, S. M. **Petrología de las rocas básicas precretácicas de la Sierra de Tepuel Provincia de Chubut.** Unpublished Doctoral Thesis. Facultad de Ciencias Exactas y Naturales de la Universidad de Buenos Aires, 1986. Available from: https://bibliotecadigital.exactas.uba.ar/download/tesis/tesis_n2005_Poma.pdf.

RODRÍGUEZ, C.; ARAGÓN, E.; CASTRO, A.; PEDREIRA, R.; SÁNCHEZ-NAVAS, A.; DÍAZ-ALVARADO, J.; D´ERAMO, F.; PINOTTI, L.; AGUILERA, E. Y.; CAVAROZZI, C.; DEMARTIS, M.; HERNANDO, I. R.; FUENTES, T. The Palaeocene Cerro Munro tonalite intrusion (Chubut Province, Argentina): A plutonic remnant of explosive volcanism? **Journal of South American Earth Sciences**, 2017. doi: 10.1016/j.jsames.2017.06.002.

SAVIGNANO, E.; MAZZOLI, S.; ARCE, M.; FRANCHINI, M.; GAUTHERON, C.; PAOLINI, M.; ZATTIN, M. Coupled thrust belt-foreland deformation in the northern Patagonian Andes: new insights from the Esquel-Gastre sector (41°30'–43° S). **Tectonics**, 2016. doi: 10.1002/2016TC004225.

SILVA NIETO, D.; MÁRQUEZ, M. Hoja Geológica 4369III, Paso de Indios. Provincia del Chubut. Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino. **Boletín 267**, 64 pp. Buenos Aires, 2005.

SPIKERMANN, J. P. **Contribución al conocimiento de la intrusividad en el Paleozoico de la región extraandina del Chubut.** Unpublished Doctoral thesis. Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires. Biblioteca Central «Luis F. Leloir», 173 pp. Buenos Aires, 1976.

SPIKERMANN, J. P. Contribución al conocimiento de la intrusividad en el Paleozoico de la región extrandina del Chubut. **Revista de la Asociación Geológica Argentina, 33** (1): 17-35. Buenos Aires, 1978.

SPIKERMANN, J. P.; LAGORIO, S.; MASSAFERRO, G.; LÓPEZ DE LUCHI, M.; RODOTZTA, A. P. La eruptividad de un sector del borde occidental de la Sierra de Languiñeo. Departamento Languiñeo, Provincia de Chubut. XII Congreso Geológico Argentino and II Congreso de Hidrocarburos, **Actas 1** (II): 108-118. Buenos Aires, 1993.

SUERO, T. Las sucesiones sedimentarias suprapaleozoicas de la zona extraandina del Chubut. **Revista de la Asociación Geológica Argentina, 8**(1): 37-53. Buenos Aires, 1953.

TWIDALE, C. R. Steepened margins of inselbergs from north-western Eyre Peninsula, South Australia. **Zeitschift für Geomorphologie 6**, 51-69, 1962.

TWIDALE, C. R. Geomorphological evolution. In: **Natural History of the Adelaide región**. (CR Twidale, MJ Tyler and BP Wel, editors). Royal Society of South Australia, 43-59, 1976.

TWIDALE, C. R. **Granite Landforms**. Elsevier, Amsterdam, 312 pp, 1982.

TWIDALE, C. R. Bornhardts and associated fracture patterns. **Asociación Geológica Argentina Revista, 62**(1), 139-153. Buenos Aires, 2007.

TWIDALE, C. R.; BOURNE, J. A. **Episodic exposure of inselbergs: Geological Society of America Bulletin, 86**, 1473-1481, 1975.

VIDAL ROMANÍ, J. R. Geomorfología granítica en Galicia (NW España). Granite Geomorphology in Galicia (NW Spain). **Cuadernos do Laboratorio Xeolóxico de Laxe O Castro**, Sada (A Coruña), Spain, 13: 89-163, 1989.

VIDAL ROMANÍ, J. R.; TWIDALE, C. R. Formas y paisajes graníticos. **Universidade da Coruña, Servicio de publicación, 55**, 411 pp. A Coruña, Spain, 1998.