Indicators of present global warming through changes in active layer-thickness, estimation of thermal diffusivity and geomorphological observations in the Morenas Coloradas rockglacier, Central Andes of Mendoza, Argentina

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A B S T R A C T

Temperature profiles from the active layer have been analysed for 2 sites on the composed rockglacier Morenas Coloradas, Córdón del Plata, Mendoza, Argentina, using monitoring data collected between 1989 and 2008 in order to characterize the impact of global warming in the cryolithozone of the Dry Andes at these latitudes (32°–33° S).

A significant change in the active layer and suprapermafrost of this rockglacier of the Córdón del Plata is registered at the monitoring sites. The observed changes imply direct consequences for the cryogenic environment and the Andean creeping permafrost. The nose of the Morenas Coloradas rockglacier for example (Balcón I, 3560 m a.s.l.), already expresses inactivity; the permafrost table is found at great depth (7.5–9 m).

Data collected at Balcón I and II allow to estimate the theoretical thermal diffusivity α at the active layer of Morenas Coloradas. Thermal diffusivity may be decisive for the study of cryogenic dynamics at other altitudes and latitudes in the region where data are still scarce. Low α values (≤0.2×10−6 m2/s) correlate with occurrence of freezing and ice at low altitudes.

While the glaciers are turning into small insignificant bodies in the high mountains, the periglacial level with creeping permafrost and linked with rockglaciers is expanding altitudinally, passing a transitional “rooting” area which is indirectly feeding the rockglaciers with their covered or “dead ice”. The ice of glacial origin contributes to the genesis of this type of permafrost.

As the permafrost table is found at greater depths, the rockglaciers need to be monitored in order to define a balance between the upper periglacial level (in terms of altitude) with mountain continuous–quasi continuous permafrost and the lower periglacial level to where the lowest fronts of creeping permafrost are reaching. The variations of the cryogenic structure of the rockglaciers of the Córdón del Plata caused by warming processes, will have direct consequences for the volume of frozen sediments and therefore for the hydrology of the entire region, a fact that has to be taken into account for future socio-economic programs of the respective provincial governments.

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1. Introduction

“Rockglaciers are lobate or tongue-shaped bodies of perennially frozen unconsolidated material supersaturated with interstitial ice and ice lenses that move downslope or downvalley by creep as a consequence of the deformation of ice contained in them and which are, thus, features of cohesive flow” (Barsch, 1996). These cryogenic mesofoms display characteristic lobes attached to the mountain slopes or tongues of sedimentary accumulations in the interior of the valleys. These cryogenic geomorphological landforms invoke the presence of mountain permafrost or permanently frozen ground and more specifically creeping permafrost (see Trombotto, 2000, 2003). This type of permafrost always involves movement. In other words, the frozen ground is moving downslope due to gravity and the plastic deformation of the frozen ground which is moulding itself to the geology and the topography of the subsoil. The activity of rockglaciers allows identification of the presence of permafrost in the Andean subsoil. The sedimentary layer above the permafrost that freezes and thaws seasonally is called “active layer” (International Permafrost Association, 1998). This layer melts in summer and reveals important physico-chemical processes. Generally, the active layer decreases in thickness with increasing altitude.

Development and evolution of rockglaciers depend on their sedimentary characteristics and the syngenetic formation of different kinds of ice in terms of genesis or the processes involved (interstitial, segregation, freezing and injection ice) under the surface of debris.
bodies or permanently frozen sediments (Barsch, 1996; Trombotto et al., 1999). Rockglaciers are considered active when they show signs of movement, when their fronts or noses are strongly inclined (over 30–35°) or when they display processes of sedimentary vertical sorting and visible signs of falling rocks. Their active surfaces are correctly described to resemble “porridge” (Barsch, 1992) with superimposed sedimentary lobes, undulations and characteristic ridges and positive braided reliefs caused by movement.

Recent changes in the cryosphere have been documented which have been linked to changes in climate although determination of the cause is not straightforward. Glaciers throughout the world are presently retreating or are even disappearing as a consequence of the present global warming (UNEP, 2007). The rise of the mean annual air temperature in the study area during the 20th century (compare Rosenblüth et al., 1997; Jones and Moberg, 2003) has affected the Andean periglacial environment and also the rockglaciers.

This paper documents an example of the changes that are occurring in the periglacial and permafrost environment of the Andes and in particular in the most characteristic bodies of the Central Andean landscape in the Argentine province of Mendoza. This work also shows the trends of the present cryogenic dynamics. Ground temperature data are analysed to characterize changes in permafrost conditions. At the same time this contribution pays special attention to thermodynamics and to how present cryogenics modify the periglacial environment. Analysis of thermal data allow deductions on important physical properties of the material which constitutes the rockglacier, for example the thermal diffusivity of its upper cover in a state of change even at a stage where data have not yet been confirmed by laboratory experiments.

The Cordón del Plata region, to which the Morenas Coloradas rockglacier belongs, is an area very rich in rockglaciers. They represent the most important natural hydrological resource for human settlements. Today however, it is assumed that the entire cryogenic basin, situated in the Andean cryolithozone is of key importance and that the rockglaciers are its main geomorphological components, or at least its predominant and most characteristic landforms.

This work is an appeal for more attention to the possible implications that the warming process might trigger in the interaction between the periglacial environment and human settlements in nearby geographic regions.

2. Former regional studies about rockglaciers in the Cordón del Plata

Rockglaciers in the Cordón del Plata region have previously been studied because of their hydrological significance (Corte, 1976a, 1978; Buk, 1983) and for the inventory of glaciers in 1981.
Corte (1976b, 1980) and Corte and Espizúa (1981) introduced and applied the idea of “facies”, which may be observed in aerial photographs, in order to distinguish morphologies and substantial changes, between the uncovered and covered glaciers and rock glaciers, which were reclassified according to whether they were active or inactive. Corte (1976b, 1980) also distinguished clearly between what he called “authentic” rock glaciers and those of glacialic origin (generated on the basis of glaciers). The latter were also denominated “secondary rock glaciers”.

Through analysis of hydrology of Mendoza an important correlation was identified between the water flow from periglacial basins where mainly rock glaciers are found, and the air temperature and soil thermal regime. This correlation indicated that the behaviour of the water flow is predictable (Trombotto et al., 1999; Buk, 2002).

Rock glaciers were also studied as geomorphological and sedimentary expression resulting from the creeping of permanently frozen ground. Different methods were applied. They helped to determine existence, thickness and characteristics of mountain permafrost, as well as the sedimentology involved, which is closely linked with the rock glaciers of the Cordón del Plata (Corte and Trombotto, 1984; Trombotto, 1985; Fournier et al., 1986; Trombotto, 1991).

In cooperation with the Argentine Institute of Snow, Ice and Environmental Sciences (IANIGLA), Barsch and King (1989) detected permafrost and measured the thickness of rock glaciers in Morenas Coloradas and “El Salto” in the Cordillera Frontal, utilizing geophysical methods (geoelectrics and seismics). In the 1980s, the existence and significance of fossil rock glaciers in the Cordillera of the Cuyo region were revised. Fossil rock glaciers appear from a height of 3000m a.s.l. on downwards at 33° S approximately. They are remnants of cryogenics during the Wuerrmian Age or latest glacial episode. At the same time it may be observed that several authors make an attempt to distinguish fossil cryogenic forms at various periglacial altitude levels (Wayne, 1981; Barsch and Happoldt, 1985; Barsch and King, 1989).

In 2000 and 2003 Trombotto presented a typology of mountain permafrost based on the mapping of cryogenic areas of the Cordón del Plata. Rock glacier permafrost was classified as creeping permafrost. Creeping permafrost is the permafrost type with the highest ice content and therefore with the greatest hydrological importance. This type is clearly to be distinguished from an “in situ” (almost unmoved) type such as “quasi continuous” (Garleff and Stingl, 1986) also very frequent in the high mountains, conditioned mainly by topography and exposition.

3. Study area

The study area (Figs. 1 and 2) is situated in the Andean Cordillera of Mendoza, a region frequently referred to as Central Andes. It comprises the area between approximately 31° and 35° S. This region belongs to the southernmost part of the Dry Andes (see Lliboutry and Corte, 1998). The valley of Morenas Coloradas, in the Cordón del Plata, Cordillera Frontal, in the Argentine province of Mendoza was chosen as an outstanding and at the same time representative cryogenic example of the region.

The valley of Morenas Coloradas (SE) consists of a composed rock glacier, of the tongue-shaped type (length/width>1) according to the classification by Wahrhaftig and Cox (1959), with interrelated and superimposed frozen bodies consisting of cryogenic sediments derived from morainic till. A tiny glacier remains at the tip of the valley but it continues with a covered glacier with a length of 2.5km at a height of over 4200m. Moreover, the valley is occupied by a covered glacier, moraines with ice cores or islands of ice covered by till and one section of uncovered ice at the tip of the valley.

Presently, the proper glacial area is strongly reduced compared with the inventory of glaciers based on aerial photographs of 1963 (Corte and Espizúa, 1981) and its surface is surpassed by an area of covered ice ending in the “root area”, where the composed rock glacier is generated (Barsch and King, 1989; Trombotto, 1991). Therefore the rock glacier is considered to be mainly of glacialic origin. The cryosediments are derived from the palaeozoic rock, predominantly rhyolithes from the upper palaeozoic age (Caminos, 1979) which outcrop in the mountains. The study area is situated at the so called high Andean level or Andean tundra (Trombotto, 1991) and on the active rock glaciers practically no vegetation is found.

Glacialic rock glaciers often are initiated in complex areas of “transition” or “periglaciation”, a continuation of the final tongues of covered glaciers. These are “rooting areas” of rock glaciers (Trombotto, 1991,) which may reveal bodies of “dead” ice, disconnected from the original glaciers. The latter together with the depressions caused by

Fig. 2. Aerial photograph (1963) of the glacialic rock glacier Morenas Coloradas (between 32° 54’ and 33° 01’ S. and 69° 15’ y 69° 27’ W. approximately, above 3300 m ASL), Central Andes, Mendoza, Argentina. I: Balcón I; II: Balcón II. Original scale of the aerial photograph 1:50.000, the N is parallel to the vertical edge of the photo.
the fusion of ice denominated thermokarst are indicators for the
degradation of glacial ice (Trombetta et al., 2008).

The Morenas Coloradas valley presents a very close interrelation
between a covered glacier at the upper part and a composed rock-
glacier at the lower part of the valley. This phenomenon may also be
observed in others valleys of the Cordón del Plata in the Cordillera
Frontal of Mendoza (compare Lliboutry, 1986). For this reason, those
rockglaciers were defined to be of glacialic origin, contrasting
with those of purely periglacial origin, also called cryogenic or talus
rockglaciers.

This study area was chosen because of its accessibility and because
regional studies had been carried out there between 1992 and 1999 –
with some interruptions – and also because the terminal part of this
mesoform has continuously being monitored since 1999. Furthermore
soil temperatures at a height of approximately 3800m a.s.l. have been
monitored since 2001 in the same valley.

The closest meteorological station is “Vallecitos” at 2550m a.s.l.
(32° 56’S and 69° 23’ W). Data collection however has been discontinuous.
The mean annual air temperature (MAAT) between 1979 and 1994 was 6.3 °C and the mean annual precipitation 442mm
(1979–1983) registered by totalizers (rain and snow). The period
registered between 1988–1992 was significantly warmer with a MAAT of
7.36 °C.

The accumulation of snow on the ground and its interrelation with the “zonda” (a warm dry wind like the foehn) (see Trombetta et al.,
1997, 1999) also is of key importance because this wind impedes snow
accumulation. There are no data on snow exclusively which may persist between July and October, but the snow cover is definitely very
thin if it is not swept away by the wind in winter. The maximum snow
cover registered in winter 1982 (written comm., Buk, 2006) was of few
cm (up to 15 cm) at 2500 m and up to 77 cm at a height of 3150m.
The thickest snow cover in the area (written comm., Hernández, 2006)
was registered at the local skiing slope between 3100 and 3460m
height and reached 3m in July 1987, but it lasted only 9days.

In the present work temperature logs from two boreholes drilled in
the rockglacier of Morenas Coloradas in 1989 and 2001/2002 are
analysed. The drilling sites were called: Balcón I (3560m a.s.l., at 32°
57’ 43” S and 69° 22’ 19” W) and Balcón II (3770m a.s.l., at 32° 56’
95” “ S and 69° 22’ 49” W). Site Balcón I is situated at the front of this active
rockglacier which occupies the main part of the valley. Site Balcón II is
situated on a talus rockglacier superimposed with the main frozen
detrict body of glacialic origin.

4. Materials and methods

In the present work monitoring tasks of Andean cryogenic areas,
which belong to the mapping attempt of periglacial areas and
permanently frozen ground in South America since the 1980s.

The applied geocryological method is based on the analysis of key
or pilot zones of previously selected and studied rockglaciers. Data
have been verified in the field, in order to obtain the corresponding periglacial geomorphological parameters and to confirm the pre-
sence of permafrost by direct and indirect methods. The areas have
been georeferenced and are part of a database in the IANIGLA. Some
areas belong to the worldwide continuous monitoring and to the
areas observed discontinuously since 1989. Monitoring sites
include rockglaciers where shallow drillings were made, according
to the international classification, to install temperature sensors.
Sensors utilized were those calibrated at the institute or data loggers
type UTL (accuracy = +/- 0.1 °C; resolution = 0.27 °C (8 bit); average
frequency= 4 h), built at the University of Bern (Switzerland). The
data collected were used to characterize the evolution of the
temperatures in the subsoil, and to determine the presence of
permafrost.

In the case of the site Balcón I (3560 m) the thermistors were
installed at different depths: –0.05 m, –0.20 m, –0.70 m, –1.20 m,
–1.70 m, –2.20 m, –2.70 m, –4.00 m, –5.00 m and at the site Balcón II
(3770 m), at 1.5 m and 3 m depth. At Balcón I, an almost continuous
record of temperatures was obtained, registered with a Grant
equipment between 1989 and 1992 (frequency = 12h). The resolution
is approximately 0.25 °C, estimated visually using a register of the
printed graphic. The Grant equipment was removed at the end of 1992
but the thermistors remained in situ and the temperatures were
recorded during each ascent to the rockglacier. Each summer the
resistivities of the thermistors where converted into temperatures
with a calibration curve. Since 11/10/99 the temperature recordings
were taken on: 03/16/04; 03/31/05; 04/08/05; 03/23/06, 02/27/07 and
02/16/08. In both cases the thermistors were installed in the active
layer above the permafrost table. This way seasonal variations could
be measured and cryodynamics of the internal structure of the
rockglaciers could be analysed. In 2005, and once corroborated that
the permafrost table did no longer exist at 5 m depth. Permafrost
was detected with a hammer drill during different drilling attempts at
various spots of the site without being able to advance and by the
characteristic sound caused when the drill hits a frozen layer.
Moreover the temperature of 0 °C has been measured and with the
help of a geoelectrical profile the ice-bearing permafrost table could
be located with greater exactness at a depth of 4.9–5.5 m (Trombotto
et al., 1999). A new surface drilling was carried out in 2006, reaching a
depth of 6m. Thermistors were installed at ~2.90, ~3.90 and ~5.90 m
depth in order to keep registering the evolution of temperatures in the
cryogenic soil.

New observation sites and more sensors were added in 2006.
Moreover all data were corroborated by new drillings. The drillings
were made applying the method developed by Hernández (2002)
with a hammer drill with an external diameter of 2.54 cm and a
system of plastic tubes with an internal diameter of 1.58 cm which
create a protection shaft for the sensors which are introduced at a
prefixed distance where ventilation holes of a diameter of 1 cm allow
the air circulation at this depth. This helped to adjust the curves and the
evolution of the temperatures monitored so far at Balcón I.

Any upward movement would affect the construction and would be
identifiable by the position of the tube and the marked rocks on the
surface. As this is not the case, it can be supposed that the casing is not
jacked up.

The temperature curves are illustrated and at the same time
optimized or linearly extrapolated looking for the respective perma-
 frost table according to the available values.

Permafrost was detected by either direct methods, that is to say
findings and temperature profiles obtained through the surface
drillings mentioned above and geomorphological deductions, or
indirect methods, such as geophysical profiles (geoelectrics) to deter-
mine the ice-bearing permafrost.

5. Results and discussion: variations in the base and thickness
of the active layer of a rockglacier during the last years: the example
of Morenas Coloradas: Balcón I and Balcón II

The upper parts of the sedimentological profiles of the active layer
of Balcón I and II display distinctive vertically sorting according to
cryogenic laws. In the upper part coarse sediments are found, blocks
with a diameter of 25–30 cm and frequently patinated. Occasionally
blocks of diameters between 70 cm and 5m appear in the area. Below,
gravel and coarser sediments with a diameter between 4 and 8 cm are
found and at a depth of 30 cm and deeper the material is of
remarkably fine granulometry with predominance of fine gravel (0
1 cm) and presence of sand. Occasionally buried blocks of varied size
may appear. Active cryogenic bodies generally do not have any
vegetation except for very few isolated examples with some
graminaceous plants and lichens.
In 1987 Barsch and King (1989; Barsch, 1996) detected the permafrost table and base in the composed rockglacier in the valley of Morenas Coloradas, in the Cordón del Plata of Mendoza, Argentina with the help of geoelectrical methods. The authors distinguished three different layers of electric resistivities in connection with the internal structure, including a superficial and a basal (basement) thawed layer. At 3440m and higher the authors showed that the rockglacier is active in one of its terminal frozen bodies and measured a permafrost thickness of over 50m. The active layers in different frozen bodies were of a thickness up to 5.5m. The active layers generally decrease in thickness with increasing altitudinal location of the geoelectrical profiles.

On Fig. 3 the appearance of permafrost on the “nose” of the rockglacier Morenas Coloradas may be observed, detected through temperature profiles. The presence of permafrost is found at a depth of 5m at Balcón I (1989–1992, Fig. 4).

5.1. Balcón I

Fig. 4 shows the trend of the temperatures at Balcón I between 1989 and 1992. These first data were registered with the English Grant equipment mentioned before. At a depth between 4 and 5m the permafrost table becomes evident.

Since 2004 changes in the active layer have been detected. The permafrost table is found at considerably greater depth. The temperature profiles were linearly extrapolated to suggest the depth of the permafrost table at around 8.5m.

New temperatures were registered at the end of the summer of 2003/2004, 2004/2005, 2005/2006, 2006/2007 and 2007/2008. In the summer of 2005/2006 a drilling was made reaching a depth of almost 6m in order to confirm the evolution of the temperature profile at a depth greater than 5m. This way, and as may be observed in Fig. 5,

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**Fig. 3.** View of Balcón I at 3560 m ASL. Presence of inactive thermokarst.

**Fig. 4.** Trend of the temperatures at BALCÓN I between 1989 and 1992.

**Fig. 5.** Balcón I evolution of the temperatures in the active layer between 2004 and 2008, the dotted line (extrapolated data) represents the trend and the hypothetic evolution down to the permafrost table. On the vertical ordinate (depth) the position of the thermistors is indicated with a mark.
extrapolation of temperature profiles was used to determine the permafrost table which was found to be at a depth of 5m until 1992.

The upper part of the curves displays daily temperature oscillations and a retarding of the minima of up to 1m depth (compare Trombotto 1991), as well as thermal offsets as described by Burn and Smith (1988) above 2m depth probably due to the occurrence of more humid finer cryosediment layers. The permafrost table was estimated between 7.5m and almost 9m depth.

The extrapolated depth however, is influenced by interannual thermal variability in the uppermost part of the soil. This seems to be associated to the meteorological variations of this year which affect the temperature profile that extends the temperature curves before the cut with the isotherm of 0 °C and thus the estimation of its depth. It may be affirmed however, that at such depth and considering thickness, permafrost should hardly be affected at all by thermal waves that annually penetrate into the layer of annual temperature variations (compare Trombotto, 1991).

The temperatures registered by the thermistors until 5m depth could be estimated between approximately +2.3 and +2.5 °C because no continuous recordings were available. The temperatures were measured at the end of the summer 2003/2004, 2004/2005 and 2005/2006, or more precisely in the month of March because this is when the maximum thickness of the active layer is corroborated.

In 2005/2006, Balcón I, presented a slight reduction of the angles of its fronts, between 35° up to 37°. In former years, these angles surpassed 37° and reached even 40°, the same is true for a wall or SW slope. From a bend downwards, on the NW slope, the front is partially covered by sorted stone stripes. From the bend upwards a steeper wall is composed by compacted sediments.

From the nose upwards (3560m) the slope angle is very steep and still very active. The front at Balcon I displays surface settlement caused by former thermokarst, not related to recent increases in thaw depth. This front is doubtlessly indicating inactivity.

5.2. Evolution of the trend in Balcón II

A variation and less pronounced deepening of the permafrost table than that at Balcón I is determined from the ground temperature records at Balcón II (Fig. 6), a monitoring site which belongs to a different identifiable active frozen body located at higher altitude (Fig. 2). This site has been monitored almost continuously since 2001 and this is most valuable to establish correlations with Balcón I.

At Balcón II, permafrost was found at a depth of 3m in 2001. By the end of the summer of 2004 however, thaw deepened by approximately 30 cm. The temperatures are positive (between 0.13 and 0.36 °C) at 3m depth between 2004 and 2007 (Fig. 7).

At Balcón II the “warming” of the suprapermafrost is also attached to the reactivation of nearby thermokarsts, which began to reveal ice visible with the naked eye and which are eroding very quickly comparing 2001 with 2006.

Thermokarsts (Fig. 8) are revealing the degree of degradation of the ice covered by sediments, disconnected or not to the original mass of glacial ice, or directly that the major landforms are about to

Fig. 6. Front of a frozen body of the composed rockglacier Morenas Coloradas. View of Balcón II at 3770 m a.s.l.

Fig. 7. Balcón II, trend of the mean monthly temperatures in the active layer from 2004–2007. Dotted lines (extrapolated data) correspond to the exponential curves representing maximum and minimum temperatures.
disappear. Thermokarsts however, are also found in direct connection with the bodies of massive glacier ice. Thermokarsts appear clearly active in the surroundings of Balcón II and particularly from a height of 3800 m approximately upwards. Original forms are already present but now the walls show an important cover of cryosediments. At present, detritic covers are continuously falling off and offer a sight of walls containing ice.

6. Estimation of thermal diffusivity

The variations of the active layer thickness $z$ can be used to understand the periodic seasonal variation of surface temperature and interannual variability in climate. The permafrost top represents the attenuation of the seasonal wave with depth.

Given the characteristics of the drillings and the temperatures obtained initially, a degrading situation, where a thermal transient zone develops, cannot be confirmed. The base of the active layer and the top of the permafrost coincided in our case at the moment of the drilling.

Changes observed in the active layer over several years express the variations in climate in short terms of time (Taylor and Brown, 1996). The variations of $z$ caused by climate warming are closely linked with the changes that are produced in the internal structure of the active layer of the rockglacier, which favour a high thermal conductivity and consequently a high diffusivity $\alpha$.

![Image](image_url)

**Fig. 8.** Ice sampling at a thermokarst at the valley of Morenas Coloradas, Mendoza.

![Image](image_url)

**Fig. 9.** Lachenbruch diagram corresponding to “Balcón 1” for the 1990–1991 period. Taking into account the resolution of temperature measurement of 0.5 °C. This figure suggests a null seasonal amplitude point and a permafrost table at about 4.9–5 m depth (1990–1991). The figure also shows the estimation of the average thermal diffusivity between 1.50 and 3 m depth (active layer) using a formula after Gold and Lachenbruch (1973).
The thermal diffusivity is the ratio of thermal conductivity to the volumetric specific heat:

$$\alpha = \frac{k}{\text{Cv}}$$

where:

- $\alpha$ thermal diffusivity (m$^2$/s)
- $k$ thermal conductivity (cal/m °C s)
- Cv volumetric specific heat (cal/m$^3$ °C)

The usual value of thermal diffusivity for the majority of rocks is about $1 \times 10^{-6}$ m$^2$/s (Lliboutry, 1982).

When a sudden thermal change in the active layer appears in a rockglacier, this rockglacier, which was in an approximate balance with the external thermal conditions before, looses this balance and tries to stabilize again. The time of this process is strongly determined by the thermal diffusivity ($\alpha$) of active layer material. This layer, according to its $\alpha$ value has an important role for the permafrost isolation and can act as a buffer and insulate the permafrost from changes in climate. When $\alpha$ is low permafrost will have higher thermal inertia to melting.

According to Gold and Lachenbruch (1973), the thickness of the active layer in a cryogenic region may be estimated as follows:

$$z_a = \sqrt{\frac{\alpha P_y}{\pi}} \times \frac{A_0}{T_0}$$

where

- $z_a$ thickness of the active layer (m)
- $P_y$ period of the temperature cycle (s)
- $A_0$ surface temperature amplitude (°C)
- $T_0$ MAAT (°C)
- $\alpha$ the thermal diffusivity (m$^2$/s$^{-1}$)

With the $z$ values and the other known variables (Trombott et al., 1997; 1999), for example those of Balcón II. Trombott (2007) calculated $\alpha$ but for ideal or hypothetic conditions of balance obtaining lower values of diffusivity, close to 0.2×10$^{-6}$m$^2$s$^{-1}$ (ice = 1.2×10$^{-6}$m$^2$s$^{-1}$).

Fig. 9 shows the Lachenbruch diagram corresponding to the site Balcón I for the period 1990–1991, according to the temperature records obtained at different depths in the active layer. Assuming the active layer as a homogeneous medium, a non-steady state is clear in this figure: the annual mean temperatures as function of depth follow a non-linear law. This means that materials in the active layer and permafrost gradually are increasing their temperatures shifting to a final stage where the non-linear temperature profile will approximately adjust to the geothermal gradient in the region (in Fig. 9 gradient of 0.03 °C/m, considered as normal is shown). This non-steady state was clearly produced by a rapid increase of air temperature. As a conclusion, this permafrost is about to melt because of the warming effect produced by two heat flows: first, the geothermal heat flow – from downwards to surface – and second, the annual mean heat flow – from surface downwards. The duration of this process is determined by thermal diffusivity of the active layer mainly.

Using the following expression (after Gold and Lachenbruch, 1973) it is possible to estimate a mean value for $\alpha$ corresponding to the active layer in a heterogeneous medium:

$$T_{z2} = T_{z1}e^{-\sqrt{\frac{z_2}{\alpha\pi}} \Delta t}$$

where: $T_{z1}, T_{z2}$ amplitudes of the seasonal temperature variations at $z_1$ and $z_2$ depths respectively. From this expression $\alpha$ is obtained:

$$\alpha = \frac{\pi}{P_y} \left( \frac{\Delta z}{\ln \frac{z_2}{z_1}} \right)^2$$

Using this formula and the data shown in Fig. 9, $\alpha=0.17 \times 10^{-6}$m$^2$/s is estimated for the active layer of Balcón I. This value already represents an imbalance with the registered thickness $z$ (Fig. 5) caused by a warming process of the active layer.

It is important to mention that $\alpha$ depends on the extent to which the surface temperature regime can be considered as a simple sine wave; but this condition is lost when there is a phase change, i.e., when latent heat is present. According to the precedent, the thermal diffusivity estimated in the present case could be considered as an apparent diffusivity. However, in Balcón I rockglacier (see Fig. 9), the latent heat does not seem to have significant influence. In fact, two estimations of $\alpha$ made from Fig. 9, considering in one case the winter temperature profile and in the other, the summer profile, give similar diffusivity values, which could be suggesting the open work structure of the layer and low content of water. Therefore, the estimation of $0.17 \times 10^{-6}$m$^2$/s can be considered to be close to the truth and acceptable.

Balcón II rockglacier is located at higher altitude than Balcón I glacier (at 3770 m a.s.l.). In this frozen body temperatures collected at

Fig. 10. March temperatures collected at different depths plotted as function of time for Balcón I. The warming tendency is visible. Symbols indicate temperatures at different depths:

- (●) 0.70 m; (▲) 1.20 m; (○) 1.70 m; (●) 2.20 m; (▲) 2.70 m; (▲) 4.00 m; (○) 5.00 m depth.
1.50 m and 3.0 m depth are the only ones available. Using the same expression, α=0.14×10⁻⁶m²/s is estimated, which is close to that estimated for Balcón I in the same period. These α values would correspond to sediments of relatively fine granulometry (see Sawada and Ohno, 1985), just like that found at shallow drillings of the rockglacier already described. This is the material frequently observed under large surficial blocks in the upper layer of the rockglacier Morenas Coloradas. The obtained value at 20 °C according to Sawada & Ohno, and according to empirical data, corresponds to cryosediments with a granulometry ranging between pebbles and granules. This upper layer is represented by a relatively discontinuous medium with openwork texture, and correlated with typical periglacial processes of cryogenic movement and vertical sorting. 

Fig. 10 shows monthly mean temperatures corresponding to March between 1990–1991 and 2004–2006 periods at different depths at Balcón I rockglacier. Despite these scarce data, this figure clearly suggests a gradual air warming in the air in contact with soil. This warming explains the features observed in Fig. 9, i.e. a non-steady state.

In addition, the temperature profiles corresponding to 4.0 m and 5.0 m depth (Fig. 10) show a higher temperature increase at the time than the others. This behaviour could be perhaps explained because in the active layer, there are in this case, two superimposed warming effects: first the warming of the air (possibly a global climate warming), and second the tendency of the system to search for a new balance, shifting the temperature profile to higher values. This second effect is more notable at 4 or 5 m depth next to the permafrost table (see Fig. 9), where the seasonal temperature variation is almost negligible.

7. Conclusions and proposals

A change in the active layer of the composed rockglacier Morenas Coloradas has been documented at the monitoring sites. This situation is also proposed for other rockglaciers of the valleys of the Cordón del Plata and ought to be closely observed because these cryogenic mesoforms have a key role for the water supply of the human settlements in the oasis of the Cuyo region in Argentina (compare Trombotto et al., 1999).

The nose of Morenas Coloradas, that is the site called Balcón I, already expresses inactivity; the permafrost table is found at great depth. Results indicated that thaw deepened at rate of approximately 25 cm per year assuming a regular gradual increase between 1992 and 2007. This means that an unfrozen layer is found now around 3.5m deeper in the ground. This deepening however, seems to be rather irregular, according to Shur et al., (2005).

At Balcón II the deepening together with the deterioration of the permafrost was approximately 15 cm per year according to the registers mentioned above (2002–2004). Balcón I shows some features indicating less activity than Balcón II: e.g. less inclination at its front slope and deepening of the active layer. This suggests that Balcón I is about to cease its activity with its permafrost in a rapid warming process. Balcón II presents more activity than Balcón I, which is consistent with the higher altitude and a lower mean annual temperature.

The deepening of the active layer needs to be monitored in order to define a balance between the upper periglacial level (in terms of altitude) with quasi continuous permafrost in contact with the upper parts of the rockglaciers and the lower periglacial level to where the lowest fronts of creeping permafrost are reaching. Regarding the descent of the permafrost table presented in this contribution, it might be added that it is hardly detected as a sudden geomorphological expression, partly due to low thaw strains in the material. Slight or abrupt superficial depressions may be a hint in certain cases as in Balcón I, but the best hint is an observation of the surroundings of leftovers of glaciogenic ice combined with thermokarst in activity, in expansion or in a process of destruction. These deep holes with lagoons are very good indicators for the assessment of the degradation of the present permafrost.

While the glaciers are turning into small insignificant bodies in the high mountains, the periglacial level with permafrost and linked with rockglaciers is expanding altitudinally, passing a transitional area which is indirectly feeding the rockglaciers with its covered or “dead” ice. The ice of glaciogenic origin contributes to the genesis of this type of permafrost.

On the other hand, the values of resistivity range from 30–50kΩm obtained in 1987 (Barsch and King, 1989) to 12kΩm in March 1990 (Trombotto et al., 1999) should be verified again to detect new changes in the internal frozen structure and/or in the ice of the active rockglacier, mainly in its distal parts and its altitudinally lowest sides, such as in suprapermafrost, because the geophysical state of these layers or areas, also is an important indicator for a cryogenic structural change.

The obtained low values of thermal diffusivity (0.14–0.17×10⁻⁶m²/s) however may very well express why the ice remains for such a long time below the Andean cryolithozone and why it may continue activating cryogenic processes. On the one hand a low theoretical α value such as the values obtained implies low thermal conductivity which is very important for the preservation of the warmth of the medium and also explains the considerably long time for the frozen sediments of a rockglacier to disappear because of a climatic disturbance (periglacial mountain areas with T0 ≥ 0 °C). At the same time, the large latent heat requirement to melt the ice, contributes to a low apparent thermal diffusivity. The process of cryowathering with the present climate and the great availability of cryosediments also reinforce the described phenomenon and inside positively in the extraordinary thickness of the periglacial level in these latitudes of the Andes.

The variations of the cryogenic structure of the rockglaciers of the Cordón del Plata caused by warming processes, will have direct consequences for the volume of frozen sediments and therefore for the hydrology of the entire region, a fact that has to be taken into account for future socio-economic programs of the respective provincial governments.

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