The periglacial environment in the semiarid and arid Andes of Argentina – hydrological significance and research frontiers

Lothar Schrott & Joachim Götz

The semiarid and arid Andes of Argentina are characterized by an extremely large vertical extension of the periglacial environment. The occurrence of permafrost in the High Andes is widespread and the potential water storage in permafrost bodies (e.g. rock glaciers) displays unique and precious, but also sensitive natural resource. Against the background of a new statute in Argentina, which was approved in 2011 to protect glaciers and the periglacial environment, the significance of the periglacial belt became of interest to several stakeholders. There is, however, a lack of knowledge regarding regional permafrost occurrence and it remains still unclear how to define accurately periglacial regions. This paper intends to focus on some aspects concerning the extension and significance of the periglacial belt and permafrost occurrence in the semiarid and arid Andes and to give suggestions for research activities.

Keywords: permafrost, periglacial belt, water storage, semiarid and arid Andes, Argentina

Die periglaziale Höhenstufe in den semiariden und ariden Anden Argentiniens – hydrologische Bedeutung und Forschungsfronten

Die semiariden und ariden argentinischen Anden sind durch eine extreme große vertikale Erstreckung periglazialer Formen und Prozesse gekennzeichnet. Das Auftreten von Permafrost in den Hochanden ist weitflächig, und das Wasserspeicherpotenzial von Permafrostkörpern (z.B. Blockgletscher) ist eine einmalige und bedeutende, aber auch sensible Naturresource. Vor dem Hintergrund neuer Rechtsbestimmungen in Argentinien, die 2011 zum Schutz von Gletschern und der periglazialen Umwelt erlassen wurden, ist die Bedeutung der periglazialen Höhenstufe in das Interesse verschiedener Stakeholder gerückt. Es gibt aber eine erhebliche Kenntnislücke über das Auftreten von Permafrost, und es ist noch unklar, wie Periglazialregionen definiert und abgegrenzt werden können. Dieser Artikel hat zum Ziel, einige Aspekte dieser Thematik zu beleuchten, insbesondere die Ausdehnung und Bedeutung der periglazialen Höhenstufe und das Auftreten von Permafrost in den semiariden und ariden Anden. Darüber hinaus werden zukünftige Forschungsstrategien aufgezeigt.

El ambiente periglacial en la región andina y semiárida de Argentina. Significancia hidrológica y fronteras para la investigación

Los Andes áridos y semiáridos de Argentina se caracterizan por una extrema extensión vertical de los ambientes periglaciales. La ocurrencia de permafrost en la alta montaña andina es un fenómeno extendido; el potencial de almacenamiento hídrico existente en glaciares rocosos, genera condiciones únicas y valiosas, pero también paisajes altamente frágiles. En el contexto de un nuevo estatuto aprobado en 2011, orientado a la protección de glaciares y de ambientes periglaciares, la significancia del cinturón periglacial atrajo el interés de diversos tomadores de decisiones. Sin embargo, existe una falta de conocimiento acerca de la ocurrencia regional de permafrost y es todavía materia de discusión la manera de definir y delimitar adecuadamente las regiones periglaciales. Este artículo aborda algunos aspectos relativos a la extensión e importancia del cinturón periglacial y del permafrost en la región árida y semiárida de los Andes Argentinos para proponer para futuras investigaciones.

1 Introduction

Periglacial geomorphology has a long tradition and the term periglacial was first mentioned in 1909 by the Polish geologist Lozinski (1909). Today periglacial studies cover a wide range from arctic and subarctic to high altidude environments focusing on fundamental and applied issues (Weise 1983). Commonly periglacial processes can be observed in association with glacial processes but in some environments – like the semiarid and arid Andes – periglacial phenomena occur also in complete absence of glaciers. In the Andes of Argentina periglacial processes are mostly associated with high mountain permafrost (Corte 1978; Schrott 1994; Trombotto 2003).

Studies of the periglacial belt in mountains have traditionally concentrated on influences of climatic factors on processes and landforms (e. g. Höllermann 1967; Stingl 1969; Garleff 1970; Graf 1971; Karte 1979). Seldomly, geoecological aspects were considered for different periglacial mountainous regions in relation to climatic types (Höllermann 1985).

In the high Andes of Chile and Argentina the periglacial belt and periglacial processes have been studied systematically since the late 1970s / early 1980s (Corte 1976; Abele 1982; Buk 1984; Corte & Buk 1984; Barsch & Happoldt 1985; Garleff & Stingl 1985; Schrott 1996, 1998; Schröder & Makki 1998; Schröder 2001; Trombotto 2003).

In most recent studies the periglacial environment in the semarid and arid Andes of South America has been of significant political importance (Arenson & Pastore 2011; Ahumada et al. 2011; Azocar & Brenning 2010; Arenson & Jakob 2010). The reason for this attention to a previously purely academic research field is also caused by a new statute in Argentina, which was approved in 2011 in order to protect glaciers and the periglacial environment with the following aims:

1. to save hydrological resources for irrigation purposes and consumption
2. to protect biodiversity,
3. to conserve this source of scientific value, and
4. to conserve these environments for touristic attractions.

The original statute published in Spanish is defined as follows: "*La Ley No 26.639 tiene por objeto establecer los presupuestos mínimos para la protección de los glaciares y del ambiente periglacial con el objeto de preservarlos como reservas estratégicas de recursos hídricos para el consumo humano; para la agricultura y como proveedores de agua para la recarga de cuencas hidrográficas; para la protección de la biodiversidad; como fuente de información científica y como atractivo turístico constituyendo a los glaciares como bienes de carácter publico" (Boletin oficial de la Republica Argentina 2011: 1).*

Beside the general positive aspects with regard to the environment, such a statute implies a number of problematic issues and open questions. For instance, the mapping of the extension of the periglacial belt is not an easy task. There is still no universal scientific concept of how a periglacial terrain can be defined. Until recently, not even a map of permafrost distribution has been available for this part of the Andes.

Moreover, the extension of the periglacial environment is not only limited to permanently frozen ground. Thus, the accurate assessment of the current extension of the periglacial belt requires a proper definition of appropriate criteria and an evaluation and mapping of large parts of the Andes. With respect to climate change the extension of glaciers and periglacial environments is subject to changes. This circumstance requires also an extensive monitoring (Arenson & Pastore 2011). This paper aims to address

1. the importance and uniqueness of the periglacial belt in the semiarid and arid part of the Andes of Argentina, and
2. to show some appropriate measures and research activities to meet the expectations of the statute No 26.639 "Protection of glaciers and periglacial environment".

2 Processes and landforms of the periglacial belt in the semiarid and arid Andes of Argentina

The processes and landforms characterizing the periglacial belt in this part of the Andes are predominantly phenomena of creeping mountain permafrost. The most visible expression of mountain permafrost between 35° and 27° S is the occurrence

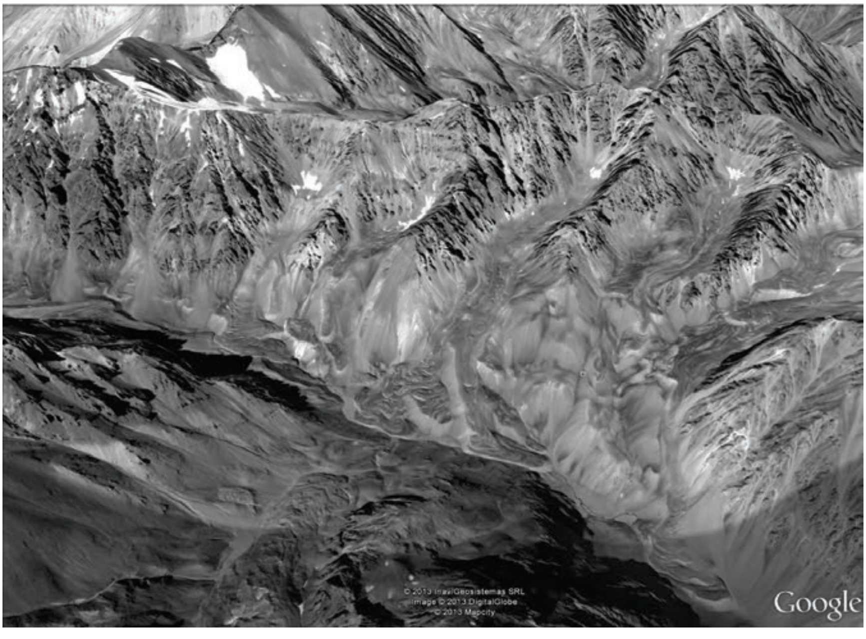

Fig. 1: Typical rock glacier distribution in the periglacial belt of the semiarid High Andes (33° 07' S, 69° 41' W). Rock glaciers are situated in cirques and cover parts of the valley bottom (valley bottom elevation approximately at 4,000 m a. s. l.; view to the south); source: Google Earth, 8.04.2013 © 2013 Inav/Geosistemas SRL Image © 2013 DigitalGlobe © 2013 Mapcity

of rock glaciers as described in several studies (Corte 1978, 1986; Barsch 1986; Brenning 2005; Schrott 1996; Fig. 1).

The Andes between 35° and 27° S are characterized by a very high density of large rock glaciers due to extremely favorable conditions such as continentality, high debris availability (large vertical extension of the periglacial belt) and low temperatures (see Fig. 1). In the Cordillera Principal near San Juan (30° S) the surface area of rock glaciers is even larger than those of glaciers (Schrott 1996). This landform is of major importance because it can be used as an indicator of mountain permafrost. Moreover, the lowest occurrence of active rock glaciers indicates the lower limit of discontinuous permafrost (Table 1).

Beside rock glaciers, protalus ramparts, frost sorting processes and solifluction occur frequently above an altitude of 4,000 m a.s.l. (see Fig. 2). Stone stripes are typical on slopes between 10° and 25°, whereas stone polygons are limited to flat areas with sufficient fine material and soil humidity (Schrott 1994). Another very common feature in the periglacial belt of the semiarid and arid Andes of Argentina is the widespread occurrence of planar scree slopes (*Glatthänge).* These slopes are mainly the result of *in situ* production of debris due to intense physical weathering and a lack of erosion (Garleff & Stingl 1985; Trombotto & Ahumada 2005). Frequently, such planar scree slopes show a vertical extension of more than 1,000 m (Schrott 1994). Below snow patches and in association with rock glaciers some debris flow activity can be observed.

Thermokarst features occur occasionally at the surface of rock glaciers indicating thawing of permafrost. Thermokarst in the periglacial environment is associated with an increase of the active layer and hence an indicator of degrading permafrost (Trombotto & Borzotta 2009).

3 Extension of the periglacial belt and water resources

Defining the upper and lower limit of the periglacial belt was subject of several studies (Karte 1979; Barsch & Happoldt 1984; Garleff & Stingl 1985). The occurrence of permafrost must be seen as an essential criterion to define the periglacial belt (Barsch 1986). The permafrost extension alone would, however, underestimate surface area of the periglacial environment. Karte (1979) suggested to use the occurrence of at least two periglacial features for defining a periglacial area.

Where glaciers are absent, the upper limit of the periglacial belt is defined by the highest ridges and peaks of the Andes as it was already proposed by Garleff & Stingl (1985). The upper limit of the periglacial belt at 25° S is probably the highest in world exceeding 2,200 m of vertical extension (Schröder 2001). In the area of Llullaillaco (24° S) the periglacial belt reaches the ice free peak at 6,739 m a.s.l. Therefore, the upper limit of the periglacial belt cannot be modeled using the snowline like in the European Alps. Between 25° and 35° S the periglacial belt varies between 1,500 and more than 2,000 m in its vertical extension and comprises an area

Table 1: Upper and lower limits of the periglacial environment in the High Andes of Argentina at 30° S (modified after Schrott 1994)

Altitude (m a.s.l.)	Limits and characteristics
> 5,300	Sparsely glaciated, extensive frost sorting processes; Continuous permafrost distribution, active layer reduced to a few centimeters
5,050	Upper limit of active rock glaciers
4,650	Upper limit of vegetation
4,200	Lower limit of patterns of frozen ground
4,000	Lower limit of active rock glaciers; lower limit of discontinuous permafrost
3,900	Lower limit of the periglacial belt

Fig. 2: Stone polygon (frost sorting) at Morenas Coloradas (3,770 m a. s. l., Cordillera Frontal, Argentina). Photograph taken in February 2012 by L. Schrott

much larger than the area covered by glaciers. A detailed inventory carried out in the High Andes of San Juan at 30° S revealed a periglacial extension of 97% versus a surface area of only 3% covered by glaciers (Schrott 1994). In the Agua Negra catchment the surface area of rock glaciers is slightly higher than those of glaciers and underpins the hydrological significance of this periglacial landform. In a previous study Corte and Espizua (1981) calculated for a larger basin at 33° S (Horcones, 197 km²) a similar glacier and rock glacier ratio.

Table 2: Inventory of the surface and potential water volumes of glacier ice, rock glacier, and permafrost areas (Agua Negra basin, 30° S) (modified from Schrott 1996).

	Thickness [m]	**Surface [km²] / [%]**	**Ice content [%]**	**Ice / water volume [10⁶ m³]**
Glacier ice	50	1.78 / 3.6	100	89
Active rock glacier	50	2.07 / 3.1	60	62
Continuous permafrost	20–30	9 / 15.8	20	36–54
Discontinuous permafrost	20–30	44 / 84.2	20	44–66
Total ice / water volume				231–271

Inspired from a classic paper by Corte (1976), Schrott (1994, 1996) measured and estimated for the first time the potential water resources of permafrost areas and water release of thawing permafrost in the Agua Negra basin during the ablation period 1990 and 1991. In a comprehensive study the water volumes of rock glaciers, glaciers and continuous / discontinuous permafrost areas were calculated for a typical catchment of this part of the Andes (see Table 2).

Particular attention can be drawn to the following outcomes with regard to water potential and water release from the periglacial environment (for details see Schrott 1994):

1. The stored water volume of active rock glaciers corresponds to 70% of the estimated glacier volume.
2. The total water volume of the entire permafrost area (this includes also areas outside active rock glaciers) is probably of similar size or even larger than those of glaciers.
3. The seasonal thawing of the active layer contributes to about 20% of the total discharge of the basin.

In a recent study Azócar & Brenning (2010) estimated a ratio of rock glacier to glacier ice volume of 3 : 1 and 1 : 2.7 for the semiarid Andes of Chile between 29° and 32° S and between 27° and 29° S, respectively. Their results show a similar rock glacier density than in the Andes of Argentina. Arenson and Jakob (2010) commented critically on parts of the methodological approach and they suggest to test the water resources of rock glaciers through monitoring and theoretical considerations.

Several studies show that permafrost degradation is occurring in this part of the Andes (e. g. Trombotto & Borzotta 2009; Schrott 1998). In times of water scarcity and global warming special attention should be drawn to this issue. In this context, a new geomorphological phenomenon can be observed which has not yet been described in the literature (see Fig. 3). Similar to proglacial lakes, a small lake has developed in front of a rock glacier tongue and indicates significant rock glacier discharge and thawing of permafrost during the ablation period. It can be considered as a new indicator of degrading permafrost in the Andes.

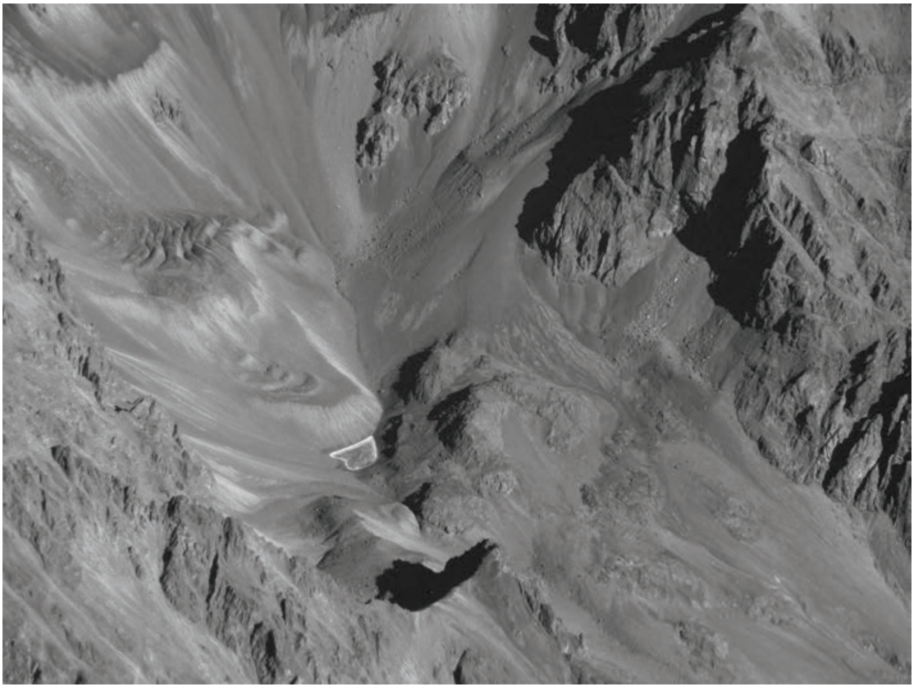

Fig. 3: Active rock glacier at approximately 4,500 m a. s. l. with a small lake in front the rock glacier tongue. Cordillera Principal at 33° S near the border between Chile and Argentina. Photograph taken in May 2011 by L. Schrott

4 Research frontiers and measures

To meet the expectations of the above mentioned statute (protection of glaciers and the periglacial environment) current and future research activities should primarily focus on the following topics:

- Creating an inventory of glaciers and periglacial landforms for the semiarid and arid part of the Argentinian Andes following the example of Corte and Espizua (1981).
- Modelling of the present permafrost distribution using regional data sets (DEMs, air photographs, local rock glacier information, etc.). Rock glacier distribution and solar radiation intensities can significantly help to develop a technically feasible and efficient modeling approach.
- Defining lower and upper limits of the periglacial environment by means of appropriate geomorphic features (e. g. rock glaciers, protalus ramparts, planar scree slopes, etc.) and in combination with the modeled permafrost map.
- Estimating potential water storage of glaciers and rock glaciers.
- Quantitative measuring and assessment of rock glacier discharge at several test sites for ground truth and validation of water volumes.

- Developing a water budget model including snow melt, glacier melt and permafrost thawing.
- Drilling and thermistor installations of boreholes (> 10 m) in debris and rock permafrost at several test sites for temperature monitoring purposes.
- Developing scenarios regarding the extension of future permafrost and periglacial areas.
- Defining hazard zones with regard to potential water scarcity and instable slopes.

This list of research activities and measures is fully in line with the latest resolutions of the International Permafrost Association. Here, it was explicitly mentioned that permafrost studies are particularly encouraged in regions where little is known regarding its occurrence, its degradation and the resulting dynamics and hazards. Furthermore innovative and accurate permafrost maps should be developed for use of multiple audiences (http://ipa.arcticportal.org/publications/resolutions.html: accessed 05/04/13). Haeberli (2013) highlighted in a recent publication the need for future research activities and long-term monitoring initiatives with regard to mountain permafrost.

5 Conclusions

Knowledge of the current state and future development of the periglacial environment is of interest to academia, federal and municipal governments, NGOs, mining companies and consultancies. For people living in the mountains and in the forelands of the semiarid and arid Andes water scarcity can become an essential risk factor. Research should focus primarily on the estimation of regional permafrost occurrence (e. g. permafrost map) and on quantitative studies concerning the hydrological significance of the periglacial environment. The future development of water storage systems can only be assessed with proper monitoring programs.

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