Periglacial phenomena in the high mountains of northwestern Argentina

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Periglacial processes and features occur at high elevations in the mountains of the Sierras Subandinas, Sierras Pampeanas, Cordillera Oriental, Puna and Cordillera del Límite of Argentina (22–28°S, 65–68°W). This paper outlines our knowledge of these periglacial processes and landforms, as reported in the literature over the last 80 years. Landforms investigated include active and inactive rock glaciers, patterned ground, solifluction, proglacial lakes and other processes such as mineral segregation and concentration. Fossil periglacial landforms are an indication of past climates. Knowledge of geocryological phenomena in the northwest of Argentina has contributed to a better understanding of climate change.

Background

The northwest of Argentina is an almost unexplored region that has been little studied in terms of its periglacial and geocryological characteristics. However, its geographic position and its significance for human settlement during the Quaternary call for a detailed analysis of its geomorphological and palaeoclimatic record.

The region is located between 22° and 28°S and from *c.* 65° to 68°W, covering four distinctive, morphostructurally different regions, which have a N–S orientation and increase in altitude towards the west. From west to east these are: the Puna de Atacama, the Sierras Subandinas, the Cordillera Oriental, and the Pampean Sierras of the north (Fig. 1).

The high mountains and relief areas are of particular importance for their effect on climate and the drainage system. The Cordillera del Límite, at the western limit of this region, is characterized by the presence of volcanic craters of Tertiary and Quaternary age, some of them now extinct. The highest summits range between 5200 m and almost 6900 m a.s.l. (Fig. 1). The most important summits are the Cerro Panizos (5259 m a.s.l.), the Cerro Vilama (5678 m), the Nevado San Pedro (5750 m), the Volcán Socompa (6301 m), the Cerro Llullaillaco (6723 m), the Volcán del Azufre (5680 m), the Cerro del Laudo (6400 m), the Cerro de Incahuasi (6620 m) and the Volcán Ojos del Salado (6885 m). The eastern limit, also called Prepuna, comprises the Cordillera Oriental, with the summits ranging between 4200 m and almost 6400 m: the Sierras Santa Victoria (Cerro Negro, 5029 m) and Zenta, which continue towards the south as the Sierras de Chañi (Nevado de Chañi, 6200 m), Acay (5950 m), Nevados del Palermo (6120 m), Nevados de Cachi (6380 m), Nevados de Catreal and Nevados de Chuscha (5468 m), the extensions of which combine with the extensions of the Sierras Pampeanas in the north; Cumbres Calchaquies, Sierra del Cajón or Sierra de Quilmes (Cerro Negroara, 4200 m) and further south, the Sierra del Aconquija with the Cordón de las Animas and the Nevados del Aconquija (Morro del Zarzo, 5064 m; Cerro Negro, 4700 m; Cerro del Bolsón, 5500 m and Nevado del Candado, 5450 m). These mountain ranges or belts, with an average height of over 5000 m, converge in the Puna region, a high-altitude plateau with an average elevation of over 3500 m, with salt pans, an arid climate and a markedly reduced humidity. The orographic belts lie above the 0°C isotherm (4600 m a.s.l.) but, at present, hardly any evidence of glaciers is found. During the Pleistocene, however, these belts were covered by glaciers at least three times.[1]

In this geographical setting the climatic changes during the Quaternary, and in particular during the Late Pleistocene and Holocene, left geomorphological evidence that may be associated with the intense action of a periglacial environment, taking into account the region's altitude with pronounced annual temperature variations and strong mechanical weathering, only one of many indicators of a periglacial high mountain environment.

Numerous authors since the beginning of the last century have referred to present and past periglacial conditions in the northwest of Argentina. Their observations are summarized here.

Climate setting

Owing to its proximity to the Tropic of Capricorn, the study area experiences a warm climate with little seasonal variation of daylight hours. However, the altitudinal diversity, the N–S orientation of the mountain ranges as well as its continentality are responsible for a complex mosaic of climatically different regions, temperature variations depending on altitude, and a variable distribution of mean annual precipitation, with a pronounced rainfall peak in summer. This creates extreme situations: very warm and humid climates in the eastern valleys and cold deserts on the plateau of the Puna region.

Rainfall is intense in summer, with a marked east to west gradient, and is associated with easterly winds from the Atlantic which penetrate as NE flows into the mountain reliefs. On the eastern borders of the mountains, orographic precipitation falls at two main levels: the one at an altitude of 1500–1800 m with annual precipitation between 1000 and 2000 mm, with a steep decline towards the west until it reaches values of less than 100 mm in the Puna region (some areas receive at little as 50 mm).[2] In some cases, in the Sierra del Aconquija and at Cumbres Calchaquíes, the first orographic barrier to the easterly winds, mean annual precipitation of 2500 mm (at 2500 m) has been recorded.[3] Above this level, rainfall declines on the eastern slopes of these mountains to 600–500 mm/yr.[2]

In the Puna region the mean annual air temperature (MAAT) is less than 5°C, with a large daily amplitude. The mean annual maximum and minimum temperatures are 16°C and –4°C, respectively. An occasional very strong effect is caused by the so-called 'white winds'. They cause snowstorms produced by the entry of westerly winds from the Pacific, which at heights above 5000 m penetrate the area in winter. In the Puna region, winds blow predominantly from the west; their frequency and intensity increase slightly during the dry winter season. Humid easterly winds blow in summer. Despite their relatively rare

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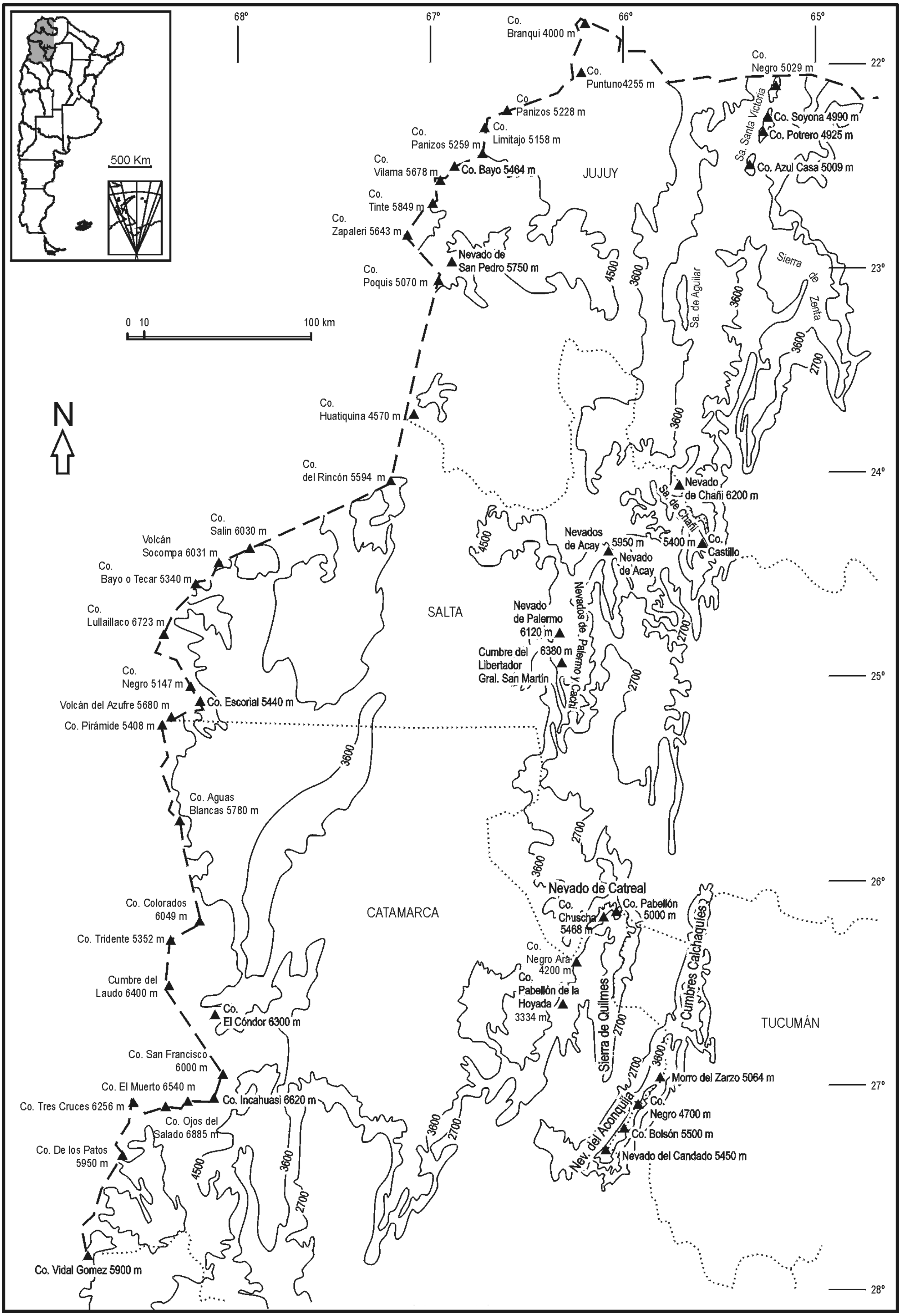

Fig. 1. Map of the study area.

occurrence, the easterly winds bring 88–96% of the area's precipitation.[4] In summary, the Puna region receives precipitation mainly during the summer, with a general decrease towards the west. The evapotranspiration is high, with the result that the mean annual relative humidity is less than 40%. The global annual radiation is over 200 kcal/cm^2, according to Minetti.[2]

Meteorological data for this part of the country are sparse and concentrated on the eastern slopes of the valleys. Weather stations in the Puna region are scarce and the few existing ones have records of a few years only. To obtain a better idea of the climatic conditions which favour a periglacial environment in a high mountain area, more climatic data will have to be collected, so that the circumstances that enhance its presence can be defined more precisely. The available climatic data for the region have been compiled by Minetti.[2]

Table 1. The glacial and periglacial processes and landforms in the northwest of Argentina reported in the literature.

Site (range) Mountain name Peak name	Reference	Summit elevation (m a.s.l.)	Periglacial processes and landforms
Puna	14	4000	Rock glaciers
Puna	15, 16	4000	Rock glaciers
Nevado de Queva	18	6130	Rock glaciers
Co Granadas	18	5705	Rock glaciers
Acay	20	4500	Rock glaciers
Nevados de Cachi	20	4500	Rock glaciers
Sierra de Santa Victoria	21, 22	4500	Rock glaciers
Sierra del Aconquija	23, 24, 26, 28	4000	Rock glaciers
Nevados de Chuscha	11	4200–4700	Rock glaciers
Mina Pirquitas	21	4000	Frost depth
Vn Ojos del Salado	27	6885	Frost depth
Puna	9	4000	Rock weathering
Puna	14	4000	Rock weathering
Puna	15, 16	4000	Rock weathering
Puna	18	4000	Rock weathering
Vn Tuzgle	29	5480	Sorted polygons.
Vn Socompa	29	6031	Sorted polygons.
Cumbres Calchaquíes	4	4200	Sorted polygons.
27°S	30	2600	Solifluction
Valle de Tafí	31	–	Solifluction
El Rincón	26, 28, 32	2500	Solifluction
Puna	14	–	Cryoplains
Cumbres Calchaquíes	33	4200–4700	Cryoplains
Cumbres Calchaquíes	4	4200	Needle ice
Nacientes del Río Los Reales	28	2800	Needle ice
Sierras del Aconquija Cumbres Calchaquíes	34	–	Mass wasting
Sierras del Aconquija Cumbres Calchaquíes	31	–	Mass wasting
Sierras del Aconquija Cumbres Calchaquíes	12	–	Mass wasting
Sierras del Aconquija Cumbres Calchaquíes	33	Over 4000	Peatlands
Nacientes del Río Los Reales	26	2800	Peatlands
Cumbres Calchaquíes y Sierra del Aconquija	12	–	Proglacial lakes
Cordillera Oriental	35	–	Proglacial lakes

Periglacial regions in the northwest of Argentina

The relation between mountain permafrost and climate is poorly understood. Mountain permafrost is the result of a complex interaction of environmental factors, the most important of which is climate. The general climatic conditions in high mountain areas depend mainly on latitude, height and continentality and, less importantly, on local conditions which produce variations on a limited geographical scale.

In high mountain areas the periglacial environment may be classified into different zones as a function of altitude. Gorbunov[5] introduced a classification of relations between permafrost/soil and temperature/vegetation based on an index of continentality. The latter is based on the difference between the elevation of the glaciers' equilibrium line and the lowest permafrost limit. This index allows us to distinguish five different types of permafrost along the Andes: the Equadorian type, the Himalayan type, the Central Andean type, the Tibetan type, and the New Zealand type. The study area belongs to the Central Andean type.

Corte,[6] in his map of current geocryological processes in Argentina, established the lower permafrost limit at 4000 m at the latitude of Salta, following a method similar to Gorbunov's, as part of a periglacial inventory of the area.

Garleff and Stingl[7] argued for a 9°C depression of the mean annual air temperature during the Pleistocene for the Puna region. On the evidence of geomorphological data, among others, the corresponding descent of so-called 'almost continuous permafrost' and strong cryogenic activity is estimated to have been 1000 m in the NW of Argentina.[8,9]

Glacial and periglacial processes and phenomena

Table 1 summarizes the glacial and periglacial processes and landforms in the northwest of Argentina that have been reported in the literature of the last 80 years.

Present-day glacial conditions. There are several records of glacial cirque floors; Penck[10] determined contemporary glacial cirque floors at 5000 m. The average height of these features on the eastern slopes of the Sierra Aconquija is 4300 m.[1] On the western slopes of the Aconquija, glacial cirque floors are formed at over 4400–4600 m.[11] In the Sierra de Quilmes and Nevados de Chuscha (5468 m), glacial cirques are at 4200–4700 m and are now occupied by several small rock glaciers.[12] In Cumbres Calchaquíes, there are glacial features at Quebrada del Matadero (*c.* 4700 m) and in the Alto de la Mina Mt (*c.* 4700 m), in the Laguna de Huaca Huasi area.[13,14]

Rock glaciers. Keidel's studies on Puna[15] were the first to describe block or rock slopes as characteristic of the region. He probably included rock glaciers in these deposits. He described their lower levels up to 4000 m a.s.l., did not observe any activity, but recognizes their palaeoclimatic importance and considers them an example of morphology characteristic of cold deserts.

Catalano,[16,17] in ref. 6, referred to glacial action in Puna and pointed out the presence of rocks agglomerated by ice and flowing under gravity as a glacier. He named these forms litho glaciers.

Igarzábal[18] noticed the presence of an ice nucleus covered by detritus in the Nevado del Queva (6130 m) and Granadas Mt (5707 m), that fed permanent streams. He called them glaciolithic deposits, using Corte's classification of rock glaciers.[19]

Igarzábal[20] compiled an inventory of active and inactive rock glaciers in the Acay region and the Nevados de Cachi, and determined the lower limit of rock glaciers at 4500 m.

In the Sierra de Santa Victoria, Corte *et al.*[21] observed active rock glaciers at 4500 m a.s.l. In the same region Zipprich *et al.*[22] distinguished three generations of rock glaciers, with presently active glaciers, and determined the lower limit of periglacial processes at 700 m, at a temperature of 6°C, corresponding to *c.* 27 980 ± 190 BP.

Ahumada[23] stressed the importance of setting high basins in the Sierras Pampeanas in order to detect rock glaciers that feed local rivers. She compiled an inventory of active and inactive rock glaciers of the northernmost region of Sierra del Aconquija.[24, 25] Figure 2 shows the location of rock glaciers in Cordón de las Ánimas, on the eastern slopes of the Sierra del Aconquija.[26]

Frost-depth measurements. Corte *et al.*[21] measured the freezing depth in Pirquitas mine (4000 m a.s.l.) and found a stable temperature of 0°C at a depth of 1 m. This observation corresponds to a depth of 1.30 m, according to thermistor readings. Cobos and Corte[27] registered a 70-cm-deep seasonal frost in permafrost at 4700 m, on the Volcán Ojos del Salado.

Needle ice. Halloy[4] described the action of needle ice on the grassland around Huaca Huasi lagoon, in Cumbres Calchaquíes, at 4000 m a.s.l. In a nearby region, at a lower elevation, Ahumada *et al.*[28] described the action of needle ice as leaving a rake-like pattern on the ground, on slopes of less than 5° at 2500 m, indicating diurnal freezing.

Cryoweathering. Penck,[10] Keidel[15] and Catalano[16] attributed the mechanical weathering phenomenon in Puna to the great daily and seasonal temperature variation. Igarzábal[18] reported the extensive cryoweathering of Puna's land surface, that causes generalized surface erosion.

Patterned ground. Corte[29] identified patterned ground associated with the Tuzgle (5480 m) and Socompa (6031 m) volcanoes. Halloy[4] found small areas of patterned ground in Cumbres Calchaquíes, at 4000 m.

Solifluction. Auer[30] reported that, at 27°S, the solifluction limit has descended 2000 m and is now at 2600 m. Sayago and Collantes[31] described solifluction processes in the smoothing of the Tafí Valley's slopes. Ahumada *et al.*[26,28,32] described solifluction grounds at El Rincón, Sierra del Aconquija, in a seasonal freeze-thaw environment, between 2500 and 4000 m a.s.l.

Cryoplanation. Keidel[15] was one of the first to mention cryoplains and he called them 'summit' cryoplanation surfaces. Though he did not indicate specific sites, he recognized their palaeoclimatic importance in Puna.

In the Sierras del Aconquija and Cumbres Calchaquíes, at over 4000 m, Halloy *et al.*[33] described a high plain modified by glacier and periglacial action, with beach-like terraces.

Mass wasting. The big clastic deposits surrounding the Sierras del Aconquija and Cumbres Calchaquíes have been described in the literature by Bossi[34] and Porto and Danieli[35] as fanglomeratic deposits accumulated by alluvial and/or periglacial activity.

Sayago and Collantes[31] and Sayago *et al.*[13] described the large cenoglomeratic clastic accumulations over the covered glacis of the eastern slopes of the Sierra del Aconquija and the Cumbres Calchaquíes. They concluded that they originated as deposits under gravity at the same time as the glacial episodes detected in the peak area, which they considered to be of periglacial origin.

Peatlands. Halloy *et al.*[33] noted the existence of mountain peatlands under conditions of seasonal freezing in the high peaks of the Sierra del Aconquija and Cumbres Calchaquíes.

Ahumada *et al.*[26] described peatland deposits at 2800 m, in the Reales River basin, in a seasonal freezing environment.

Proglacial lakes. Proglacial lake sequences have been described by Sayago and Collantes[31] and Sayago *et al.*[13] in the Mollar region, Sierra del Aconquija. Ahumada and Vides[36] deduced periglacial conditions in the lake deposits of Cordillera Oriental.

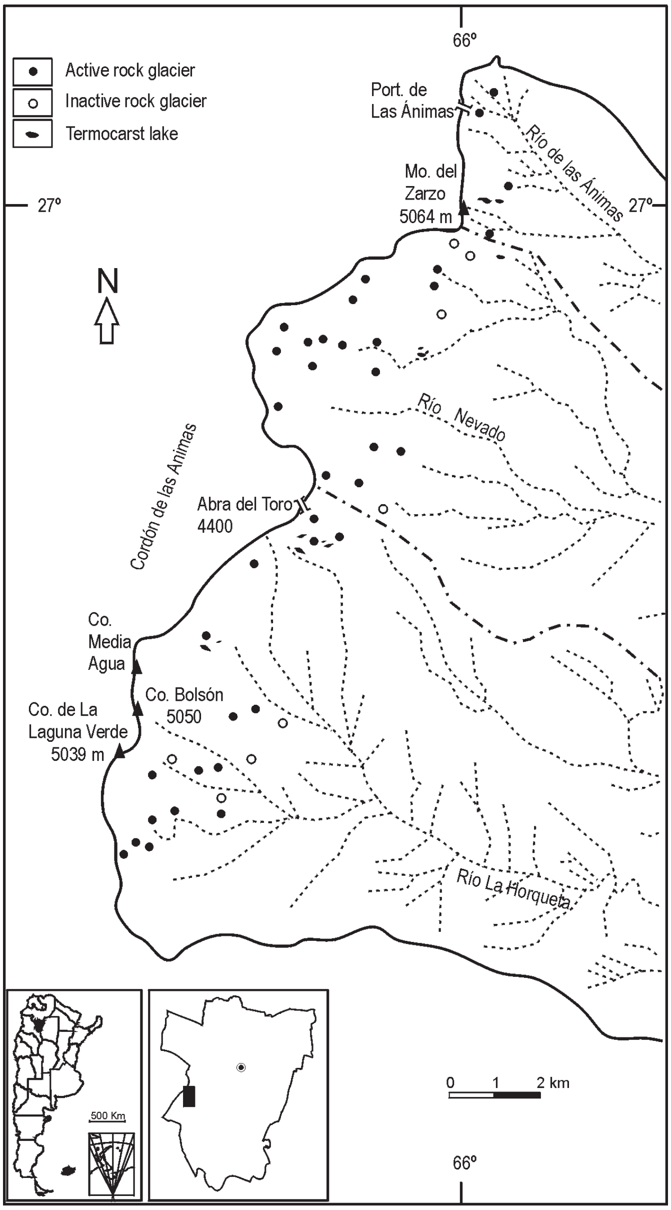

Fig. 2. The location of rock glaciers in Cordón de las Ánimas.

Chemical segregation in freezing conditions. Ahumada and Vides[36] identified mirabilite ($Na_2SO_4.10H_2O$) by X-ray diffraction in lake sequences of the southern region of Cordillera Oriental. The presence of hyper-hydrated sulphate indicates a cooling of the water due to the proximity of glaciers. Mirabilite[37] is produced by the segregation of pure sodium sulphate crystals. These deposits are evidence for an active periglacial environment, and were dated by Trauth and Strecker[38] as 35 650 ± 380 yr BP.

Heavy minerals concentration. Ahumada and Heinrich[39] analysed the Pb, Sn and Ag content of 230 drillings in the alluvium terraces at Pirquitas mine in Puna. The metals were concentrated mainly at a depth of 1.10–1.30 m. They attributed these concentrations to the seasonal freezing and thawing that took place after mineral deposition during the Late Pleistocene.

Altitudinal zonation. Garleff and Stingl[7] defined the regional characterization of periglacial activity in relation to altitude. More recently, Ahumada *et al.*[26] established the elevation of periglacial processes in the Reales River basin (Sierra del Aconquija), and distinguished two levels: a lower level, from 2500 to 4000 m, with seasonal frosts, needle ice action and solifluction; and an upper level, from 4000 to an average of 4500–5000 m, with intense gelifraction, active and inactive rock glaciers, talus, old moraine deposits, and glacial cirques.

Conclusions

Many periglacial landforms have been reported from the high mountains of northwestern Argentina. They include rock glaciers, sorted polygons, frost weathering, solifluction, lakes, and periglacial mass wasting. Some periglacial phenomena, such as rock glaciers, solifluction, and frost weathering are active today. No investigations involving instrumented measurements of actual conditions have been conducted. Several authors deduced, however, that during the Last Glacial Maximum the altitude of periglacial activity descended between 1000 and 700 m below the present, corresponding to a temperature decrease of approximately 9°C to 6°C.

Among the questions to be addressed regarding periglacial phenomena in northwestern Argentina are the following:

- What is the extent and character of large-scale landforms in the high mountains?
- How much did climate permit the development of such geological features in a subtropical region?
- What is the relationship between the nature and altitude of fossil periglacial phenomena and past climate?

Improved knowledge of the character of the periglacial environment in this region will contribute to the development of models for sustainable development. These models may assist in the protection against natural disasters caused by anthropogenic interference in the environment.

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