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Hydrological and Geomorphological Significance of Rock Glaciers in the Dry Andes, Chile (27°–33°S)

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ABSTRACT

The latitudinal-altitudinal distribution of rock glaciers in the dry Chilean Andes between 27° and 33°S was analysed and their hydrological and geomorphological significance evaluated. Statistical estimation techniques were used based on digital elevation models and air photo interpretation, and sediment budget models were applied to assess surface-lowering rates. The estimated specific density of rock glaciers in the study area is 1.4 per cent, which corresponds to 147.5 km^2 and a water equivalent of 2.37 km^3. A comparison with glacier water equivalents derived from revised glacier inventory data shows that rock glaciers are more significant stores of frozen water than glaciers between 29° and 32°S. The latitudinal-altitudinal distribution of rock glacier limits roughly follows the mean annual air 0°C isotherm, but in the southern part of the study area it extends into elevations where modern regional mean annual air temperatures exceed 0°C. High Andean surface-lowering rates inferred from rock glacier sediment budget models are in the order of 0.6–0.7 mm yr^{-1}, which is comparable to previous results from the dry Chilean Andes, but lower than in the more humid Andes further south. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: rock glacier; Andes; water equivalent; denudation rate; statistical estimation; Chile; surface lowering

INTRODUCTION

Although rock glaciers are known to be abundant and very well developed in the semi-arid Andes (Trombotto *et al.*, 1999; Schröder, 2001; Brenning, 2005a,b), critical gaps in present knowledge of the Andean mountain cryosphere exist. These gaps are important because of the impact of mining activities on Chilean rock glaciers (Brenning, 2008) and the unknown contribution of these features to the baseflow of rivers in summer (Favier *et al.*, 2009). The Chilean government has recently developed a National Glacier Policy that implies the creation of new inventories of cryospheric water resources and promises some level of protection against the impacts of mining on glaciers and rock glaciers.

In this context, our objective is to assess the regional-scale distribution of rock glaciers and their hydrological-geomorphological significance in the dry Chilean Andes between 27°S and 33°S (Figure 1). For this purpose, we develop the first estimate of the water equivalent of rock glaciers as stores of frozen water in this area, and synthesise their latitudinal-altitudinal distribution in relation to regional climatic trends. We further assess the geomorphic significance of rock glaciers in terms of sediment budget models that allow us to estimate post-glacial geomorphic process rates such as average rock glacier advance and vertical surface lowering in rock glacier catchment areas. In order to achieve these objectives efficiently over a large study area (~26 000 km^2 above 3000 m a.s.l.), we conduct a statistical sample survey based on air photo interpretation and digital elevation models (DEMs). In a second step of the analysis (Brenning and Azócar, 2009), catchment-scale topographic and climatic controls as well as spectral characteristics of rock glaciers are investigated with statistical models based on random sample data obtained in the present study.

STUDY AREA AND PREVIOUS RESEARCH

The study area is a ~670-km long section of the Chilean Andes (27°–33°S) and covers 25 830 km^2 above 3000 m

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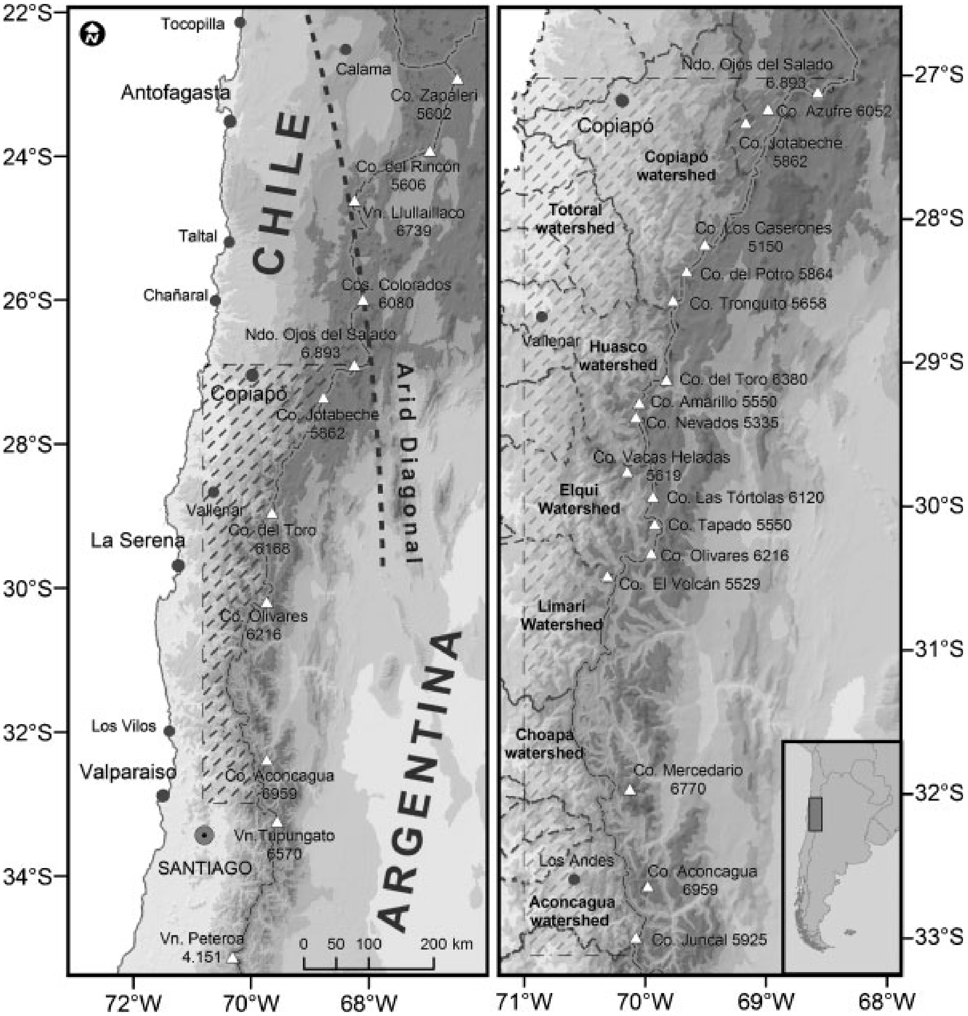

Figure 1 Overview map of the southern Central Andes (left) and the study area (right).

(Figure 1). It is situated south of the Arid Diagonal of South America, which crosses the Andes at 24°–25°S and separates the subtropical winter precipitation area in the south from the area to the north with predominantly tropical summer precipitation. Precipitation at high elevations (>3000–4000 m a.s.l.) in the study area ranges from ~200 mm at the northern edge to 700–800 mm yr y^{-1} in the south. Superimposed upon this spatial trend are El Niño Southern Oscillation events, which increase precipitation in El Niño periods and often reduce it in subsequent La Niña years. The 0°C isotherm of mean annual air temperature (MAAT) rises from ~3700 m a.s.l. in the south to ~4300 m a.s.l. at the study area's northern limit (refer to Brenning, 2005b, for data sources).

As a consequence of the extreme aridity in the Arid Diagonal, the potential snowline altitude exceeds most summit elevations in this area. The modern equilibrium line altitude (ELA) of glaciers follows the meridional changes in precipitation and temperature (Figure 2). It surpasses 5000 m a.s.l. north of 30°S (Cerro Tapado: ELA at ~5300 m; Kull *et al.*, 2002) and drops to 4300–4400 m a.s.l. around 32.5°–33°S. The Juncal Norte glacier (7.6 km^2) on the north slope of Cerro Juncal (33°03′S, 5925 m) just south of our study area is the northernmost valley glacier from there to the Arid Diagonal.

Rock glaciers in the study area and the neighbouring Argentine Andes have previously been studied on a local scale (compare Schrott, 1994; Trombotto *et al.*, 1999; Schröder, 2001; Croce and Milana, 2002; Brenning, 2005a,b) and in relation to their regional distribution (Brenning, 2005b). The specific density of rock glaciers (i.e. the fractional area above the lower limit of rock glaciers that is covered by these features) is often used to characterise their general distribution. It was estimated for some of the most significant culminations of the dry Andes by Schrott (1994) and more widely by Brenning (2005b), who reported rock glacier densities of 3 per cent at Cerro del Potro (28° 23′S, 5864 m), 5 per cent at Cerro Tapado (30° 8′S, 5550 m) and 4 per cent at Paso del Agua Negra (30°S).

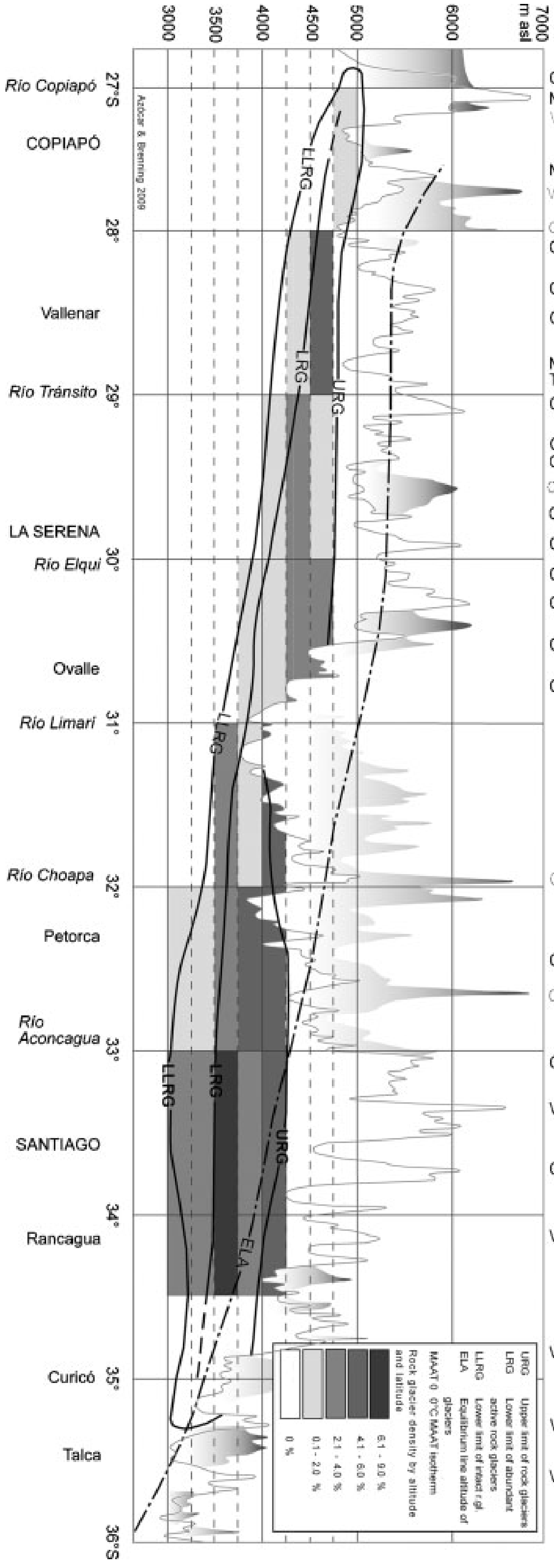

Figure 2 Upper and lower limits of rock glacier distribution along a north-south profile of the Chilean Andes, and specific densities of rock glaciers within latitudinal-altitudinal strata. Rock glacier density south of 33°S is based on Brenning (2005b). Rock glacier distribution limits modified after Brenning (2005b).

North of our study area, rock glacier distribution is interrupted in the Arid Diagonal over a north-south distance of about 400 km between Cerro Lejía (23° 23′S, 5793 m) and Cerro San Francisco (26° 55′S, 6018 m; Hintermayr, 1997; Kammer, 1998; Brenning, 2005b). Further south, in the Andes of Santiago and Mendoza at ~33°–34°S, glaciers are dominant in the highest parts of the Andes as a consequence of higher humidity. Nevertheless, high rock glacier densities (4% specific density of rock glaciers $>0.1\,\mathrm{km}^2$ above their regional lower limit of distribution) and large rock glaciers (Cuerno Blanco rock glacier: $2.0\,\mathrm{km}^2$; Rabicano rock glacier: $1.9\,\mathrm{km}^2$) are related to the numerous nearly unglacierised Andean catchment areas with summit elevations between 4500 and 5000 m a.s.l. (Brenning, 2005a,b).

METHODS

Statistical estimation based on air photo interpretation is an efficient method for regional-scale quantification of rock glacier area and water equivalent (Brenning, 2005a,b), and generalised additive models are flexible tools for analysis of rock glacier distribution data (Brenning *et al.*, 2007). These methods are used in this and the companion paper (Brenning and Azócar, 2009) to assess the importance of rock glaciers as stores of frozen water in the dry Andes, and to identify the topographic and climatic controls on rock glaciers. The focus of this paper is on the application of statistical estimation techniques, and on sediment budget models for the estimation of geomorphic process rates.

Stratified Sample Survey and Statistical Estimation

To obtain data for the statistical estimation of rock glacier areas, 5308 random point locations were generated and evaluated regarding the presence or absence of rock glaciers as described below. The study area was stratified into subregions of 1° latitudinal extent, and further into five altitudinal zones and four aspect classes (N, E, S, W). The altitudinal strata start at the approximate lower limit of rock glacier distribution based on previous research (Brenning, 2005b), and extend upward in 250-m steps; the uppermost stratum extends to the highest summits. Sampling density is $0.5\,\mathrm{km}^{-2}$ within each stratum.

Before performing the time-consuming air photo interpretation to identify rock glaciers, the following rule-of-thumb was derived from previous studies (Brenning, 2005b; Brenning *et al.*, 2007) in order to pre-classify a substantial number of points as non-rock glacier areas and thus to increase efficiency. At each grid location **s**, we define an *unsuitability score* $0 \leq u(\mathbf{s}) \leq 4$ by adding a value of 1 for each of the following conditions that holds:

- Elevation is above the upper rock glacier limit or below the absolute lower rock glacier limit (both as functions of latitude), as determined by Brenning (2005b; 'URG' and 'LLRG' in Figure 2);
- Catchment area $<10^4\,\mathrm{m}^2$ or $>10^{6.5}\,\mathrm{m}^2$ (i.e. $<0.01\,\mathrm{km}^2$ or $>3.16\,\mathrm{km}^2$);
- Catchment slope <15°;
- Local slope >45°.

All conditions refer to a smoothed DEM of the Shuttle Radar Topography Mission (SRTM from Consultative Group for International Agricultue Research Consortium for Spatial Information (CGIAR) version 3, filled version without data voids; details in Brenning and Azócar, 2009).

A total of 2748 samples had a positive score, indicating an almost zero probability of hosting a rock glacier; these samples were diagnosed as non-rock glaciers without further evaluation except from isolated checks. Of the remaining 2560 samples, most (2485) could be classified either as rock glaciers (active or inactive) or as non-rock glaciers based on air photos (Servicio Aerofotogramétrico of the Chilean Air Force, GEOTEC flights, scale ~1:50 000, years 1996–2000) or, where air photos were unavailable, imagery from Google Earth where image quality was acceptable. Overall, 2177 samples were evaluated using air photos, 308 samples with QuickBird and Spot imagery from Google Earth, while 75 remained unclassified and were excluded from subsequent analyses. In the statistical analysis, no distinction was made between active and inactive rock glaciers while relict ones were classified as non-rock glaciers. Standard methods of statistical point estimation were used to determine planimetric areas covered by rock glaciers in the study area and within the strata. All statistical analyses were performed with the data analysis software R.

Water Equivalent of Rock Glaciers and Glaciers

We estimate the water equivalent of rock glaciers and glaciers in order to assess their importance as stores of frozen water. We assume that the ice-rich layer of rock glacier permafrost has an average ice content of 50 per cent by volume with an ice density of $0.9\,\mathrm{g\,cm}^{-3}$ (compare Barsch, 1996; Burger *et al.*, 1999; Arenson *et al.*, 2002). The thickness of this ice-rich permafrost layer is estimated using an empirical rule proposed by Brenning (2005b) based on field measurements of rock glacier geometry. According to this power-law relationship shown in Table 1, a 0.01-km^2 rock glacier contains a 20-m thick ice-debris layer, while a 1-km^2 rock glacier's ice-rich interior is expected to be 50 m thick.

For comparison with the water equivalent of glaciers, we combined glacier inventory data from Garín (1987), Golder Associates (2005), Bown *et al.* (2008) and Vivero (2008). Objects smaller than $0.1\,\mathrm{km}^2$ are considered to be snowbanks and are therefore excluded (Haeberli, 2000). We applied the empirical power-law relationship of Chen and Ohmura (1990), which is shown in Table 1, to estimate glacier thickness. The resulting glacier thicknesses are approximately 50 per cent lower than those reported in the Chilean glacier inventories (Marangunic, 1979). As an example, Kull *et al.* (2002) reported a maximum ice thickness of 40 m for the glacier of Cerro Tapado. This is

Table 1 Assumptions made for estimating rock glacier and glacier equivalents.

Parameter	Value	Source
Average rock glacier ice content	50%	Barsch (1996); Burger *et al.* (1999); Arenson *et al.* (2002)
Density of ice	$0.9\,\mathrm{g\,cm^{-3}}$	Paterson (1994)
Thickness of ice-rich rock glacier permafrost [m]	$50 \times (\text{area [km}^2])^{0.2}$	Brenning (2005b)
Glacier thickness [m]	$28.5 \times (\text{area [km}^2])^{0.357}$	Chen and Ohmura (1990)

close to the estimate of 48 m using the formula of Chen and Ohmura (1990), but is much lower than the 90-m estimate according to Marangunic (1979). Again, we use an ice density of $0.9\,\mathrm{g\,cm^{-3}}$.

Sediment Budget Modelling

Rock glaciers, while active, are material sinks within the debris transport system of mountain areas. They and their talus sheds therefore form closed systems if we ignore solute transport. Consequently, the amount of rock material stored within rock glaciers can be used to estimate geomorphic process rates (Barsch, 1977; Humlum, 2000; Brenning, 2005b). The variables required for this analysis are morphometric properties of rock glaciers, the size of the talus shed and an estimate of rock glacier ages. Our analysis is only based on singular talus rock glaciers (classification according to Barsch, 1996) from the random sample that have a direct connection to the source area, and that are considered to be active with substantial confidence based on air photo interpretation ($N = 12$).

In the study area, there is sufficient evidence to assume that rock glaciers are of post-glacial age (see Jenny and Kammer, 1996; Ammann *et al.*, 2001; Brenning, 2005b; Zech *et al.*, 2008). Late-glacial advances in the study area ended by about 11 ka BP (Zech *et al.*, 2008). We therefore assume that active rock glacier sites became ice-free by about 10 ka BP, and that rock glaciers are generally not older than 10 000 years.

We use two models to estimate the post-glacial vertical surface-lowering rate of relief D in the talus sheds of talus rock glaciers. The first model represents the sediment budget of rock glaciers and their talus sheds as a mass conservation equation,

$$pta = sDA, \qquad (1)$$

where the left-hand side estimates the talus volume stored within a rock glacier as the product of the volumetric talus content of a rock glacier, p, its thickness t and its planimetric area a. The right-hand side expresses the total volume of post-glacial vertical lowering as a function of talus shed size s, denudation rate D in the sense of a vertical lowering rate and rock glacier age A. Morphometric input parameters to this and the following models were digitised based on air photo interpretation and SRTM DEMs.

The second model focuses on rock glacier growth at the interface between the talus slope and the rock glacier's rooting zone. On average, the amount of material sD supplied to a rock glacier in a unit of time is equal to its talus cross-section in the rooting zone multiplied by the advance rate:

$$ptwC = sD \qquad (2)$$

where w is the rock glacier width at its upper end. To solve this equation, a rock glacier's advance rate C is estimated from its relation to the maximum rock glacier length along the flowlines, l, by

$$C = l/A \qquad (3)$$

This advance rate represents an average rate over the rock glacier's lifetime. Since we only have an upper bound of rock glacier age in the study area and did not want to make assumptions on individual rock glacier ages, we used the following criterion to estimate the average denudation rate of rock glacier talus sheds in the study area. For a given denudation rate D, we calculated the age of each rock glacier according to (1), and based on the combination of (2) and (3). Each assumed denudation rate results in a different age distribution over the rock glacier sample; we picked the rate that reflected our age constraint of a post-glacial evolution of rock glaciers. To account for random variation and measurement error, we allowed one-quarter of the estimated ages to exceed 10 000 years.

Conversely, once the regional surface-lowering rate and individual rock glacier ages have been estimated, the advance rate C can be calculated for each rock glacier using equation (3).

The present models do not represent post-glacial changes in material storage within the talus shed (e.g. talus slopes) and preexisting material sources (e.g. moraines). The removal of chemical weathering products by solute transport is also disregarded.

RESULTS

Rock Glacier Area and Water Equivalent

Estimates of the specific density, area and water equivalent of rock glaciers are summarised in Table 2 on a latitudinal

Table 2 Specific density, area and water equivalent of rock glaciers and glaciers in the dry Chilean Andes.

Latitudinal class	Rock glacier density [%]	Rock glacier area [km^2]	Rock glacier water equivalent [km^3]	Glacier area [km^2]	Glacier water equivalent [km^3]	Ratio of rock glacier to glacier water equivalent
27–28°S	0.1	2.0	0.03	3.6	0.09	1:2.9
28–29°S	1.8	20.1	0.32	29.1	0.85	1:2.7
29–30°S	1.1	24.0	0.39	14.5	0.32	1.2:1
30–31°S	1.4	30.0	0.48	1.9	0.06	8.3:1
31–32°S	2.0	16.3	0.26	0	0	∞
32–33°S	2.5	55.2	0.89	n.a.	n.a.	n.a.
Total	1.4	147.5	2.37	49.0	1.32	

n.a.: Data not available.

Table 3 Area and water equivalent of rock glaciers and glaciers in the dry Chilean Andes on a basin scale. Rock glacier area estimates are based on prediction by the GAM-TA-RS model of Brenning and Azócar (2009).

River basin	Basin area [km^2]	Estimated rock glacier area [km^2]	Estimated rock glacier water equivalent [km^3]	Glacier area	Glacier water equivalent	Ratio of rock glacier to glacier water equivalent
Endorrheic altiplano[a]	3091	1.2	0.02	2.5	0.07	1:3.5
Río Copiapó	18704	11.4	0.18	21.1	0.67	1:3.7
Río Huasco	9813	23.5	0.38	21.3	0.48	1:1.3
Río Elqui	9826	32.2	0.52	4.1	0.10	5.2:1
Río Limarí	11696	16.8	0.27	0	0	∞
Río Choapa	7654	18.4	0.30	0	0	∞
Río Aconcagua	7334	43.5[b]	0.70[b]	~80[c]	n.a.[c]	n.a.[c]

[a] Only area south of 27°S.

[b] Only rock glaciers north of 33°S; excludes 487-km^2 high mountain area.

[c] Total area of 121.2 km^2 estimated by Bown *et al.* (2008) includes rock glaciers and snowfields as well as areas south of 33°S. Estimation of glacier water equivalent not possible.

basis and in Table 3 for each river basin. The average rock glacier density in the study area is 1.4 per cent, which corresponds to 147.5 km^2 of rock glacier area and 2.37-km^3 water equivalent. These are conservative estimates because the pre-classified area with a positive unsuitability score may potentially contain a small number of rock glaciers. The estimated mean size of all rock glaciers $>$0.01 km^2 is 0.09 km^2 (median: 0.04 km^2). Thus, there are approximately 1600 rock glaciers $>$0.01 km^2 in the Chilean Andes between 27° and 33°S.

The specific density of rock glaciers is highest in the southernmost portion of the study area between 32° and 33°S, where 2.5 per cent of the surveyed area is covered by rock glaciers. More than one-third of the total rock glacier area in the study area is concentrated in this zone. An impressive debris rock glacier from this zone is shown in Figure 3. Rock glacier density is nearly zero between 27° and 28°S near the Arid Diagonal of South America.

The largest rock glacier detected in the study area is located at ~3800 m a.s.l. in the Colorado river watershed (northern part of the Aconcagua river basin). It is a complex-shaped debris rock glacier with several frontal lobes, a well-developed surface structure and thermokarst features on part of its surface. Its size is 1.0 km^2, which corresponds to a water equivalent of approximately 22 million m^3.

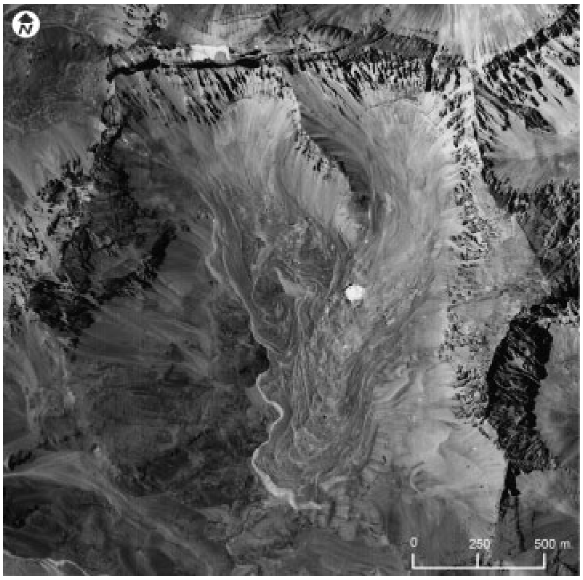

Figure 3 A tongue-shaped debris rock glacier (0.9 km^2) with thermokarst features, Riecillos valley, 32° 37.2′S, 70° 14.3′W (northern part of the Aconcagua river basin). Air photo: GEOTEC-SAF 1996, reproduced with permission.

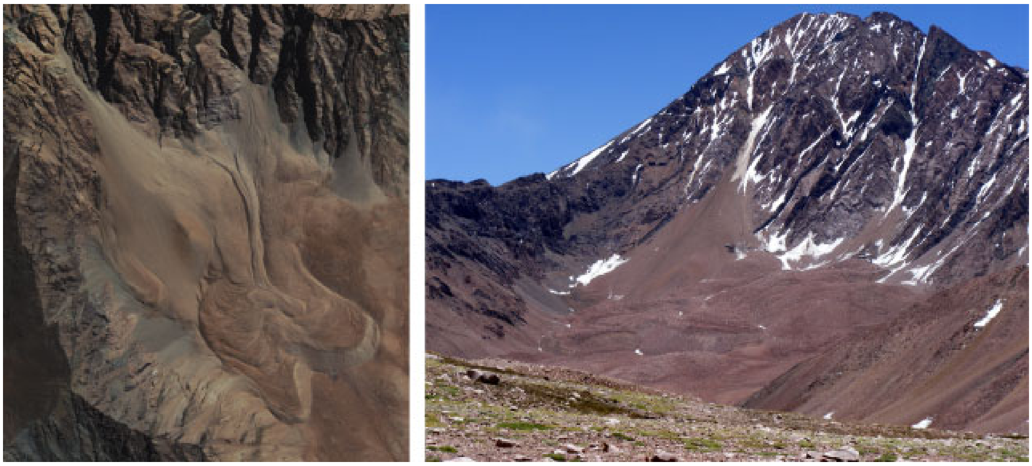

Figure 4 Multi-tongue rock glacier Barriales 1 in the upper Copiapó river basin (29° 14′S, 70° 3′W). Left: IKONOS image, 2005; right: photograph, 2007. This figure is available in colour online at www.interscience.wiley.com/journal/ppp

Based on the method described above, the glacier area in the Chilean Andes between 27° and 32°S is 49 km^2 (most of it between 28° and 30°S), and the water equivalent is 1.32 km^3 (Table 2; 32°–33°S is excluded because detailed data are not available). According to the revised data, the glacier of Cerro del Potro (28° 23′S, 5864 m a.s.l.) is the largest one in our study area (~7-km^2 total area, 4.9 km^2 in Chile; Brenning, 2005b; Vivero, 2008).

The water equivalent of rock glaciers between 30° and 32°S in Chile (0.74 km^3) is 12 times larger than the glacier water equivalent in the same area, which is concentrated in two glaciers at Cerro Tapado (1.8 km^2) and Cerro El Volcán (0.1 km^2); glaciers are absent between 30.5° and 32°S in Chile. Overall, rock glaciers between 27° and 32°S in the Chilean Andes contain 12 per cent more ice than glaciers in this area. However, the uncertainties in these estimates are greater than this nominal difference (see Discussion).

Latitudinal-altitudinal Distribution Related to MAAT

The latitudinal-altitudinal pattern of rock glacier distribution and density is depicted in Figure 2, which also summarises the results of Brenning (2005b). Following Brenning (2005b), we distinguish a lower altitudinal zone of rock glacier distribution in which active and inactive rock glaciers coexist, and an upper zone where rock glaciers are active and usually relatively abundant.

The altitudinal range of rock glacier distribution is widest south of 32°S towards the Andes of Santiago (3000–4250 m a.s.l). Rock glaciers become rare and restricted to a relatively narrow (~4500–5000 m a.s.l) altitudinal zone north of 28°S towards the northern limit of rock glacier distribution.

The lower limit of active rock glacier occurrence (LRG) in the absence of inactive rock glaciers follows a positive (~0.5–1.0°C) modern regional MAAT isotherm between 33° and 31°S. It then shifts to negative MAAT levels north of 31°S. The lowermost active rock glaciers (LLRG) are situated at positive modern regional MAAT levels further north to about 30°S, reaching highest regional MAAT levels of about +4°C in the Andes of Santiago (Figure 2).

The LRG, if used as an indicator of the lower limit of discontinuous mountain permafrost (Barsch, 1996), suggests that 5150 km^2 of mountain terrain in Chile between 27° and 33°S are potentially underlain by discontinuous mountain permafrost.

Geomorphic Process Rates

The sediment budget model of equation (1) and the talus supply model of equations (2) and (3) yield an estimated post-glacial vertical lowering rate of 0.6–0.7 mm yr^{-1} if we require three-quarters of the rock-glacier age estimates to be no older than 10 000 years. The estimates of the talus supply model are slightly higher than the sediment budget-based values.

The distribution of estimated ages of the 12 active talus rock glaciers is shown in Figure 5 for different assumed denudation rates D. Median rock glacier ages under these assumptions are between 3900 and 4900 years, and mean ages between 7400 and 8500 years, with the younger ages being estimated by the talus supply model.

Based on equation (3), the median rock glacier advance rate is 4.3 cm yr^{-1} (mean: 6.5 cm yr^{-1}) according to the sediment budget model and assuming a denudation rate of 0.6 mm yr^{-1}. The talus-supply model yields a higher median advance rate of 5.0 cm yr^{-1} (mean: 7.6 cm yr^{-1}) assuming a denudation rate of 0.7 mm yr^{-1} as estimated from this model.

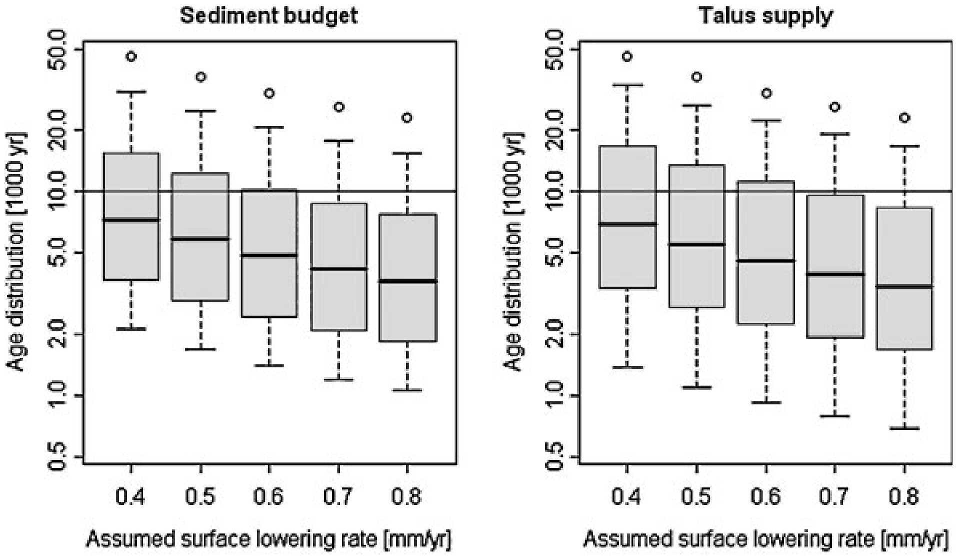

Figure 5 Age distribution of talus rock glaciers with different surface-lowering rates using the sediment budget approach (left) and the talus supply approach (right). The horizontal line represents an assumed age threshold of 10 000 years.

DISCUSSION

Rock Glacier Distribution Limits

Rock glaciers in the Chilean Andes north of the Santiago area (33°S) are abundant in the high southern parts of this study area (32°–33°S) and remain characteristic of the high Andes up to approximately 28°S. They become insignificant in number and size further north toward the Arid Diagonal of South America, where their occurrence is interrupted between Cerro San Francisco (26° 55′S) and Cerro Lejía (23° 33′S) (Hintermayr, 1997; Kammer, 1998; Brenning, 2005b).

It has been suggested that several influences are jointly responsible for the interruption of rock glacier distribution near the Arid Diagonal (Brenning, 2005b):

- Topography in the altiplano and in the transition to it is dominated by individual volcanic cones and mountain ranges that are separated by tectonic basins. This basin-and-range topography and especially the cone-shaped, divergent volcanoes provide few topographic niches with convergent sediment transport that would be suitable for rock glaciers.
- Quaternary volcanism becomes widespread north of 26.5°S, resulting in young, weathering-resistant rocks that do not provide sufficient talus supply for rock glacier development.
- Aridity may reduce talus supply directly through reduced weathering, and indirectly through reduced Pleistocene glacial and periglacial activity. Reduced talus supply is supported by estimates of denudation rates in the dry Andes compared to the Andes of Santiago (Brenning, 2005b).

Based on our findings, the global-scale schematic representation of the potential distribution of mountain permafrost and rock glaciers as a function of precipitation and MAAT as presented by Haeberli and Burn (2002) can be modified for the dry southern Andes. While this scheme sets the lower limit of discontinuous permafrost at the MAAT −1°C isotherm, in the semi-arid Andes a modern regional MAAT of about +1°C appears to allow abundant active rock glacier development. On the other hand, the increasing aridity and rise of the ELA of glaciers towards the arid Andes would lead us to expect a widening of the altitudinal zone of rock glacier existence towards the Arid Diagonal. The aforementioned regional effects – and the global limits of elevation – however impose practical constraints on the hypothetical upper limit provided by the ELA of glaciers. Thus, rock glaciers only reach a MAAT of about −5°C in our study area and not the level of the theoretical ELA (MAAT approximately −11°C).

Hydrological Significance

The hydrological significance of rock glaciers primarily relates to the long-term storage of frozen water, the seasonal storage and release of water, and the interaction with water flowing through or beneath rock glaciers (Burger *et al.*, 1999). As indicators of the potential for mountain permafrost in their surroundings (Barsch, 1996), rock glaciers also help identify areas with permanent and seasonal storage of soil water. As with glaciers, water

Table 4 Significance of rock glaciers as stores of frozen water in mountain areas worldwide.

Area	Specific density [%]	Ratio of rock glacier to glacier ice volume	Source
Arid Andes 27°–29°S (Chile)	0.8	1:2.7	This paper
— Cerro del Potro area (Chile)	3	1:3	Brenning (2005b)
Semi-arid Andes 29°–32°S (Chile)	1.6	3.0:1	This paper
— Cerro Tapado area (Chile)	5	1.4:1	Brenning (2005b)
— Paso del Agua Negra area (Argentina)	4	1:1.4	Schrott (1994)
Andes of Santiago (Chile)	6.7	1:7	Brenning (2005b)
Andes of Mendoza (Argentina)	5.0		Brenning (2005b)
Swiss Alps	0.3	1:83	Brenning (2005b) based on data from Barsch (compare Barsch, 1996)
— Turtmanntal, Wallis	4	—	Nyenhuis (2005)
Zailyiskiy and Kungey Alatau (Kazakhstan and Kyrgyzstan)	2.65	1:31	Bolch and Marchenko (2006)

storage in rock glaciers and other mountain permafrost is energy-controlled as opposed to precipitation-controlled. Energy-controlled components of the hydrological system are critically important for river runoff during the dry summer season of the subtropical Andes.

Rock glaciers as long-term stores of frozen water have accumulated significant amounts of ground ice during post-glacial times. They may therefore be considered frozen fossil groundwater bodies, or nonrenewable water resources. The amount of water stored in rock glaciers in the Chilean Andes between 29° and approximately 32°S greatly exceeds the water equivalent of glaciers in this area. This might help explain the excess river discharge observed in the dry Chilean Andes that cannot be explained by glacier retreat (Favier *et al.*, 2009). At a local scale, Schrott (1994) attributed a substantial share (30%) of stream discharge in the Agua Negra basin (Argentina) to thawing permafrost.

Rock glaciers cover 1.4 per cent of the total area studied; this estimate approximates the specific density of rock glaciers above their regional lower limit. Higher densities of rock glaciers are encountered near the highest parts of the Andes in the study area, both around glacierised summits (Cerro del Potro: 3% rock glacier density; Cerro Tapado: 5%; Brenning, 2005b) and unglacierised ones. Rock glacier-contributing areas cover approximately 2.9 per cent of the study area according to statistical estimation based on digitised sample data.

Glaciers (which usually lack significant unglacierised contributing areas) cover only one-sixth of the area of corresponding rock glaciers and their talus sheds; thus, rock glacier watersheds may capture six times more precipitation than the snow accumulated on glaciers. Since exposed glacier ice is subject to sublimation in the high-radiation environment of the dry Andes, the relative importance of rock glaciers and their watersheds for river discharge in the study area may be much greater than for glaciers, although water sequestration by active rock glaciers should also be considered. On the other hand, it has previously been suggested that discharge from rock glaciers is smaller than the discharge from glaciers of a similar size (Krainer and Mostler, 2002). This underlines the need for increased research into rock glacier hydrology and hydrogeology, and for monitoring the volume changes of active and inactive rock glaciers.

Data from other mountain areas in the Andes and worldwide show that the study area is almost unique in terms of the relative importance of rock glacier water storage compared to glaciers (Table 4). Similar situations are only found in the driest parts of the high mountains of Central and South Asia such as the Ladakh area (Ladakh and Zanskar ranges, Kashmir) and in part of the southwestern United States (southern Sierra Nevada, California; San Juan Mountains, Colorado) (Owen and England, 1998; Mitchell and Taylor, 2001; Millar and Westfall, 2008; M. Richter, personal communication, 2008).

River basins in the dry Andes contain varying relative areas of rock glaciers and glaciers. The Choapa and Limarí watersheds (30.5°S to 32.1°S), for example, have a significant portion of rock glacier area but no glaciers (Table 3). As the most important perennial cryospheric water storage systems, rock glaciers are expected to influence runoff of the Choapa and Limarí rivers during the dry summer months after the end of the snow ablation period.

Estimation Uncertainties in Glacier and Rock Glacier Volumes

Our study reveals substantial and previously unquantified uncertainties in estimates of glacier and rock glacier water equivalents in the study area. Glacier thicknesses used in this study were estimated using the empirical relationship of Chen and Ohmura (1990), which results in glacier volumes 49 per cent lower than those obtained with the relationship of Marangunic (1979). The latter was applied in the Chilean glacier inventories, producing overly optimistic estimates of glacier volumes (e.g. Garín, 1987; Vivero, 2008). The exponent used in the power-law volume-area-scaling rule of Chen and Ohmura (1990) is consistent with the results of Bahr *et al.* (1997).

Glacier areas reported by Garín (1987), Bown *et al.* (2008) and in other inventories include some snowfields, rock glaciers and debris-covered massive ice with thermokarst (dead ice?), and some represent glacier geometries of 1955–56, which may have retreated since then. As an example, Garín (1987) reports the area of the Tapado glacier as 4.28 km^2, while Kull *et al.* (2002) indicate it to be 1.5 km^2. Brenning (2005b) mapped 1.8 km^2 of glacier and 0.7 km^2 of debris-covered massive ice with thermokarst in several separate units at Cerro Tapado using aerial photographs of 1955 (HYCON flight). In addition, Garín's inventory is incomplete between 28.5°S and 29.6°S, where 22.6 km^2 of glacier area were recently reported (Golder Associates, 2005). Vivero (2008) also described discrepancies between the different inventories. Overall, the revised glacier area used in this study for comparison is 14 per cent smaller than previous estimates of Garín (1987). Similarly, in the Aconcagua basin, several large rock glaciers identified by Brenning (2005b) in the field or from air photos were mapped by Bown *et al.* (2008) as debris-covered or even uncovered glaciers based on remote-sensing imagery.

On the other hand, rock glacier areas estimated in our study may be biased downwards because the masking based on an unsuitability score may have excluded some rock glaciers or parts thereof. However, it is believed that rock glacier density in the masked area (5500 km^2) is at least one order of magnitude lower than elsewhere, or no more than 0.1 per cent of the masked area. This would correspond to 5 km^2, or a 3 per cent underestimation of the total rock glacier area and water equivalent.

Larger uncertainties in rock glacier water equivalent are due to sampling variance (estimated coefficient of variation of overall specific density of rock glaciers: $\pm 24\%$), estimated rock glacier thickness ($\pm 20\%$ error) and unknown ice content (-20 to $+40\%$). Thus, the approximate overall uncertainty may be on the order of -50 per cent to $+100$ per cent.

Geomorphological Significance

Our estimated post-glacial surface-lowering rate of 0.6–0.7 cm yr^{-1} in the talus sheds of rock glaciers compares well with the results of Brenning (2005b). He used a non-random sample of rock glaciers in the Cerro Tapado and Cerro del Potro areas and obtained an average lowering rate of 0.5 mm yr^{-1} or slightly higher (but <0.75 mm yr^{-1}). Consequently, the median advance rate of about 3 cm yr^{-1} estimated by Brenning (2005b) is lower than our rock glacier advance rate of 4.3–5.0 cm yr^{-1}. However, our estimated median rock glacier age of 3900–4900 years is younger than the previously estimated 6000–7000 years BP. The estimated advance rates represent averages over the entire lifespan of rock glaciers and an entire mountain area. Direct observations indicate mean surface displacement rates and advance rates between a few centimetres and 1 m per yr^{-1} (Barsch, 1996; Burger *et al.*, 1999; Frauenfelder *et al.*, 2003), with an increasing trend possibly in reaction to climate change (Delaloye *et al.*, 2008; Bodin *et al.*, 2009). Averages over several millennia can be expected to be lower because of the potential for phases of inactivity. Thus, the estimated mean advance rates appear to be of a reasonable order of magnitude, and comparisons with rock glaciers in other climates could help identify environmental controls on rock glacier velocities.

Post-glacial lowering rates between 0.5 and 1.1 mm yr^{-1} in the mountains of Colorado, USA, have been calculated based on rock glacier sediment budgets (Caine, 1974; Brenning *et al.*, 2007). Barsch (1977) obtained similar to higher values in the Swiss Alps, and Humlum (2000) estimated a headwall retreat rate of 2 mm yr^{-1} from talus rock glaciers in west Greenland. Post-glacial surface-lowering rates in the sub-humid to semi-arid Andes of Santiago and Mendoza are higher (0.75–1.0 mm yr^{-1}; Brenning, 2005a) than those in our semi-arid to arid study area (Brenning, 2005b). Montgomery *et al.* (2001) studied relationships between tectonics, climate and erosion rates based on morphometric considerations at the continental scale and on a geologic time scale (>10 Ma), indicating a strong latitudinal, climatically influenced excess erosion rate of almost 2 mm yr^{-1} in the Andes of Santiago and about 0.5 mm yr^{-1} towards the Arid Diagonal of South America. On a geologic time scale, smaller erosion rates also influence orogen morphology, resulting in tectonically controlled landscapes in the Atacama Desert and glacially and fluvially sculpted topography towards more humid areas.

While lack of humidity may be one cause of reduced denudation rates in the study area compared to more humid areas, there are several potential confounding factors such as lithology, seismic activity and tectonic uplift that may influence weathering rates and mass movements (Hovius *et al.*, 2004). In addition, late-glacial debris storage in moraines may have provided different initial conditions for rock glacier development in different parts of the Andes and may bias our sediment budget calculations. Moreover, weathering and retreat rates may have decreased in the same place by several orders of magnitude after a phase of rapid retreat due to post-glacial stress relaxation (André, 2003).

Rock glacier sediment budgets are observational units that have many replications with varying characteristics (e.g. lithology, jointing, catchment slope) across a mountain range. Consequently, statistical analysis of rock glacier sediment budgets would be an ideal instrument for understanding different topographic and geological influences on post-glacial denudation rates both within complex mountain ranges and continentally or globally.

CONCLUSIONS

Knowledge about the spatial distribution of rock glaciers and mountain permafrost is of critical importance for the environmental impact assessment of mining projects (Brenning, 2008) and more generally for water management and policy development. Rock glaciers are more important stores of frozen water than glaciers in the Chilean Andes between 29° and 32°S (ratio 3:1), but less important north

(1:3) and south (1:7) of this area. This ratio of ice volumes is only partly a function of humidity, but also of topography, because elevation of the highest summits relative to the regional snowline is decisive for the presence and size of glaciers. Areas where rock glaciers are the only or the predominant perennial cryospheric water resource include watersheds of the Elqui, Limarí and Choapa rivers, which are of great importance for export-oriented agriculture.

Post-glacial surface-lowering rates of 0.6–0.7 cm yr^{-1} in our semi-arid to arid study area are relatively low compared to more humid areas in Chile and worldwide. Beyond this regional comparison, the study of rock glacier sediment budgets may provide a powerful tool for analysing a variety of geological and topographic influences on denudation rates.

The presence of active rock glaciers in the southern part of the study area and further south at positive regional modern MAAT levels may partly be explained by local topographic effects and a delayed response of rock glaciers to climatic warming, but it requires further research, including long-term monitoring.

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