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ORIGINAL ARTICLE

Glaciers and rock glaciers' distribution at 28° SL, Dry Andes of Argentina, and some considerations about their hydrological significance

Laura Perucca · María Yanina Esper Angillieri

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Abstract The area studied includes a little-known portion on the Dry Andes of the San Juan Frontal Cordillera, Argentina, where the hydrological significance of glaciers and rock glaciers was earlier never studied. The surveyed sector includes Cerro El Potro (5,870 m ASL) and nearby mountain chains (28°S). The predominant landforms in these areas were shaped in a periglacial environment superimposed on an earlier glacial landscape. These regions comprise abundant rock glaciers, a noteworthy rock glacier zone in the world, of which little is known in South America. This work employs geomorphological mapping to analyze the distribution of active rock glaciers in relation to altitude, aspect and slope using optical remote sensing techniques with GIS. Statistical estimation techniques were used based on a Digital Elevation Model (DEM) and aerial photos and Spot images interpretation. The specific density of rock glaciers' estimation in the surveyed area (Argentine border) is 1.56% with corresponds to 38 rock glaciers with an area of 5.86 km^2 and 0.12 km^3 of water equivalent. Furthermore, the analytical results show that elevations >4,270 m ASL, a southeast-facing aspect, and slope between 2° and 40° favor the existence of rock glaciers, Finally, a comparison with glacier water equivalent, which covers an area of $\sim$16 km^2 and 0.9 km^3 of water equivalent, shows that glaciers are the main stores of water at 28°S (Cerro El Potro Glacier). However, the importance of rock glaciers as water reserves in this portion of Argentina should not be underestimated.

Keywords Rock glacier · Water equivalent · Geomorphology · Dry Andes · San Juan · Argentina

Introduction

In the highest sectors of the Central Andes of Argentina, the dominant landforms are related to their present glacial (depending on the altitude and latitude) and periglacial environments. The latter one modifies a previous glacial environment which was able to cover topographically lower areas in Pleistocene times.

Rock glaciers conform one of the most salient features of the periglacial zone of this region. They are conformed by ice and angular clasts, with a lobate or spatulate design that slowly move downward the slope. Some of them have surface reliefs showing longitudinal furrows and ridges, indicating flow structures. Generally, they occur at the foot of steep walls, which sometimes conforms to the rim of the glacial cirques or steep slopes of glacial trough valleys (Martin and Walley 1987). Morphologically they are classified into tongue-shaped rock glaciers (Wahrhaftig and Cox 1959) or simply debris rock glaciers, when their length is greater than their width, and are featured by their well-defined flow structures, as well as by presenting an steep front (Barsch 1996); they are lobate rock glaciers when they are rather wide than long (Wahrhaftig and Cox 1959), also called in this paper talus rock glaciers, valley-wall rock glaciers or protalus lobe (Walley and Martin 1992). In general, they are small bodies of up to 1,000 m in length. Besides, the common subdivision of rock glaciers into active, inactive and fossil based on morphological criteria (Wahrhaftig and Cox 1959; Martin and Walley 1987) was applied to rock glaciers in this study.

L. Perucca (✉) · M. Y. Esper Angillieri
CONICET-Gabinete de Neotectónica y Geomorphology, Instituto de Geología, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de San Juan, Av. Ignacio de La Rosa y Meglioli s/n, 5400 San Juan, Argentina
e-mail: lauraperucca@yahoo.com.ar

Moreover, rock glaciers are the geomorphological expression of creeping mountain permafrost in the region (Barsch 1996) and contain approximately 40–70% of ice by volume constituting sizeable stores of water (Arenson et al. 2002; Corte 1976a; Croce and Milana 2002; Schrott 1994, among others). Although rock glaciers have been widely studied on the Chilean side (Brenning 2005a, b; Azócar and Brenning 2009; Brenning and Azócar 2009a, b), there are only some studies in San Juan (Argentina), in the Agua Negra basin at 30°S (Schrott 1991; Croce and Milana 2002, 2006). Instead, there is little knowledge about their distribution, size, and significance as water stores north of 29°S, excepting for studies of Perucca and Esper (2008), Esper Angillieri (2009) in Argentina and Brenning (2005b) and Azócar and Brenning (2009) in the Chilean territory.

Several authors have studied rock glacier distribution (Chueca 1992; Johnson et al. 2007; Brenning et al. 2007) for determining the factors that control rock glacier development. There are some collected inventories of rock glaciers for investigating the influence of topography (Wahrhaftig and Cox 1959; White 1979; Ellis and Calkin 1979) on their development. Therefore, one of the purposes of this work is to discuss the distribution of active-inactive rock glaciers in the Cerro El Potro area, in relation to altitude, aspect, and slope, by analyzing topographical maps, aerial photographs and satellite images.

On the other hand, an important mining project (El Potro) stands in the studied area that comprises more than 8,000 ha of highly prospective ground, situated on the north margin of Rio Blanco, the political divide between La Rioja and San Juan provinces. This project has surface mineralization hosted in similar Permo-Triassic and Tertiary intrusive-volcanic complexes. Previous sampling and initial geophysics have outlined a copper-molybdenum system, rich in stockworks with strong silicified and sulfide (molybdenite) veining, and a lateral silica cap. This mining project could affect the area with the construction of roads over rock glaciers, the creation of deposits of sterile rock or even the complete or partial removal of rock glaciers as occurred in other areas of Central Andes of Chile (Brenning and Azócar 2009b).

Therefore, intensive research is required on the distribution of rock glaciers and their geomorphological and hydrological importance in the portion of the Argentine Dry Andes because of the growing number of mining projects, exploration, and mining activities in the region.

Regional setting and previous research

The studied area is located in the northwest (between latitudes 28°15′S–28°30′S and longitudes 69°32′–69°40′W) (Fig. 1) of San Juan province, Iglesia Department, in the central western Andes of Argentina, on the border with Chile.

From a geological point of view, Cerro El Potro area shows outcrops of Paleozoic granitoids and volcanic rocks in uplifted blocks. To the south, continental sandstones and volcanoclastic rocks overlap the rocks of Permo-Triassic age. The Tertiary units are of volcanic, pyroclastic, and subvolcanic sequences. The region also shows Quaternary deposits caused by mass movement, rock glaciers, and glacial and fluvial deposits. The main alignments crossing the region show a WNW–ESE and NE–SW trend. The dominant structural feature is compressive tectonic with horst and graben blocks, elongated in an N–S trend, which expose basement rocks and NW–SE dextral strike slip faults, which have generated distensive basins.

The studied region is situated south of the Arid Diagonal of South America, with precipitation that ranges from 150 to 200 mm. Dry climates with rigorous winters, such as the one that characterizes the Andes from 28° to 32°S latitudes, present very low temperatures in winter, short-lived summers, scarce precipitations and violent winds.

The Dry Andes high-mountain region has its own climatic conditions, which differ from those of the larger climate zone to which it belongs. Because of the temperature drop at higher altitudes, it is typically dry and cold. A negative thermal gradient of 0.5–1°C every 100 m altitude increase would suggest an increase in the relative humidity of the air and the occurrence of important precipitation rates on the windward slope and lower rates on the leeward side (rain shadow). The slope orientation, prevailing wind direction, and sunshine angle are also critical factors because of the specific wind pattern and higher isolation in certain directions, thus giving rise to a differentiated topoclimate (topographical climate).

The temperature is above freezing only during approximately 4 months a year. From 3,500 to 4,000 m ASL, temperatures range between −18°C and 10°C.

Above 4,300 m ASL, the climate is characterized by perpetual ice, where the average temperature in the warmest month is lower than 0°C.

The highest winter temperatures recorded in the Cordillera are caused by the influence of the so-called Zonda wind, which produces a foehn effect. The yearly thermal amplitude between winter and summer is high: 70.1°C.

Between 4,000 and 6,000 m ASL, the precipitations are mainly snow and hail, the former associated with the foehn effect. Below 4,000 m, rain is scarce and very irregular; snow precipitations in the Cordilleran zone, north of San Juan are small and decrease considerably from south to north. Minetti et al. (1986) used annual averages from the meteorological stations in the surrounding areas and determined a regional average of 150 mm per year at 29°S.

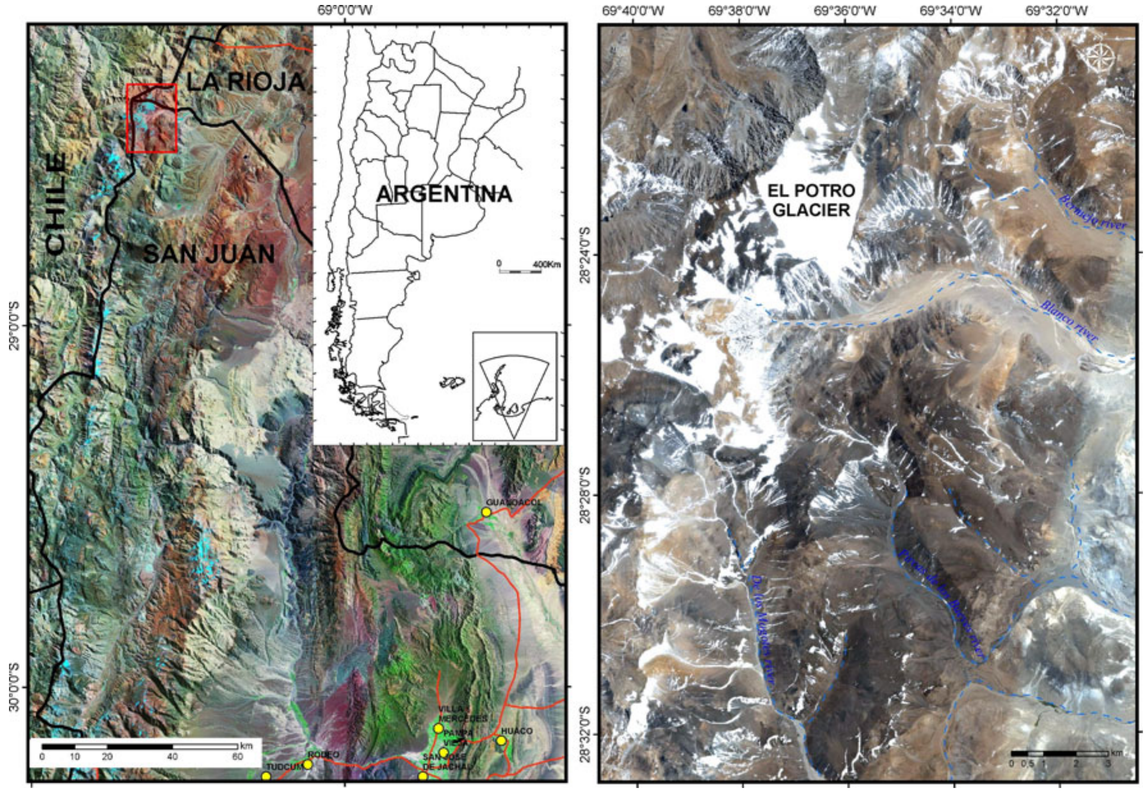


Fig. 1 Overview of the studied area (approximately 28°) in the semi-arid Andes. *Rectangle* shows the specific study area

Most precipitations in the area take place in winter, mostly snow or sleet. The frequency of days with rain or snow precipitations is very low.

The relationship between mountain permafrost and the weather parameters is not clearly defined, as it is the result of complex interactions between various environmental factors of which climate is the most important. The climatic conditions of these high-mountain zones depend mainly on the latitude, altitude, and local conditions.

For example, Ahumada (2002) recognized the presence of periglacial phenomena between 22° and 28°S and from 65° to 68° W longitude. She set two levels in the Sierra del Aconquija; a lower level, between 2,500 and 4,000 m ASL, with seasonal freezing and solifluction, and a higher level, between 4,000 and 4,500 m ASL, with intensive gelifraction, inactive or active debris rock glaciers.

Kammer (1998) and Brenning (2005b) observed that between ~23° and 27°S, rock glacier distribution is interrupted, even though there is sufficient debris available. On the other hand, Corte (1982) set the lower limit of permafrost at 4,000 m ASL at 25°S.

At 30°S, the Andes are characterized by semi-arid conditions, with extreme solar radiation intensities throughout the year. Precipitations occur above 4,000 m during winter, as snow or graupel. Annual precipitation ranges from 100 to 350 mm (Minetti et al. 1986). The snow cover is neither thick nor long-lasting. In the area of Agua Negra, at about 30°S, the snow baseline is developed above 5,300 m, with a permanent snow cover lying frequently, in the south-facing slopes. The continuous permafrost is found between 4,000 and 4,800 m ASL, whereas below 4,000 m, the permafrost is found rather sporadically (Schrott 1994).

At 33°S, Brenning (2005a, b) indicated that the snow baseline is found above 3,800 m ASL, which corresponds to the feeding zones for glaciers, snowfields, and gelifraction. Between 3,500 and 3,800 m ASL, the baseline of the discontinuous permafrost is found. Here, the prevailing features are rock glaciers, talus rock glaciers, ablation zones of small glaciers, and dead glacier tongues from thermokarst. Between 3,500 and 3,000 m, the insular permafrost takes place, with the presence of inactive and fossil rock glaciers. Finally, below 3,000 m, the predominant occurrences are the fluvial and gravitational processes of the region.

Rock glaciers are the main landforms of interest analyzed in the present contribution. They are frequently described in the Central Andes of Chile and Argentina (Corte 1976a, b; Marangunic 1979; Corte and Espizúa 1981; Schrott 1996; Scholl 1992; Trombotto et al. 1999; Trombotto 2000; Brenning 2003, 2005a, b, 2009; Croce and Milana 2002; Milana and Güell 2008), These records, however, are preliminary, due to the terminology difficulties found in differentiating rock glaciers, glaciers and massive ice affected by thermokarst. Brenning et al. (2005) have made a quantification of the regional distribution of glaciers in the Andes of Santiago. Brenning and Azócar (2009a) and Azócar and Brenning (2009) have analyzed the hydrological and geomorphological importance and the topographic and climatic controls of rock glaciers in the Dry Andes of Chile at 27°–33°S.

From a geological point of view, the Cerro El Potro area shows outcrops of Paleozoic granitoid and volcanic rocks in uplifted blocks. To the south, continental sandstones and volcanoclastic rocks overlap the rocks of the Permo-Triassic age. The Tertiary units are of volcanic, pyroclastic, and subvolcanic sequences. The region also shows Quaternary deposits caused by mass movement, rock glaciers, and glacial and fluvial deposits. The main alignments crossing the region show a WNW–ESE and NE–SW trend. The dominant structural feature is a compressive tectonic with horst and graben blocks, elongated in an N–S trend, which expose basement rocks. Also visible are NW–SE dextral strike slip faults, which have generated distensive basins.

Methods

For the analysis of the area, stereoscopic pairs of aerial photographs, scale ~1:50,000 obtained in a regional flight during the fall seasons of the 1960s were interpreted. Photographic mosaics were arranged with ortho-rectified air photography and Spot satellite images with a resolution of 2.5 m obtained in 2006 which were georeferenced within a geographical information system (GIS).

On this array, an inventory of active rock glaciers and glaciers was prepared in order to identify their possible relationships with altitude, slope, and aspect (Fig. 2).

Altitudes were obtained from 1:100,000 topographical charts (50 m contour line) supplied by the Instituto Geográfico Militar de Argentina (Argentine Military Geographic Institute), and from topographical information obtained from the Radar Shuttle Topographical Mission (USGS 2000). Therefore, a digital elevation model (DEM), expressed in degrees was made for the region (Fig. 3). Using the DEM, slope aspect map (Fig. 4) was performed. These maps have simplified the analysis of geomorphological processes. The aspect of the talus slope from where each rock glacier originates was recorded too (Table 1).

Statistical assessment for quantification of rock glacier and glaciers areas and water equivalent (Brenning 2005a, b) was carried out, in order to determine rock glacier and glacier distribution, considering the importance of these landforms as stores of water in the Argentine Dry Andes portion and by comparison with the Chilean sector.

As previously presented by Barsch (1996), Burger et al. (2009), Arenson et al. (2002) and Azócar and Brenning (2009), water equivalent of rock glaciers and glaciers was estimated assuming that the ice-rich layer of rock glacier permafrost has an ice content (in average) of 50% by volume with an ice density of 0.9 g cm^{-3}. The thickness of this layer is estimated using the empirical rule proposed by Brenning (2005b) based on rock glacier geometry obtained during ground measurements:

$$50 \times [\text{area}(\text{km}^2)]^{0.2}$$

Glaciers smaller than 0.1 km^2 were considered snow banks and excluded (Haeberli 2000; Chen and Ohmura 1990) empirical relationship was applied to estimate glacier thickness as Azócar and Brenning (2009) carried out in ×the Dry Andes of Chile:

$$28.5 \times [\text{area}(\text{km}^2)]^{0.357}$$

However, as Azócar and Brenning (2009) explained, the estimation of glacier thicknesses based on the empirical relationship of Chen and Ohmura (1990), results in glacier volumes 49% lower than those obtained with the relationship of Marangunic (1979), with overly optimistic estimates of glacier volumes.

Results and discussion

In the highest sectors of Cerro El Potro area, the dominant landforms are related to their present glacial (depending on the altitude and latitude) and periglacial environments. The latter one modifies a previous glacial environment, which was able to cover topographically lower areas in earlier times. Although the actual glacial activity is scarce, during Pleistocene it was an active shaping agent. It is possible to see in this region various erosion-formed features and extensive accumulations of glacial deposits. Fluvial activity is rather scarce in the area, limited to the action of main rivers. They are permanent flows which re-work the ancient glacial, periglacial and mass movement deposits. Although their erosive power is not significant, the most visible effects are the deepening of outwash plains.

The modern equilibrium line altitude (ELA) of glacier north of 30°S is consistent with meridional changes in temperature and precipitation, surpassing 5,000 m ASL north of 30° (Brenning 2005b; Azócar and Brenning 2008, 2009). In the Cerro El Potro area, ELA is approximately at 5,320 m (Brenning 2005b).

Main glacial forms currently observed at 28°S are restricted to higher areas, above 5,500 m ASL, with the

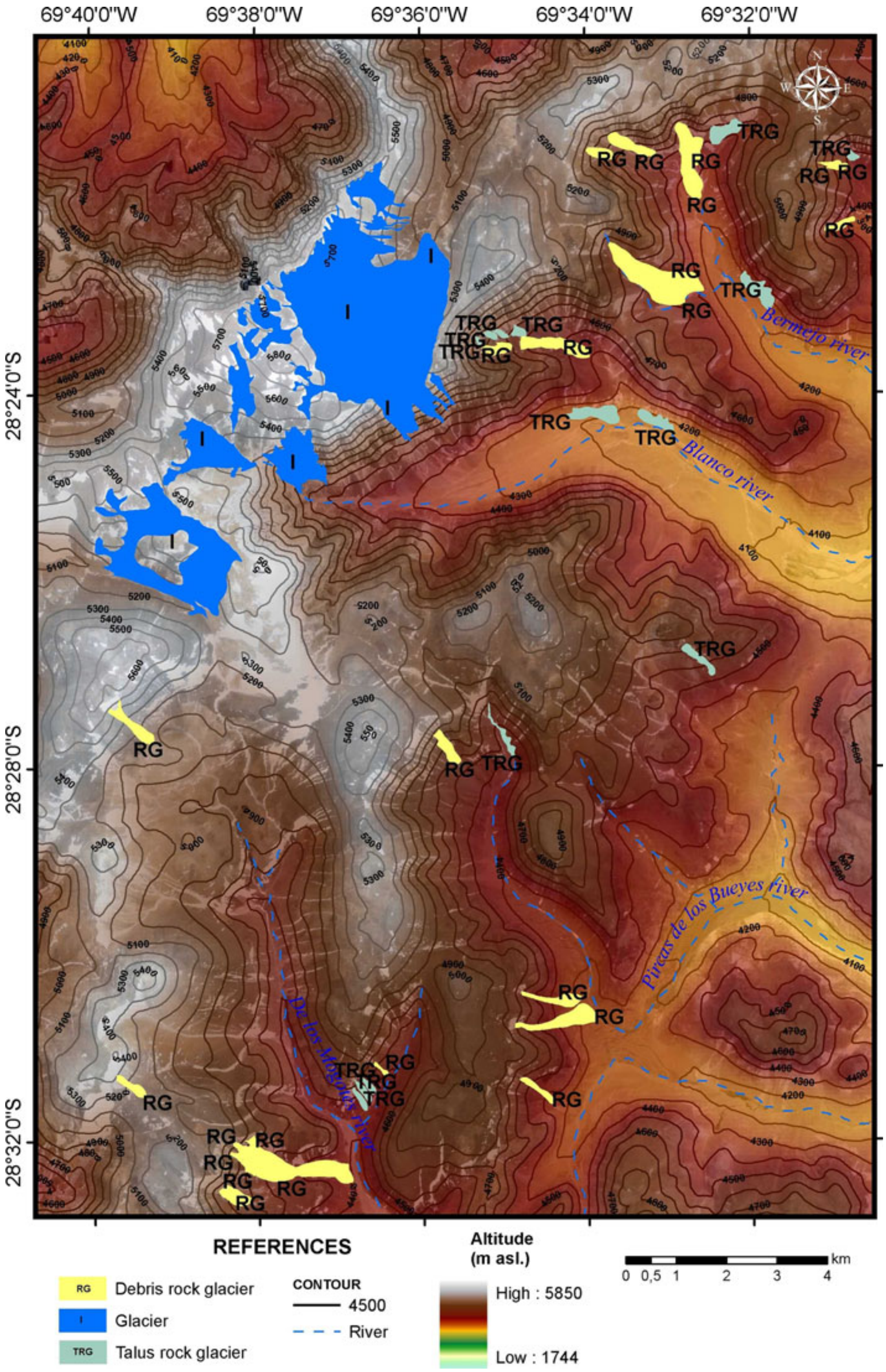
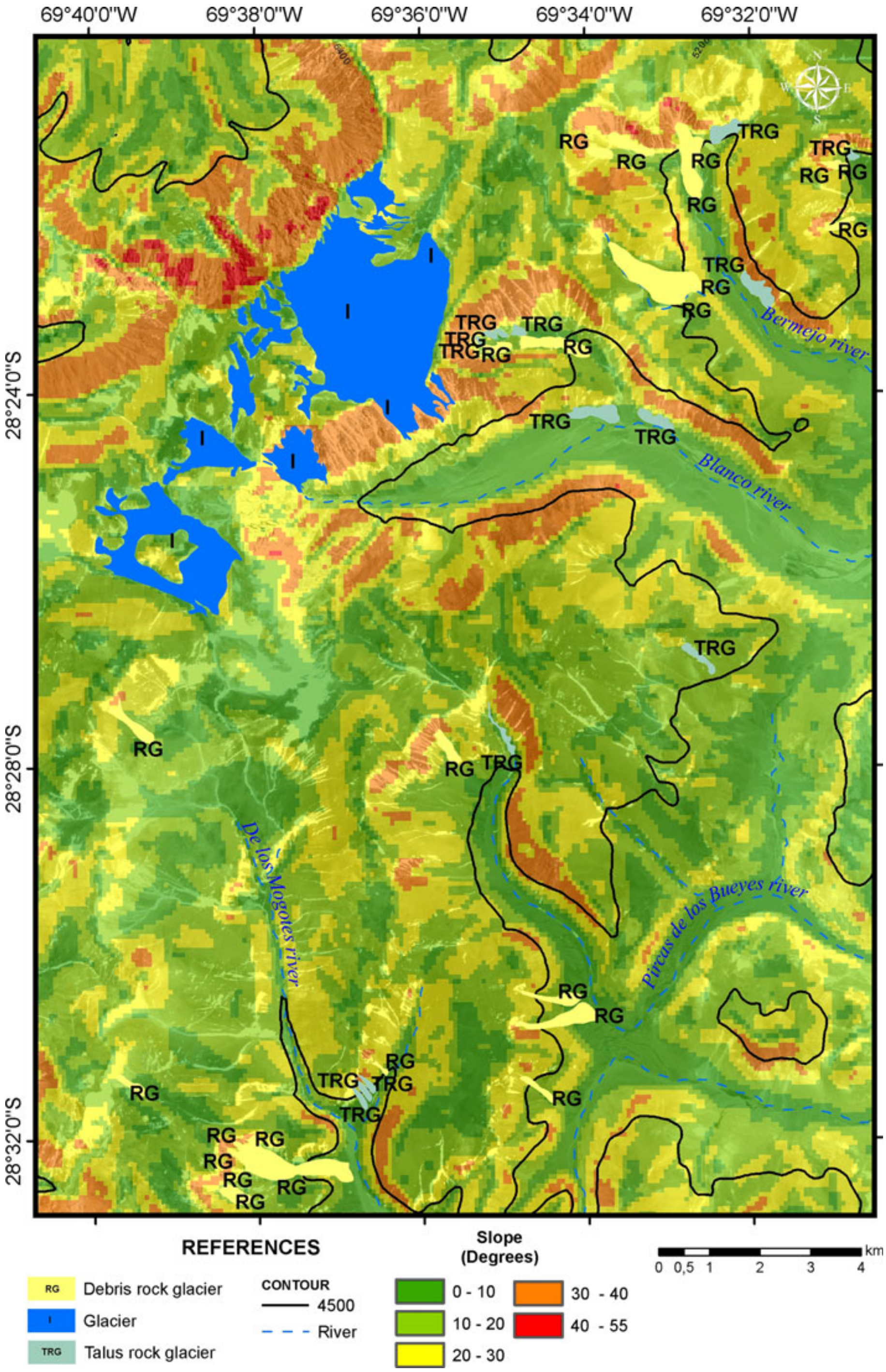


Fig. 2 Map of altitude and distribution of glacier and active-inactive rock glaciers in the Cerro El Potro-Argentine border

permanent ice field located in Cerro El Potro (5,879 m ASL). At this elevation, neighboring smaller glaciers and moraine deposits have also been noted. In addition, a large number of perennial snow patches have been observed whose lower boundary at the latitude of Cerro El Potro (28°15′S) was 5,000 m ASL, mainly on the south eastern-facing slopes (Perucca and Esper 2008). The summit plateau of Cerro El Potro hosts a 7 km^2 large, mainly east-exposed glacier (Brenning 2005b), only ~3% located in Argentina. It is the largest glacier in the area.

In the area of Cerro El Potro, the most frequent rock glaciers are the talus-derived rock glaciers and the debris rock glaciers (tongue-shaped glaciers). On the eastern flank of Cerro El Potro, numerous little tongue-shaped rock glaciers are found. In general, they are less than 1 km long and 300 m maximum width and they are

Fig. 3 Map of slope angle and localization of glaciers/active-inactive rock glaciers

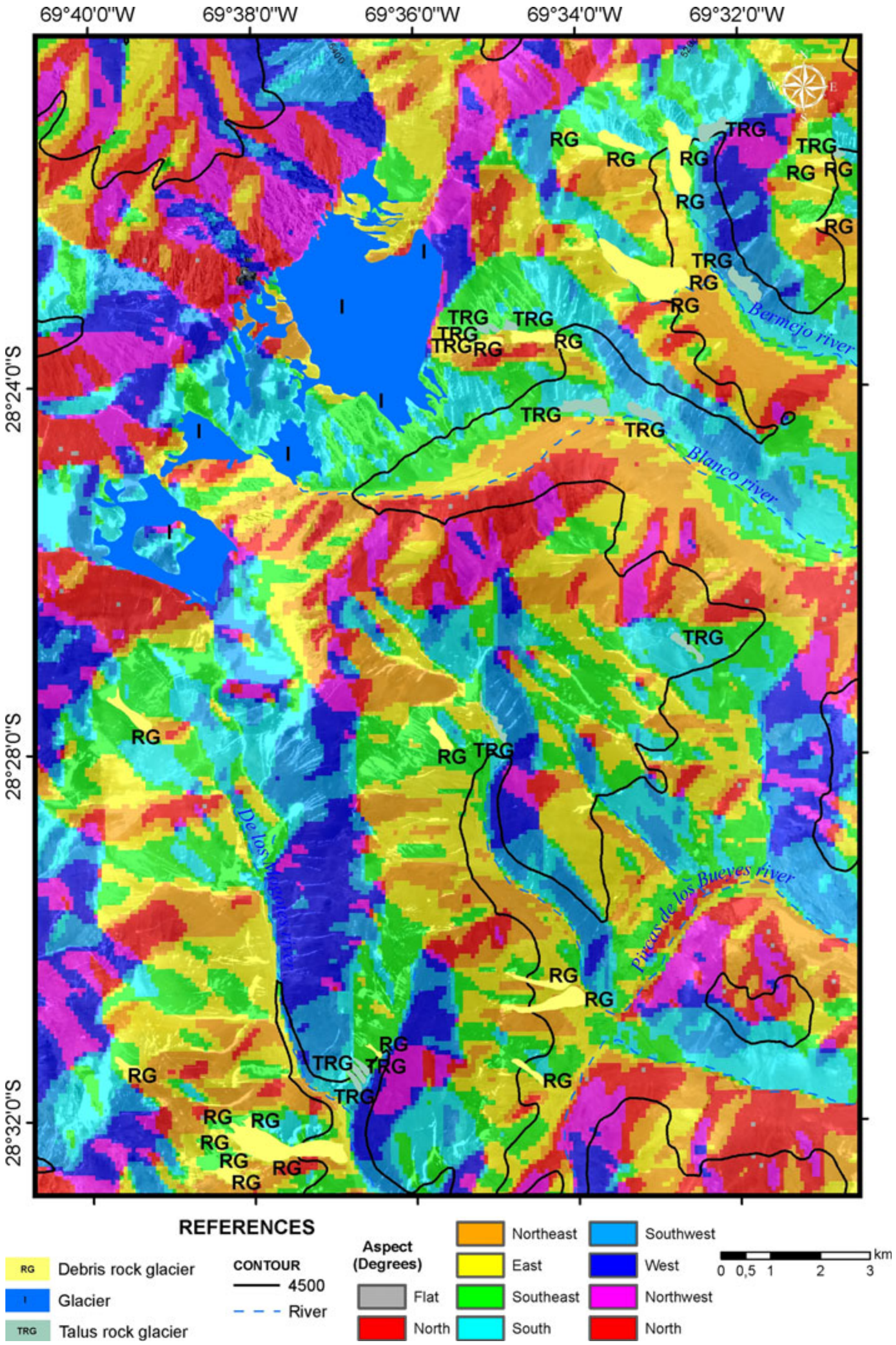


generally smaller than those in the Chilean sector west of the studied area.

By analyzing the altitude and slope cartography (Fig. 3), on a 1:100,000 scale with 100 m contour lines, it is possible to recognize that the slopes are generally found above 20°. Only on the valleys of main rivers (Blanco and Bermejo), the slopes are considerably smaller (between 0° and 10°). This map has simplified the analysis of geomorphological processes. For example, debris rock glaciers are located in areas with slopes between 5° and 20°, and talus rock glacier in slopes between 20° and 40° (Fig. 3).

All the active-inactive rock glaciers mapped occur above 4,270 m pointing to the possible minimum elevation for the development of rock glaciers. From the satellite image analysis, the limit between active and inactive rock glaciers is estimated at 4,200 m a.s.l. in the study area (28°S latitude).

Fig. 4 Map of slope aspect and distribution of glaciers and active-inactive rock glacier



A total of 38 active-inactive rock glaciers, occupying an area of 5.86 km^2, were identified. Most of them (24) are debris rock glaciers (tongue-shaped glaciers) and only 14 are talus rock glaciers (Table 1).

In the studied area, rock glaciers are found mostly on the southeast-facing hillsides, which get lower sunshine radiation, though they are also found on some east-facing sides, yet limited to areas with relatively low sunshine radiation levels (Fig. 4). Therefore, if we consider aspect with topographic positions, 25 active-inactive rock glaciers located along valley walls occur on southeast-facing slopes, 4 located along valley floors occur on southwest-facing slopes, 6 located along valley floors occur on eastern-facing slopes and only three are recognized on valley floors with south-facing slopes (Table 1).

Table 2 summarizes specific density estimations and water equivalent of rock glaciers in the El Potro area (Argentina border). In this study, the rock glacier area is 5.9 km^2, which corresponds to 38 rock glaciers with 0.12 km^3 water equivalent. The values obtained in the

Table 1 Summary of El Potro area inventory showing the location, area, depth, water content and aspect of glaciers and rock glaciers by considering only features over 0.1 km^2

		Area	*X*	*Y*	Latitude	Longitude	Area (km^2)	Depth (m)	50%	Ice (km^3)	Water (km^3)	Altitude (m a.s.l).	Aspect
1	Glacier	1,457,278.30	2,437,198.30	6,858,603.11	S 28 24 20,54	W 69 38 30,46	1.457	32.601		0.0475	0.05278731		
2	Glacier	858,280.89	2,438,756.85	6,858,022.14	S 28 24 39,68	W 69 37 33,32	0.858	26.987		0.0232	0.02573579		
3	Glacier	527,015.53	2,441,412.00	6,861,907.90	S 28 22 33,90	W 69 35 55,06	0.527	22.674		0.0119	0.01327751		
4	Glacier	9,657,420.27	2,439,987.66	6,860,926.16	S 28 23 05,56	W 69 36 47,56	9.657	64.038		0.6184	0.68716164		
5	Glacier	418,701.30	2,440,762.01	6,858,920.19	S 28 24 10,84	W 69 36 19,49	0.419	20.886		0.0087	0.00971687		
6	Glacier	3,064,372.37	2,436,270.59	6,856,204.65	S 28 25 38,28	W 69 39 05,02	3.064	42.508		0.1303	0.14473308		
1	RG	13,651.64	2,437,562.41	6,844,197.49	S 28 32 08,51	W 69 38 19,90	0.014	21.184	10.592	0.0001	0.00016066	4,800	Southeast
2	RG	62,288.28	2,437,793.44	6,844,028.61	S 28 32 14,04	W 69 38 11,43	0.062	28.698	14.349	0.0009	0.00099308	4,660	Southeast
3	RG	31,996.71	2,437,636.03	6,844,405.67	S 28 32 01,76	W 69 38 17,15	0.032	25.118	12.559	0.0004	0.0004465	4,764	Southeast
4	RG	22,847.5	2,437,879.66	6,844,433.39	S 28 32 00,90	W 69 38 08,18	0.023	23.482	11.741	0.0003	0.00029806	4,679	Southeast
5	RG	817,554.21	2,438,659.64	6,844,023.07	S 28 32 14,36	W 69 37 39,58	0.818	48.026	24.013	0.0196	0.0218131	4,394	Southeast
6	TRG	93,809.64	2,442,840.44	6,852,555.05	S 28 27 37,92	W 69 35 04,27	0.094	31.147	15.574	0.0015	0.00162328	4,738	Southwest
7	RG	107,934.63	2,442,718.57	6,860,215.8	S 28 23 29,07	W 69 35 07,38	0.108	32.033	16.017	0.0017	0.00192084	4,284	East
8	TRG	29,886.22	2,442,791.56	6,860,515.52	S 28 23 19,35	W 69 35 04,65	0.030	24.778	12.389	0.0004	0.0004114	4,285	Southeast
9	TRG	49,721.99	2,443,135.92	6,860,556.43	S 28 23 18,07	W 69 34 51,99	0.050	27.433	13.717	0.0007	0.0007578	4,268	Southeast
10	TRG	36,418.65	2,442,578.65	6,860,489.92	S 28 23 20,15	W 69 35 12,47	0.036	25.777	12.889	0.0005	0.00052154	4,298	Southeast
11	TRG	15,918.87	2,442,347.58	6,860,363.91	S 28 23 24,20	W 69 35 20,98	0.016	21.845	10.923	0.0002	0.00019319	4,318	Southeast
12	RG	317,658.49	2,443,868.77	6,860,279.96	S 28 23 27,17	W 69 34 25,12	0.318	39.752	19.876	0.0063	0.00701536	4,271	East
13	TRG	114,197.89	2,446,702.34	6,854,092.27	S 28 26 48,58	W 69 32 42,07	0.114	32.397	16.198	0.0018	0.00205536	4,336	Southwest
14	RG	444,263.61	2,445,656.36	6,861,548.25	S 28 22 46,24	W 69 33 19,25	0.444	42.511	21.255	0.0094	0.0104922	4,147	Southeast
15	RG	504,835.42	2,446,061.76	6,861,652.87	S 28 22 42,91	W 69 33 04,34	0.505	43.611	21.806	0.0110	0.01223143	4,183	Southeast
16	RG	408,988.21	2,446,496.6	6,863,905.38	S 28 21 29,80	W 69 32 48,00	0.409	41.813	20.907	0.0086	0.00950059	4,474	South
17	RG	101,124.53	2,446,660.41	6,864,142.28	S 28 21 22,13	W 69 32 41,94	0.101	31.619	15.809	0.0016	0.00177634	4,440	Southeast
18	TRG	175,678.82	2,447,207.95	6,864,524.33	S 28 21 09,80	W 69 32 21,77	0.176	35.311	17.656	0.0031	0.00344636	4,270	Southeast
19	TRG	34,892.92	2,449,744.51	6,864,036.67	S 28 21 26,00	W 69 30 48,71	0.035	25.557	12.779	0.0004	0.00049543	4,540	Southwest
20	RG	36,330.67	2,449,335.83	6,863,885.52	S 28 21 30,86	W 69 31 03,74	0.036	25.765	12.882	0.0005	0.00052003	4,623	East
21	RG	35,005.69	2,449,491.98	6,863,816.88	S 28 21 33,11	W 69 30 58,02	0.035	25.574	12.787	0.0004	0.00049735	4,549	East
22	RG	80,212.97	2,449,490.65	6,862,672.29	S 28 22 10,29	W 69 30 58,25	0.080	30.187	15.093	0.0012	0.00134521	4,176	Northeast
23	RG	100,697.52	2,435,488.85	6,845,605.45	S 28 31 22,41	W 69 39 35,88	0.101	31.592	15.796	0.0016	0.00176734	5,140	Southeast
24	RG	157,265	2,437,530.59	6,843,439.64	S 28 32 33,12	W 69 38 21,22	0.157	34.538	17.269	0.0027	0.00301756	4,707	Southeast
25	RG	200,227.42	2,435,510.1	6,852,748.41	S 28 27 30,41	W 69 39 33,66	0.200	36.247	18.124	0.0036	0.00403205	5,084	Southeast
26	TRG	249,587.8	2,444,673.06	6,858,926.05	S 28 24 11,27	W 69 33 55,81	0.250	37.880	18.940	0.0047	0.00525249	4,537	South
27	TRG	147,999.16	2,445,845.41	6,858,801.5	S 28 24 15,49	W 69 33 12,77	0.148	34.121	17.061	0.0025	0.00280549	4,634	South
28	RG	92,871.54	2,443,530.74	6,845,553.37	S 28 31 25,45	W 69 34 40,14	0.093	31.085	15.542	0.0014	0.00160382	4,353	Southeast
29	RG	29,546.61	2,440,413.88	6,845,958.2	S 28 31 11,80	W 69 36 34,69	0.030	24.721	12.361	0.0004	0.00040579	4,487	Southeast

Table 1 continued

		Area	*X*	*Y*	Latitude	Longitude	Area (km^2)	Depth (m)	50%	Ice (km^3)	Water (km^3)	Altitude (m a.s.l).	Aspect
30	TRG	52,867.76	2,440,013.11	6,845,352.23	S 28 31 31,42	W 69 36 49,54	0.053	27.772	13.886	0.0007	0.00081569	4,426	Southeast
31	TRG	58,018.9	2,440,077.45	6,845,514.39	S 28 31 26,16	W 69 36 47,15	0.058	28.293	14.147	0.0008	0.00091197	4,439	Southeast
32	TRG	46,543.5	2,440,171.66	6,845,627.65	S 28 31 22,50	W 69 36 43,66	0.047	27.073	13.537	0.0006	0.00070005	4,457	Southeast
33	RG	352,443.31	2,444,070.72	6,846,944	S 28 30 40,37	W 69 34 20,04	0.352	40.587	20.294	0.0072	0.00794703	4,275	East
34	RG	173,905.89	2,443,917.41	6,847,340.55	S 28 30 27,46	W 69 34 25,60	0.174	35.240	17.620	0.0031	0.00340467	4,284	East
35	RG	149,419.06	2,441,728.09	6,852,312.63	S 28 27 45,62	W 69 35 45,20	0.149	34.186	17.093	0.0026	0.00283782	4,888	Southeast
36	TRG	219,311.14	2,447,883.54	6,861,372.38	S 28 22 52,28	W 69 31 57,48	0.219	36.913	18.457	0.0040	0.00449749	4,480	Southwest
37	RG	193,189.85	2,445,332.34	6,864,248.75	S 28 21 18,48	W 69 33 30,69	0.193	35.989	17.994	0.0035	0.00386259	4,584	Southeast
38	RG	97,283.9	2,444,753.01	6,864,091.35	S 28 21 23,50	W 69 33 51,99	0.097	31.375	15.687	0.0015	0.00169569	4,755	Southeast

Table 2 Areas and water equivalence of active-inactive rock glaciers and glaciers in the Cerro El Potro area (Argentine border)

	Number of features	Area		Water equivalent (km^3)
		km^2	%	
Active-inactive rock glaciers	38	5.86	1.56	0.12
Glaciers	6	15.98	4.27	0.93

Argentine portion are consistent with those determined by Brenning (2005a) for the Cerro El Potro area in the Chilean portion where 42 rock glaciers were recognized with a water equivalent of 53–80 (10^6 m^3).

Brenning (2005a) reported rock glacier densities of 3% at Cerro El Potro. However, rock glacier density in the studied area (Argentina border) is approximately half (1.6%) of that obtained from the Chilean side. The glacier area in the Argentine border (28°S) is ~16 km^2, with a water equivalent of 0.9 km^3 and covers 4.3% of the total area studied (374 km^2) (Table 2).

Conclusion

Factors such as topographic shading, relief, aspect, and elevation determine the development and preservation of rock glaciers. Analysis of these factors in the Cerro El Potro area (28°S) shows that, elevation >4,200 m and a southeast-facing aspect are some of the necessary conditions for the existence of rock glaciers in any form. A slope angle below 40° is favorable for talus rock glaciers formation and <20° for tongue-shaped debris rock glaciers.

Permanent snowfields and the glaciers are located above 5,500 m ASL. Between 5,500 and 4,300 m ASL, 38 active-inactive rock glaciers are found, mainly on southeast-facing hillsides. Where slopes are steeper than 20°, there occur talus rock glaciers, whereas in cirques above 4,300 m ASL, the probable active tongue-shaped rock glaciers are found. Below 4,000 m ASL, the predominant features are the fluvial and glacifluvial landforms.

These baselines are contrastive with those of 30°S, which has active glaciers above 3,600 m ASL, and with those of 32°S, where the active landforms are located above 3,200 m ASL.

The present work constitutes a first approach to the identification and knowledge of the glacial and periglacial processes in this little-known portion on the Dry Andes of the San Juan and La Rioja Frontal Cordillera, at 28° and 32°S latitudes.

At 28°S, the glacial and periglacial landforms, mainly the rock glaciers, are characteristic elements of the highest sector of the area chosen for the present study. Above 5,500 m ASL, the ice cap of Cerro El Potro is found. Between 5,500 and 4,300 m ASL, approximately, the active and inactive rock glaciers are observed. Below 4,300 m ASL, the prevailing features are the fossil glacial and/or periglacial features and glacifluvial and/or fluvial landforms.

Knowledge about the spatial distribution of glaciers and rock glaciers is very necessary for the environmental impact assessment of mining projects exploring the area of Cerro El Potro. Rock glaciers are important at 28°S, but covering minor areas than glaciers.

The results presented in this work, although constituting an important advance in knowing the number, features and distribution of ice and rock glacier bodies lying at these altitudes, should be regarded as indicative parameters, though not definite ones on the hydrology of this portion of the High Andes. From the information of this study, it is still not possible to establish a direct and absolute relationship between the water flow of rivers, the basin areas, and the percentage of glazed areas.

The techniques of geophysical prospection (e.g., ground penetrating radar, geoelectric survey, seismic wave refraction, and the like) will allow detecting the occurrence of permafrost in the region and, with this, to permit delimiting the active and inactive glaciers that still keep ice, from fossil rock glaciers.

Finally, the maps along with a GIS base will help in readily visualizing the actual incidence of mining activities on the landforms.

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