ROCK GLACIERS IN THE PATAGONIAN ANDES: AN INVENTORY FOR THE MONTE SAN LORENZO (CERRO COCHRANE) MASSIF, 47° S

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ABSTRACT. Although rock glaciers in the Central and Desert Andes of Argentina and Chile have been previously studied in detail, much less attention has been paid to the occurrence of these permafrost forms in Patagonia. Recently, however, the establishment of the Argentinean Glacier Inventory program, which intends to inventory and monitor all ice masses along the Argentinean Andes, has started a large amount of new geocryological research. The project is designed to provide reliable and worldwide comparable results, supported by well established technical procedures and background information.

Presented here is the first rock glacier inventory of the Monte San Lorenzo (Cerro Cochrane) region in the southern Patagonian Andes. A total of 130 intact (9.86 km²) and 47 fossil (1.45 km²) landforms were inventoried using two 2.5 m resolution ALOS Panchromatic Remote-sensing Instruments for Stereo Mapping images.

Since the Argentinean federal initiative described above legally protects all rock glaciers in the country as water reserves, and due to the little scientific knowledge concerning rock glaciers in the vast majority of the Patagonian Andes, this inventory provides an important basis for political decision-making and opens further geocryological research avenues for the Patagonian region in general.

Key words: rock glacier inventory, Monte San Lorenzo, Patagonian Andes, ALOS

Introduction

Mountain permafrost in South America is commonly found at high elevations in the Andes, and appears mostly as groups of rock glaciers. Active rock glaciers are striking tongue or lobate-shaped features present in many alpine (high mountain) environments around the world. They represent the geomorphologic, visible expression of ice-supersaturated mountain permafrost creep in unconsolidated material, and are composed of frozen but unconsolidated debris, which in turn can be talus or till-derived (Barsch 1996). Downslope movement of active rock glaciers is a consequence of internal ice deformation, and thus rock glaciers are examples of cohesive flow features (Barsch 1992).

Rock glacier inventories are helpful in providing basic information on the distribution of mountain (alpine) permafrost, and can assist in validating and adjusting permafrost distribution models (Boeckli et al. 2012). Contrary to the rock glaciers in the Central and Desert Andes (Lliboutry 1956), where they have been extensively studied and in some cases inventoried (e.g. Perucca and Esper Angillieri 2008; Azócar and Brenning 2010; Trombotto et al. 2012; Falaschi et al. 2014), these landforms have received much less attention in the Patagonian Andes. The relatively smaller size and lower abundance of Patagonian rock glaciers compared with the rock glaciers in the Central Andes, and hence, their minor importance as freshwater suppliers, has resulted in a considerable lower amount of scientific efforts aiming to understand the interaction between climate and the cryosphere.

Study site and previous studies

Monte San Lorenzo (or Cerro Cochrane in Chile) (47° 35′ S, 72° 18′ W, 3706 m a.s.l.; Fig. 1) lies in the heart of the Patagonian Andes, at the international border between Chile and Argentina, forming a N–S stretching mountain range with an elevation above 3000 m a.s.l. Together with
the surrounding Cerro Penitentes, Cerro Hermoso and Cerro W, they represent the largest glaciated area beyond the Northern and Southern Patagonian Icefields at this latitude. Recently, Falaschi et al. (2013) inventoried 213 glaciers (∼206 km²) and assessed around 18% glacier retreat over 1985–2008.

It was probably Garleff and Stingl (Garleff 1977; Garleff and Stingl 1983, 1988) who first identified a series of present day periglacial landforms and
processes in several W–E transects, from the Andes to the Patagonian steppe, and recognized temperature as the key factor influencing the Andean permafrost and periglacial phenomena. More recently, Trombotto (2000, 2002; Trombotto Liudat 2008) did a comprehensive review of cryogenic processes, periglacial landforms and the permafrost state in South America, inventorying relict landforms (e.g. sorted polygons, rock glaciers, pingos, palsas) of the outer-Andes Patagonia at a regional scale. He established the mountain permafrost altitudinal lower limit in a latitudinal transect between 39° S and 55° S. For the Monte San Lorenzo area, he mentioned the existence of rock glaciers and estimated the lowermost limit of permafrost at 1600–1700 m a.s.l.

The geology of the Monte San Lorenzo area comprises a Paleozoic low-grade metamorphic basement of Devonian to Lower Carboniferous age (Río Lácteo Fm; Bell and Suárez 2000; Giacosa and Franchi 2001), and a thick volcanic and sedimentary sequence of Meozoic age (El Quemado volcanic complex; Riccardi 1971). The Patagonian Batholith (Upper Kretaceous) intruded the whole sequence in successive magma injections: the Monte San Lorenzo and Cerro Penitentes are composed chiefly of granite rocks (Suárez and Welkner 1999; Welkner 2000).

Because of the interaction between the dominant westerly winds and the N–S orientation of the Patagonian Andes, a strong precipitation W–E gradient has developed in the San Lorenzo area. Villalba et al. (2003) estimated that annual precipitation decreases from ~10 m in the Southern Patagonian Icefield to less than 300 mm within 100 km east of the main water divide at this latitude. Hence, the area has a transitional climate signature, ranging from maritime in the western flank of the main Chilean–Argentine divide towards continental in the eastern side. Wolff et al. (2013), citing Hijmans et al. (2005), locate the Argentinean flank of Monte San Lorenzo in a precipitation latitudinal strip between 400 and 600 mm. Aravena (2007) reports a mean annual precipitation of 731 mm and 8.1°C mean annual temperature for the Cochrane weather station (47° 14′ S, 72° 34′ W, 180 m a.s.l.), 46 km to the northwest of the study area. Temperature surveys between 2002 and 2013 by means of a HOBO logger located in the western lateral moraine of San Lorenzo Sur glacier (47° 42′ S, 72° 19′ W; Fig. 1) yielded a mean air annual temperature of 3.8°C at 1140 m a.s.l. elevation. Based on these later data, a theoretical temperature lapse rate of 0.65°C/100 m would indicate that the 0°C isotherm altitude of present-day mean air annual temperature (MAAT) is located at ~1725 m a.s.l.

Materials and methods
We used two 2.5 m spatial resolution ALOS Panchromatic Remote-sensing Instruments for Stereo Mapping (PRISM) images from April 2008 to identify and map intact and fossil rock glaciers (Fig. 2). Both scenes lack any seasonal snow coverage, which is ideal for accurate landform identification. When rock glaciers were located in cast shadows and therefore not visible in the ALOS PRISM images, mapping was performed in freely available high-definition images on Google Earth.

Intact rock glaciers include both active and inactive landforms and contain ice-rich permafrost, whereas in the latter case, permafrost thaw has led to rock glacier and permafrost degradation and therefore, fossil rock glaciers lack any interstitial ice. Rock glacier identification and classification was based on a series of geomorphological evidence. The following features were considered as characteristic of fossil rock glaciers: a subdued surface where the typical rock glacier furrows and ridges topography is mostly eroded; a less pronounced front talus in comparison with intact rock glaciers; and accumulation of large boulders at the rock glaciers’ front talus feet. Additionally, the frontal and lateral slopes of landforms may be colonized with variable amounts of vegetation (Haeberli 1985; Ikeda and Matsuoka 2002; Brenning 2005; Kääb 2007). Other morphological indicators, such as the presence of thermokarst and ice outcrops, were not featured in the inventoried landforms. Although the distinction between relict and intact rock glaciers (i.e. the presence of permafrost) must be determined by means of in situ measurements (such as boreholes or thermal datalogging), geomorphological mapping of rock glaciers can still provide a reliable estimation of permafrost distribution at a regional scale (Roer and Nyenhuis 2007).

Rock glacier outlines were manually digitized on screen and the areas were calculated using the opensource KOSMO GIS software (www.opengis.es, 11 Aug., 2015) to produce the present polygon-based inventory. Landforms were mapped from the root zone to the bottom of the foot of the front slope, including lateral and frontal slopes as part of a landform’s outline. Additionally, rock glaciers were classified into tongue, lobate and coalescent-shaped landforms. An inventory map of the region...
was produced, including all of the identified rock glaciers as well as the glacier covered area as retrieved by Falaschi et al. (2013); the projection used was UTM zone 18 with WGS84 datum.

To investigate the influence of lithology on rock glacier size, the rock type of each rock glacier was retrieved by combining fieldwork with the interpretation of very high resolution images available from Google Earth and the 1:250,000 scale geological maps from the Argentinean National Geographic Institute (Giacosa and Franchi 2001).

An ALOS PRISM stereopair-generated, 10 m resolution digital surface model (DSM) was generated, with the DSM and Ortho-image Generation Software specially designed for PRISM data by the Japan Aerospace Exploration Agency. Topographic parameters for each landform (maximum, minimum and mean elevation, mean slope and aspect) were derived from this model. The horizontal accuracy of ALOS PRISM DSMs was reported as less than 6 m and the vertical error was 2–18 m without the use of ground control points (GCPs) (Takaku and Tadono 2009). During successive field campaigns 16 Global Navigation Satellite System (GNSS) points were surveyed using a Trimble 5700 receiver (Trimble Navigation, Sunnyvale, California, USA) and used as GCPs to validate the DSM. Coordinates and elevation of these points were differentially corrected using data from a private permanent global positioning station (GPS) base station in Cochrane, Chile. The coordinates of the GCP were compared with those in the DSM and showed minor differences; we found a negligible horizontal shift and a mean vertical bias of 6.7 m, with a standard deviation of 6.6 m. These values were considered acceptable given the purposes of this study.

Results

We inventoried a total of 177 rock glaciers, accounting for 11.31 km$^2$. A total of 130 landforms (9.86 km$^2$, 87%) correspond to intact ones (Fig. 3), whereas the remaining 47 (1.45 km$^2$, 13%) are relict. A summary of the rock glacier inventory is presented in Table 1.

The largest intact inventoried landform has an area of 1.21 km$^2$, which is comparable to the rock glaciers found in the Tien Shan mountains (Bolch and Gorbunov 2014), which are said to host the largest rock glaciers on the Earth’s surface (Dario Trombotto 2014, pers. com.). It must be noted, however, that this landform is in fact a two-lobe coalescent unit. The largest non-compound rock glacier covers an area of ~0.6 km$^2$. Table 1 also shows that intact rock glaciers have a larger mean size (0.092 km$^2$) than fossil rock glaciers (0.036 km$^2$).

At least 55% of the intact rock glaciers (and 65% in the case of fossil ones) were classified as debris rock glaciers (Barsch 1996). Regarding rock glacier
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Fig. 3. Tongue-shaped rock glaciers in the Rio Oro (field photograph a-1 and Google Earth imagery a-2); multi-unit rock glacier in the Río Lácteo Valley (field photograph b-1 and ALOS PRISM image b-2).

A striking feature is that the prevailing orientation of rock glaciers in the area is towards west to southwest (see Fig. 4a), and thus at odds with the expected east to southeast aspect that is commonly found in other sites in the South American Andes (e.g. Brenning and Trombotto 2006; Perucca and Esper Angillieri 2008; Esper Angillieri 2009; Martini et al. 2013; Rangecroft et al. 2014).

The front talus of intact rock glaciers in the area are located at a minimum altitude of 1400 m a.s.l. Rock glacier spatial density was calculated as the ratio between the total rock glacier area and the area above 1400 m a.s.l. in 1.4% (Fig. 4b). This elevation of 1400 m a.s.l. can be regarded as the lowermost limit of the discontinuous mountain permafrost at a regional scale (Barsch 1978; Brenning 2005).

With respect to rock glacier lithologic composition, it can be said that, in general terms, the rock types involved in rock glacier formation belong to three distinct groups: plutonic (mainly granitic), volcanic (mainly volcanic agglomerates and breccias) and metasedimentary (mainly greywacke) (see Table 2). Since the most extensively

**Table 1. Summary of the Monte San Lorenzo region rock glacier inventory**

<table>
<thead>
<tr>
<th>Rock glaciers</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>130</td>
</tr>
<tr>
<td>Area (km²)</td>
<td>9.86</td>
</tr>
<tr>
<td>Mean size (km²)</td>
<td>0.092</td>
</tr>
<tr>
<td>Maximum size (km²)</td>
<td>2.155</td>
</tr>
<tr>
<td>Minimum size (m)</td>
<td>1.335</td>
</tr>
</tbody>
</table>

**Table 2. Rock glacier morphology**

<table>
<thead>
<tr>
<th>Form</th>
<th>Rock glaciers</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tongue</td>
<td>111</td>
<td>7.04</td>
</tr>
<tr>
<td>Lobate</td>
<td>31</td>
<td>0.5</td>
</tr>
<tr>
<td>Coalescent</td>
<td>35</td>
<td>3.77</td>
</tr>
<tr>
<td>Number</td>
<td>177</td>
<td>11.31</td>
</tr>
<tr>
<td>Area (km²)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Distribution of rock glacier lithologic composition.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>San Lorenzo granites</th>
<th>Río Lácteo metamorphites</th>
<th>El Quemado vulcanites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>36</td>
<td>58</td>
<td>36</td>
</tr>
<tr>
<td>Area (km²)</td>
<td>4.623</td>
<td>2.735</td>
<td>2.514</td>
</tr>
</tbody>
</table>

Distributed outcrops in the area correspond to the metamorphic rocks of the Río Lácteo Fm, most of the landforms (44%) are composed of this rock type. However, their mean size is smaller in comparison to landforms made of other lithologies, granite rock glaciers being the largest on average. The median size of the granite (San Lorenzo Fm) intact rock glaciers is 0.036 km², whereas metamorphic rock glaciers (Río Lácteo Fm) and vulcanites (El Quemado Fm) have median sizes of 0.028 km² and 0.039 km², respectively.

**Discussion**

The estimated rock glacier spatial density of 1.4% for the study area is lower than in other, drier Andean sites such as the Andes of Santiago and Mendoza (4%; Azócar and Brenning 2010), or the Valles Calchaqués region (2.2%; Falaschi et al. 2014). This comparison may lead to the conclusion that rock glacier spatial density increases with decreasing precipitation, an assertion recently made by Boeckli et al. (2012) for several areas in the Alps. Hence, the lower limit of mountain permafrost occurs at lower elevations in dryer climate regions.

Guodong and Dramis (1992) suggested that in high latitudes, the limit of mountain permafrost descends with continentality. Similar findings were made by Barsch (1978) and King (1986), who stated that the permafrost boundary is located at lower elevations in dry, continental areas. If a similar pattern is assumed for the Monte San Lorenzo area, a lower elevation of the rock glaciers’ front talus should be expected in the Monte Zeballos (47° 02′ S, 71° 41′ W), ~50 km east of Monte San Lorenzo and therefore in a drier and more continental environment. Fittingly, preliminary analyses led to an estimation of ~1750 m as the lower limit of rock glaciers in the Monte Zeballos area. Here, however, a strong topographic control probably exists, since rock glaciers are developed directly at the foot of the 500 m high vertical rock walls that delimitate the eastern extent of the Lago Buenos Aires plateau.

Debris rock glaciers flow downslope from the inside of glacier cirques, originating from basal or lateral moraines affected by cryogenic processes. Their large size and abundance probably reflect the importance of the previous glacier processes and the impact on landscape evolution for rock glacier formation and growth. Glacier cirques serve as catchment areas of snow avalanches and frost-weathered material, and also provide sun-sheltered slopes, which in addition to the above, make them perfectly suited for rock glacier formation. However, glacier cirques may have the proper slope necessary to exceed the shear stresses required for permafrost creep (Barsch 1996).
Permafrost distribution in mountain terrain, at a local scale, is largely affected by topography, by controlling the temperature, air circulation and incoming solar radiation. Haebelri (1983) and Haeberli and Burn (2002) found that in the Alps, MAATs of \(-1{\degree}C\) to \(-2{\degree}C\) are necessary for the formation and development of active rock glaciers and discontinuous permafrost. In the Andes, however, other studies have suggested the presence of active rock glaciers under positive present-day MAAT regimes (Azócar and Brenning 2010).

In the San Lorenzo Sur glacier, air temperature was surveyed by means of a HOBO datalogger (“San Lorenzo Sur”, 47° 42’ S, 72° 19’ W, 1140 m a.s.l.; see Fig. 1) between 2002 and 2013. From these data, and using a theoretical lapse rate of 0.65\(\degree\)C/100 m, the present-day \(-1{\degree}\)C MAAT isotherm was calculated at \(-1870\) m a.s.l. If this elevation is to be trusted, and keeping in mind that the intact rock glaciers occur between 1400 and 2600 m a.s.l. in the area, this would mean that at least some of these landforms might be above present-day \(0{\degree}\)C MAAT conditions. Hence, it can be argued that the occurrence of these intact rock glaciers is in fact indicative of past thermal conditions and rock glaciers are resilient to present-day climate conditions. The slow response rate of the permafrost’s temperature field can result in permafrost subsisting decadal to century scale periods under positive temperature conditions (Gruber and Haeberli 2007; Kääb et al. 2007).

Alternatively, rock glaciers might reach a thermal equilibrium state owing to local topoclimatic factors (Haeberli 1985), such as topographic shading and circulation of cold air originating from large glaciers (Brenning 2005). Increasing air temperature can lead to rock glacier flow acceleration and permafrost degradation, eventually triggering rock glacier destabilization and collapse (Kääb et al. 2007; Roer et al. 2008; Iribarren Anacona and Bodin 2010). However, no visible signs of rock glacier acceleration such as crevasses or rupture were identified in the inventoried landforms.

Another interesting issue is the relationship between the local glacier equilibrium line altitude (ELA) and the discontinuous mountain permafrost limit. In the Monte San Lorenzo region, the ELA was estimated at 1800–1900 m a.s.l. (Wenzens 2002; Condom et al. 2007; Falaschi et al. 2013). In accordance with the above-mentioned points with regard to the discontinuous mountain permafrost limit, it may be concluded that climate conditions found at rock glacier sites are, to a large extent, not dissimilar to those found at glaciers’ ELA. As a result, it can be argued that the location of glaciers and rock glaciers is mainly a consequence of particular topoclimatic factors, rather than the product of regional climatic differences. Hence, the required conditions in the Andes mountains for rock glacier development are not strictly dry or continental, as has often been seen for the Central and Arid Andes (Barsh 1992, 1996), but may be dry to moderately humid with cool summers for other regions further south.

Conclusions

The inventory presented here represents the first comprehensive and detailed rock glacier inventory for the Monte San Lorenzo area in southern Patagonia. The use of ALOS PRISM images highlights the importance of relying on high-resolution optical imagery for the clear identification of rock glaciers and their geomorphological features. Within the intact rock glacier group, more detailed methods such as photogrammetric or differential GPS surveys are required for determining rock glacier flow and the differentiation between active or inactive landforms. The major drawback of these techniques lies in the limited number of landforms that can be investigated.

However, this inventory provides the first well documented evidence of rock glacier occurrence in the Patagonian Andes published so far, and identifies research avenues for future regional geocryological studies. Because of the small amount of geocryological research that has previously been carried out in Patagonia comprising rock glaciers, there is still a vast, unexplored research field in this regard. Basic questions such as rock glacier flow and velocity, permafrost content, rock glacier–climate interactions, hydrology and its significance as a water source, just to name a few, need to be answered.

To improve our knowledge of the current state of these frozen water resources in these remote areas, further effort needs to be aimed at the establishment of high-altitude, \textit{in situ} hydro-climatic data records. Presently, however, with no available \textit{in situ} ground temperature surveys, the present mountain permafrost distribution cannot be anything but approximated at a regional scale by means of rock glacier inventories.

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