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Short Communication

Monitoring of Mountain Permafrost in the Central Andes, Cordon del Plata, Mendoza, Argentina

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ABSTRACT

Sixty per cent of the Rio Blanco basin (54 km^2), located between 32°54′ and 33°01′S and between 69°27′ and 69°15′W, in the Cordón del Plata, Frontal Cordillera, can be considered to be periglacial. The most important forms in the area are rock glaciers, two of which, Morenas Coloradas and El Salto, are active down to 3400 and 3600 m ASL respectively. The rock glaciers are not in equilibrium with the present climate since the mean annual air temperature is 1.6 °C at 3560 m ASL and the 0 °C air isotherm is calculated to be at 3860 m ASL. A third landform is the cryoplanation surface Lagunita del Plata which, at an elevation of approximately 4000 m ASL, has a mean annual temperature of −2 °C and contains bodies of insular permafrost. © 1997 by John Wiley & Sons, Ltd.

RÉSUMÉ

Soixante pour cent du bassin du Rio Blanco (54 km2), situé entre 32°54′ et 33°01′S et entre 69°27′ et 69°15′ ouest, dans le "Cordon del Plata, Frontal Cordillera" peuvent être considérés comme périglaciaires. Les formes les plus importantes de la région sont des glaciers rocheux dont deux d'entre eux, "Morenas Coloradas" et "El Salto", sont actifs respectivement jusqu'à 3400 m et 3600 m d'altitude. Les glaciers rocheux ne sont pas en équilibre avec le climat actuel bien que la température moyenne actuelle de l'air est de 1.6 °C à 3560 m et que l'isotherme de l'air est, par calcul, estimée se trouver à 3860 m d'altitude. Une troisième forme est la surface de cryoplanation "Lagunita del Plata" qui, à une altitude d'approximativement 4000 m au dessus du niveau de la mer, a une température moyenne annuelle de −2 °C et contient de îlots de pergélisol. © 1997 by John Wiley & Sons, Ltd.

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KEY WORDS: rock glaciers; cryoplanation terraces; mountain permafrost

INTRODUCTION

South American periglacial geomorphology has focused on cryogenic processes associated with mountain permafrost (particularly in the Andes) and on periglacial phenomena that develop at high altitudes where low temperatures occur daily or seasonally. During the Pleistocene, however, permafrost extended beyond the Andes into the extra-Andean sierras and far into Patagonia (Trombotto, 1996). This short communication summarizes investigations of periglacial features and permafrost

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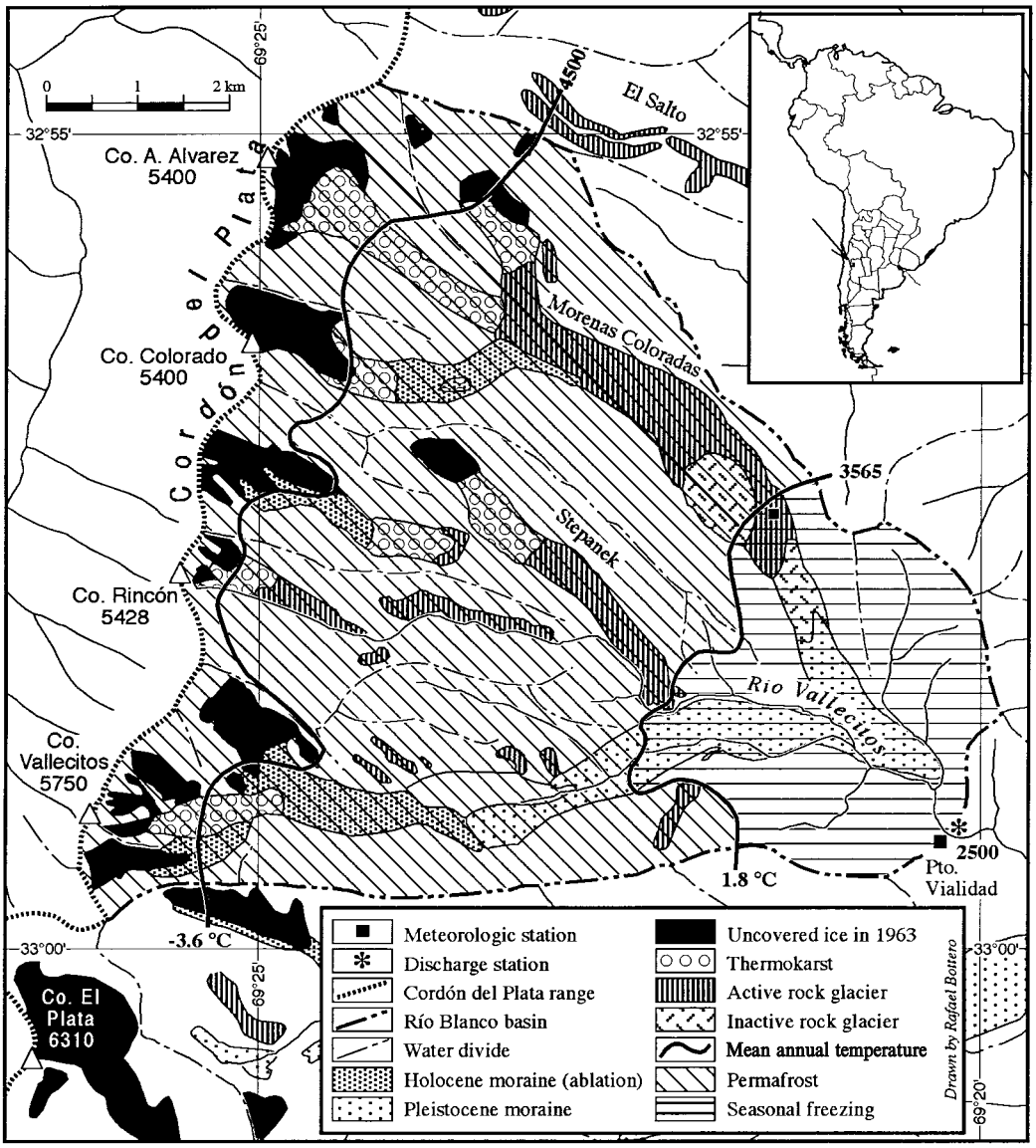

Figure 1 Map of study area, Cordón del Plata range, Mendoza, Argentina. Modified from Corte and Espizua (1981).

carried out since 1980 at Cordón del Plata, Frontal Cordillera, Mendoza, Argentina (Figure 1).

STUDY AREA

The study area lies between 32°54′ and 33°01′S and between 69°27′ and 69°15′W. The most important cryogenic processes in this part of the Central Andes are frost shattering, vertical and horizontal sorting, cryoturbation, solifluction, nivation, permafrost creep and frost-related mass movement processes on slopes. These processes create micro and meso landforms including patterned ground (nets, stripes, circles and polygons), tors, solifluction lobes, solifluction terraces, garlands, nivation hollows, Richter denudation slopes (Glatthänge), detrital slopes, asymmetrical valleys, avalanche chutes, cryoplanation surfaces and rock glaciers.

Three features comprise the focus of studies in the region: (i) the Lagunita del Plata cryoplanation surface, (ii) El Salto, a rock glacier of cryogenic or

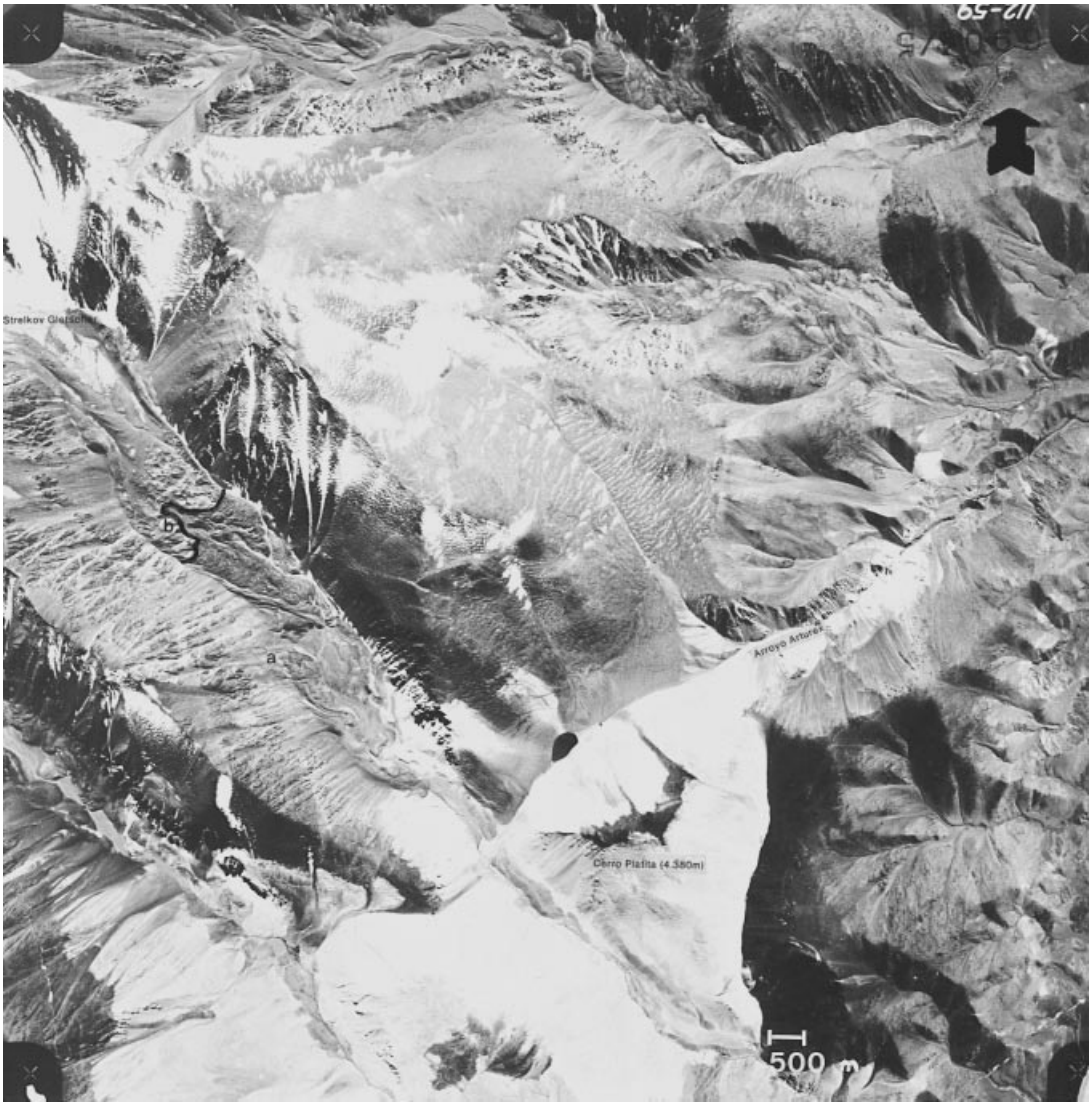

Figure 2 Aerial photograph of Lagunita del Plata, Strelkov Glacier and south wall of the Cerro El Plata (6310 m ASL). (a) Talus rock glacier; (b) 'Roots' of glacigenic rock glaciers. Photo source: IGM, 1963.

talus origin, and (iii) Morenas Coloradas, a rock glacier of glacigenic origin. These forms are typical of the present-day semi-arid cryogenic environment in the Central Andes.

The term 'glacigenic' rock glacier is used here to describe a feature whose genesis is related to a glacier and its moraines. This landform is common and readily distinguishable in the Cuyo region of Argentina. In its upper part, there is an obvious glacial cirque and trough. This is connected to relatively clean ice which becomes progressively covered by sediment, often shows signs of thermokarst, and eventually leads to an area where the sediment cover is deformed. The lowest zone has the typical characteristics of a rock glacier: a porridge type appearance (Barsch, 1992) with surface forms indicating flow in varying directions downslope. Above a certain elevation, the morainic material forms 'roots' and this is where the creep of perennially frozen moraines starts (Figure 2b). The kind of ice described by Haeberli and Vonder Mühll (1996) has not yet been observed for glacigenic rock glaciers in the study area. Corte (1980) called these forms secondary rock glaciers to

distinguish them from primary or talus rock glaciers where glacial cirques are absent.

Primary rock glaciers are small, develop on single valley sides, and are connected to one or more avalanche chutes (Figure 2). These rock glaciers have developed since the last glaciation when the Andean valleys were filled with large glaciers.

RESULTS

Lagunita del Plata

The Lagunita del Plata (see Figure 2) has a mean annual temperature of about −2 °C and a mean annual precipitation of 600–650 mm at a height of approximately 4000 m ASL. The lower elevational limit of perennial snowpatches is about 4300 m ASL on south-facing slopes.

The presence of embryonic rock glaciers or protalus ramparts with signs of movement indicates that the lower limit of discontinuous permafrost in the valley of the Strelkov glacier (southern slope of Cerro El Plata, 6310 m) is at 3700 m ASL. Below this elevation, processes associated with seasonal frost prevail. On the southern slope of the Lagunita del Plata, the active layer is 90 cm thick at elevations of 4400–4500 m ASL. Seismic and temperature data show that insular permafrost exists only below depths of 9–10 m, even on south-facing slopes (Trombotto, 1991).

Stone circles on the Lagunita can reach a diameter of more than 6 m and stripes exhibit a range of deformation structures depending on solifluction movements on individual slopes. Stripes are frequently associated with thermal contraction cracks. Solifluction lobes composed of greywacke move at speeds of 3–6 cm/a. Maximum rates of solifluction occur on detrital slopes at elevations above 4300 m ASL. As in the valleys, the periglacial slopes are asymmetrical and tend to appear as two different types: detrital slopes with frequent solifluction forms and Richter denudation slopes. Granitic slopes vary in angle between 21° and 34° and greywacke slopes between 24° and 31°.

Solar insolation is very high in the Andean region and influences cryogenic phenomena and the flow of streams and rivers. Soil temperatures on the northern slopes of the Lagunita del Plata can exceed 30 °C during the summer. Daily temperature cycles have been registered to a depth of 90 cm and the intensity of insolation controls soil thaw. Arroyos and rivulets emerge from rock glaciers and detrital slopes. The significance of periglacial hydrology for the semiarid areas of Mendoza bordering the Andes and particularly the importance of rock glaciers has been pointed out by Corte (1976; 1978) and Buk (1983). Similarly, Trombotto (1991) recognized the importance of the detrital slopes as water sources.

The origin of the cryoplanation surface at the Lagunita del Plata and of other Andean landforms suggests greater cryogenic activity during the Pleistocene, which may have coincided with a time of increased humidity in the region. Intense periglacial conditions favoured great accumulation of frost-shattered material and large rock glaciers developed. Active forms are much smaller (Trombotto, 1991).

El Salto

Primary rock glaciers are fed by avalanche chutes (see Figure 2). At the rock glacier El Salto (see Figure 1) surveys have been undertaken in order to determine the creep rate. Between 1981 and 1986 temperatures at elevations between 3500 and 3600 m were measured in the active layer to a depth of 1 m with a multipoint temperature recorder (Grant). On the basis of these measurements Buk (1983) determined that the permafrost table was at a depth of about 3 m and the base of the permafrost at 68 m. Similar conclusions were reached by Barsch and King (1989). As an illustration of the importance of avalanches to these forms, the base camp there was destroyed by an avalanche in November 1983.

Morenas Coloradas

The surface of the basin of Morenas Coloradas (see Figure 1) is 54 km^2, of which 10.4 km^2 is uncovered ice and 10.5 km^2 seasonally frozen ground. The remaining 60% of the surface is typically periglacial with rock glaciers as the most important forms.

In a glacigenic rock glacier, the clean glacier ice ends in detritus-covered or morainic tongues which result in glacigenic ice being incorporated within the substrate. In this way, ice persists at lower altitudes and under very arid conditions (Lliboutry, 1986; Garleff and Stingl, 1986; Schrott, 1992). Interconnected rock glaciers are generated which undergo different phases of activity not always in agreement with those expected as a result of their elevations. That is, they continue to show signs of activity not only at the height of the present

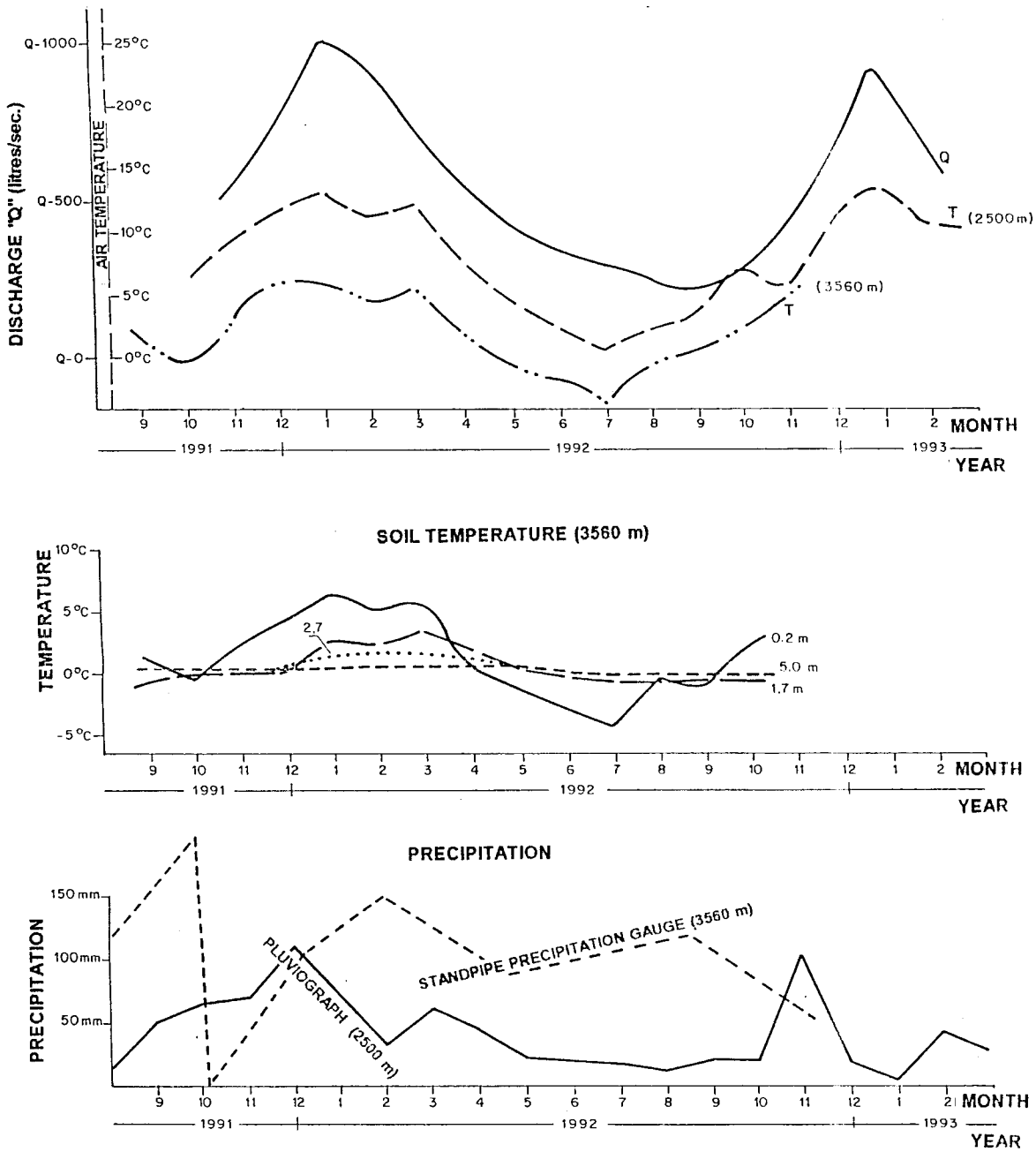

Figure 3 Discharge, precipitation, air and soil temperature recorded at Morenas Coloradas rock glacier, Cordón del Plata, Mendoza, Argentina.

0 °C air isotherm, but at lower elevations. In the last step downwards towards the valleys these rock glaciers become inactive, and finally morphologically relict or fossil rock glaciers are found.

Meteorological, hydrological and geophysical measurements as well as drillings 5 to a depth of 5 m have been carried out in Morenas Coloradas (Figure 3). At an elevation of 3560 m the temperature oscillates around 0 °C (with a maximum variation of 0.5 °C) at depths between 4 and 5 m. The annual precipitation (1991–93) is 630 mm and the mean annual temperature is 1.6 °C. Using a

calculated lapse rate of 0.52 °C per 100 m, the 0 °C isotherm occurs at approximately 3860 m, which represents a considerable rise in comparison with earlier years. It is assumed that this value is strongly influenced by climate warming in the 1980s and 1990s.

Temperatures measured at different depths in Morenas Coloradas at 3560 m are positively correlated with the discharge of Rio Vallecitos (see Figure 3) (correlation coefficients of 0.8–0.9; significance $p = 0.01$). There is no correlation with snowfall data, however, because of the influence of the 'zonda', a very dry and warm wind (up to 100 km/h) which impedes the accumulation of snow. Between 1978 and 1979, the zonda was active for more than 1000 hours. Discharge from the basin is of good quality and averages 505 l/s with a range from 230 l/s (early spring) to >1000 l/s (summer). In comparison, Schrott (1994) calculated the discharge of a rock glacier in the arid region of San Juan, Argentina to be only 5–8 l/s.

DISCUSSION

Haeberli (1983) shows an activity field for the periglacial mountain environment of the Alps in which cryogenic processes are determined by the temperature (elevation) and precipitation (continentality). The lower boundary of discontinuous permafrost restricts the presence of rock glaciers and cryogenic processes. Above this limit cryogenic processes are possible but below it, precipitation and continentality restrict the occurrence of permafrost. The permafrost limit in the Swiss Alps is between −1 °C and −2 °C, and this is similar to the discontinuous permafrost boundary in the Sub-Arctic. In the Central Andes, however, a higher temperature limit exists since discontinuous permafrost occurs within active rock glaciers right down to the 0°C isotherm and even 100 m or more below its elevation. It appears that regional aridity intensifies present-day periglacial processes. In this context, Garleff and Stingl (1986) mention that the limit of 'almost' continuous permafrost is between the −2 °C and −4 °C air isotherms with precipitations of 500 to 900 mm. This elevation limit is approximately 4500 m ASL at 33° S and over 5000 m at 30° S (Scholl, 1992) and from there on downwards, in a strip over 1 km wide, active cryogenic phenomena are found.

The activity of the rock glaciers El Salto and Morenas Coloradas has been interpreted on the basis of geophysical data. In the case of El Salto activity extends down to an elevation of 3600 m, and in Morenas Coloradas the limit is still lower at 3400 m (Barsch and King, 1989). Within the altitudinal limit of inactivity,* Corte (1988) has interpreted the occurrence and internal structure of permafrost using geoelectrical data.

The distribution of permafrost in the area is best described as insular. It is probable that insular permafrost outside the environment of rock glaciers even occurs below 4500 m in connection with perennial snow patches and detrital slopes, as at the Lagunita del Plata. It can certainly be stated that owing to warming in the last few years, the tongues of many big rock glaciers in the Central Andes have become remarkably unbalanced and even show an inertia towards a climatic readjustment. It is questionable, however, whether the scale of a short-term climatic fluctuation is relevant for the rock glacier. Despite the evidence that between 3400 and 3700 m certain parts of the rock glaciers are active, abundant thermokarst also indicates permafrost degradation. It should be noted, however, that ground ice may be preserved for long periods, as at the salt lakes in the Puna de Atacama at 4300 m at approximately 22° S where ice is interpreted as being a relic of the Little Ice Age (Hurlbert and Chang, 1984).

CONCLUSIONS

The following are the criteria for permafrost occurrence in the Central Andes at 33° S:

(1) Periglacial processes are active near Mendoza with a regional character due to the effect of the aridity. The 0 °C mean annual air isotherm is not the decisive factor for the presence of cryogenic activity (e.g. Morenas Coloradas and El Salto rock glaciers).
(2) Insular permafrost occurs outside rock glaciers at elevations above 3600 m ASL (as at the Lagunita del Plata), but as expected, local variability in factors such as geomorphology, exposure, wind, bedrock, snow patches, etc. cause it to be very patchy.
(3) Permafrost distribution is influenced by local conditions: for example, the lower limit is at 3400 m ASL on the Morenas Coloradas rock glacier and 3600 m ASL at the El Salto rock glacier.

* Approaching the altitudinal limit of inactivity (3200 m ASL., see Barsch and Happoldt, 1985).

(4) The thermophysical inertia of medium-scale landforms to climatic fluctuations means that a considerable amount of time must elapse before the forms attain equilibrium with new climatic conditions.

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