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A preliminary inventory of rock glaciers at 30°S latitude, Cordillera Frontal of San Juan, Argentina

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Abstract

The Dry Andes of the Cordillera Frontal of San Juan (30°S latitude) is characterized by high relief with peaks up to 5000 m a.s.l. This geological province is mainly made up of a suite of Triassic to Miocene volcanic rocks. Modern ice glaciers are small and few in number, and persistent snow fields are similarly small and scattered. The predominant landforms in these areas have been shaped in a periglacial environment superimposed on an earlier glacial landscape. A preliminary inventory map of rock glaciers was constructed using optical remote sensing techniques, digital topographic analysis and aerial photograph data organized in a geographic information system (GIS). Over 140 rock glaciers have been identified: 90% are active or inactive and the rest are fossil. A total of 88 rock glaciers are considered active. The most common periglacial features recognized in the area are talus glaciers, and only 23% are tongue-shaped glaciers.

1. Introduction

Rock glaciers are frequent in dry, continental mountain areas. They are by definition permafrost features (Haeberli, 1996).

Permafrost is a temperature phenomenon defined as ground that remains at or below 0 °C continuously for more than 1 year (Brown and Péwé, 1973). Most permafrost is located at high latitudes, but alpine (Fujii and Higuchi, 1978) or mountain permafrost exists at high altitudes, in mid-latitude regions. If the mean annual air temperature is only slightly below 0 °C, permafrost will form only in spots that are sheltered. This creates discontinuous permafrost. Today, approximately 20% of the Earth's land mass is covered by permafrost (including discontinuous permafrost) or glacial ice (Washburn, 1979; French, 1996).

Since degradation of permafrost in rock glaciers directly affects the discharge volume of Andean rivers, permafrost warming could temporarily enhance the regional supply of fresh water (Trombotto et al., 1999). In this region of the Andean Cordillera of Argentina, the economic possibilities for humans are closely linked to the meltwater yielded in the course of the year. Agriculture, for example, totally depends on irrigation, mainly drawing upon the meltwater of the mountain rivers (Minetti and Sierra, 1989). While ice glaciers have been retreating worldwide, water contained in the ice of rock glaciers is protected from thermal changes by insulating rock mantles. As a result, a detailed analysis of these periglacial features will likely become increasingly important in prolonging water storage during the warm season and providing small but locally significant alpine water reservoirs (Schrott, 1996).

Giardino and Vick (1987) describe rock glaciers as tongue-like or lobate-shaped bodies of frozen debris that are separated from the surrounding terrain by a steep front and side slopes and that have a surface expression of furrows and ridges, which are generally at right angles to the direction of flow. Their length may be as much as several kilometers, but the typical length is 200–800 m measured parallel to the flow direction (Barsch, 1996).

Several authors distinguish between rock glaciers, that is, features having tongue-like-shaped bodies, steep fronts (Wahrhafting and Cox, 1959; White, 1971; André, 1992), length greater than width (Martin and Whalley, 1987; Hamilton and Whalley, 1995) and existing on a valley floor (Outcalt and Benedict, 1965); and protalus lobe or talus

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rock glaciers, with similar morphology but occurring on valley walls (Outcalt and Benedict, 1965), in front of talus slopes, and generally wider than long (Martin and Whalley, 1987; Hamilton and Whalley, 1995).

In terms of the activity status, rock glaciers are classified into active, inactive and relict or fossil types (Martin and Whalley, 1987; Barsch, 1996). Active rock glaciers contain water which is permanently frozen. For their formation, development, and best preservation they must be at temperatures below $-1\,^{\circ}$C. The inactive ones still have interstitial ice, but they have ceased to move. Fossil rock glaciers lack both movement and ice. Active rock glaciers are indicators of the presence, distribution and recent evolution of discontinuous permafrost.

Several authors have studied rock glaciers, on the Andean Cordillera of Argentina (Corte, 1976; Schrott, 1994, 1996; Zipprich et al., 1998; Trombotto et al., 1999; Trombotto, 2000; Brenning and Trombotto, 2006). Corte and Espizua (1981) worked at 32°S latitude and made a preliminary inventory. Igarzábal (1983) compiled an inventory of active and inactive rock glaciers at 24°S latitude and Ahumada (1995, 1999, 2000, 2002) at 27°S latitude.

Most mountain permafrost in South America is found at high elevations in the Andes. Permafrost mostly appears in groups of rock glaciers. The lower limit of Andean permafrost is marked by the absence of rock glaciers. From the analysis and review of previous papers, the limit of Andean permafrost in Argentina is distributed as follows:

- At 22°30′S, Corte et al. (1982) observed active rock glaciers at 4500 m a.s.l.
- At 24°S, Igarzábal (1982, 1983) compiled an inventory of active and inactive rock glaciers and determined the lower limit of rock glaciers at 4500 m a.s.l.
- At 24°30′S, Corte (1982), in his map of current geocryological processes in Argentina, established the lower permafrost limit at 4000 m a.s.l.
- Between 22° and 28°S, Ahumada (2002) established that discontinuous permafrost is founded at an elevation of 4500–5000 m a.s.l.
- At about 28°S, the lower limit of Andean permafrost is restricted by a type of discontinuous permafrost, with abundant rock glaciers (Barsch, 1978) at an elevation of 4300–4500 m a.s.l. Perucca and Esper Angillieri (2007) recognized the limit of approximately discontinuous permafrost to be at about 5000 m a.s.l.
- At 30°S, Brenning (2003), observed active rock glaciers at 4000 m a.s.l. Schrott (1996) established that the discontinuous permafrost is detected at 4150 m a.s.l.
- In the study area at 30°S latitude, the limit between active/inactive rock glacier is estimated at 3651 m a.s.l.
- At 32–33°S, discontinuous permafrost is found at 3600 m a.s.l.
- At 34°S, this limit reaches 3500–3600 m a.s.l. (Trombotto et al., 1999); and at 44°S, an altitude of 2060 m a.s.l. (Trombotto, 2002).
- At 51°30′S, permafrost was reported at an altitude of 980–1100 m a.s.l. (Roig, 1986).

The aim of the present study is to make a preliminary inventory of rock glaciers and to check the distribution of these periglacial features in relation to altitude and latitude. This work constitutes a first approach to the identification and knowledge of a little known portion of the Dry Andes of the Cordillera Frontal of San Juan, Argentina.

2. Regional setting

2.1. Location and climate

The study area is located between latitudes 29°41′–30°5′S and longitudes 69°23′–69°39′W, on the NE side of the Cordillera Frontal, characterized by high relief with peaks up to 5000 m a.s.l. (Fig. 1). In this sector, the most important summits are Cerro Salado (5577 m a.s.l.), Cerro Bramador (3445 m a.s.l.), Nevado de Colanguil (5269 m a.s.l.) and Cerro Las Raíces (5131 m a.s.l.). These

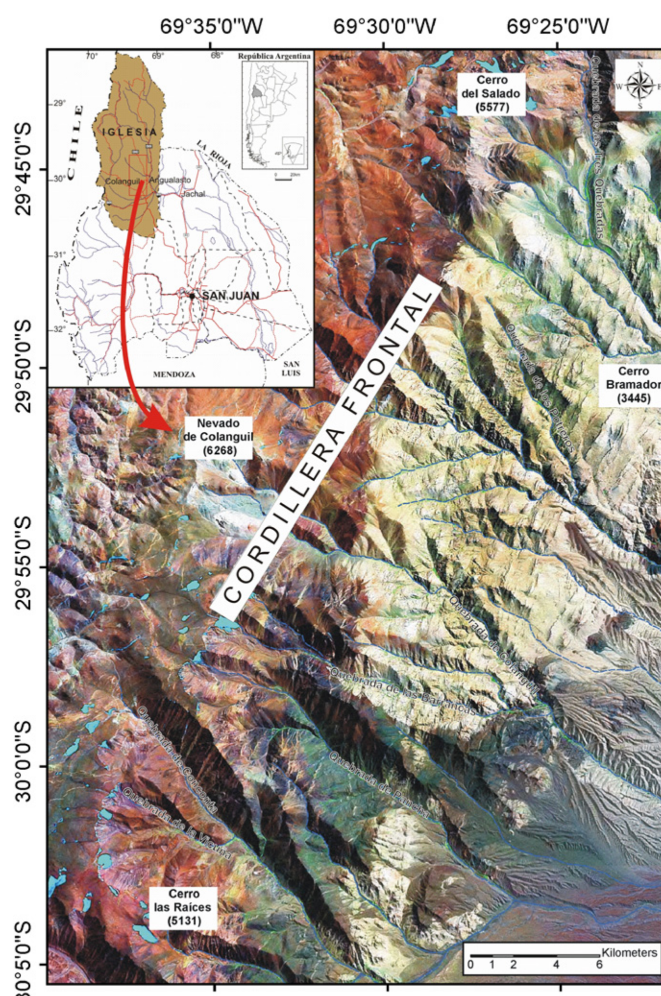

Fig. 1. Location of the study area.

high mountains are of particular importance because of their effect on climate.

The climate and topography vary along the length of the Andes Mountains, creating different environments for the formation of glaciers. For this reason, the Andean Range is divided into the *Dry Andes*, covering the region from lat. 17°30′S to 35°S, and the *Wet Andes,* covering the region south of lat. 35°S. The *Dry Andes* section has been further divided into the *Desert Andes* from lat. 17°30′S to 31°S and the *Central Andes* from lat. 31°S to 35°S (Fig. 2). In the *Desert Andes,* arid conditions limit the ice-and-snow formation to small patches on the highest peaks (Lliboutry et al., 1958). Here, most of the small ice-and-snow areas are found on the main range, which is the border between Argentina and Chile. Precipitation results from local storms.

Due to its geographical location on the rain shadow slope of the Andes, the Province of San Juan has a generally arid and semi-arid climate, characterized by a seasonal rainfall pattern. The total annual rainfall average is very small: about 93.3 mm per year. Winter temperatures are generally mild, ranging between 1.0 and 18.0 °C, whereas summers are hot and very dry, with temperatures between 19.0 and 35.0 °C.

In the specific study area, meteorological observations have been carried out since 1969. The climate is characterized by semi-arid conditions, short-lived summers and rigorous winters with very low temperatures (−18 to 10 °C), scarce precipitation and strong winds. Above 4000 m a.s.l., precipitation is mainly snow and ice pellets; precipitation events are rare and of irregular frequency. Precipitation for most of the area is between 100 and 200 mm annually (Minetti et al., 1986).

2.2. Geologic setting

The Cordillera Frontal geological province is mainly made up of a suite of Triassic to Miocene volcanic rocks (Ramos, 1995), and the study area shows a wide range of geologic units (Fig. 3). The oldest unit is made up of Upper Carboniferous–Lower Permian sedimentary rocks, mainly composed of dark green lutites interbedded with banks of sandstones and rarer outcrops of conglomerate. This unit is overlain unconformably by a Permo-Lower Triassic

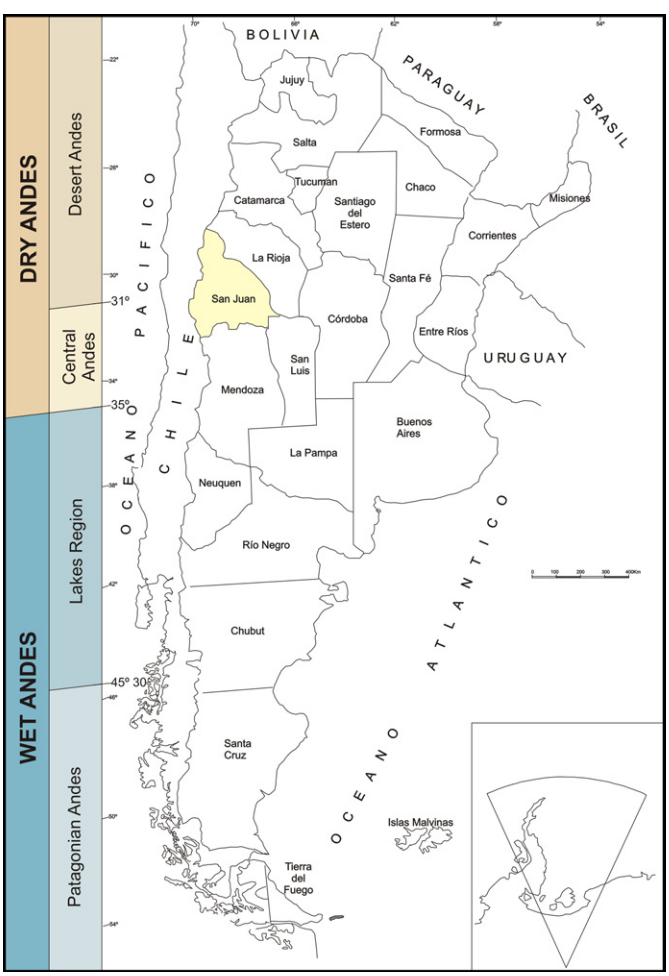

Fig. 2. Climatic environments of Argentina. Modified of Lliboutry et al. (1958).

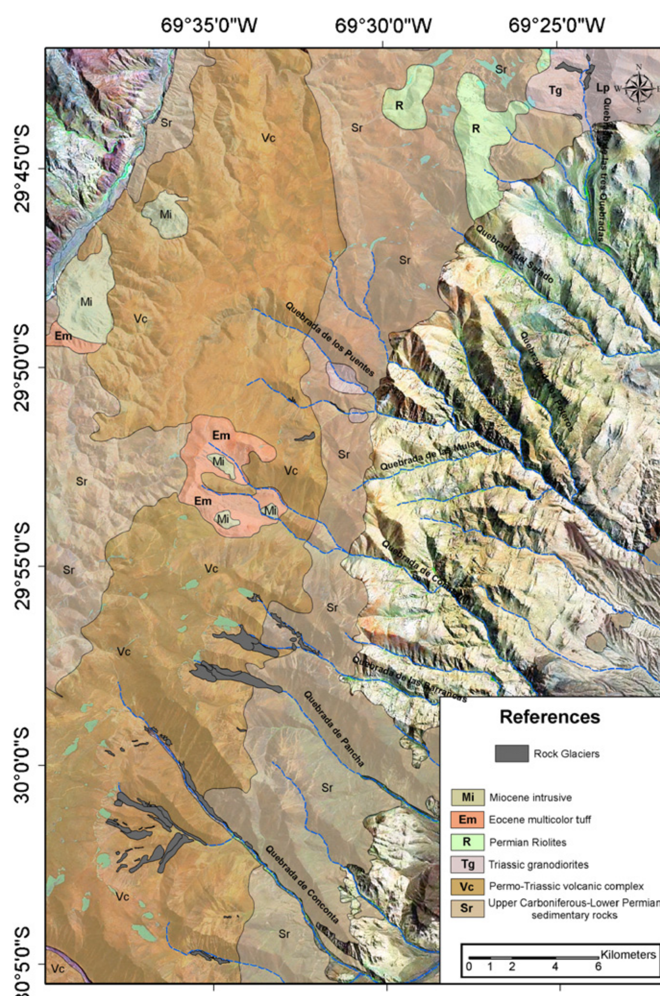

Fig. 3. Lithological map.

volcanic complex that includes pyroclastic, subvolcanic and intrusive rocks, consisting of a lower andesitic to dacitic section and an upper section mainly rhyolitic in composition. Both units are intruded by medium-grained Triassic greyish granodiorites, which in turn are intruded by pink-red rhyolitic bodies.

The sequence continues with an Eocene unit composed of conglomerates, sandstones, multicolor tuff, andesites, breccia and ignimbrite which rests unconformably on the Permo-Lower Triassic volcanic complex and is intruded by Miocene intrusive rocks of varied composition (granodioritic, andesitic, dacitic, dioritic, and granitic). The Paleogene–Neogene is represented by sedimentary units, composed of alluvial and colluvial deposits. The modern deposits, gravels, sands, marls, and clay, occupy the valleys and river beds.

3. Materials and methods

An inventory of the rock glaciers was prepared (Fig. 4). This study was carried out using 1:15,000 panchromatic aerial photographs taken during regional flights in the autumn months in the 1960s, and digital satellite imagery

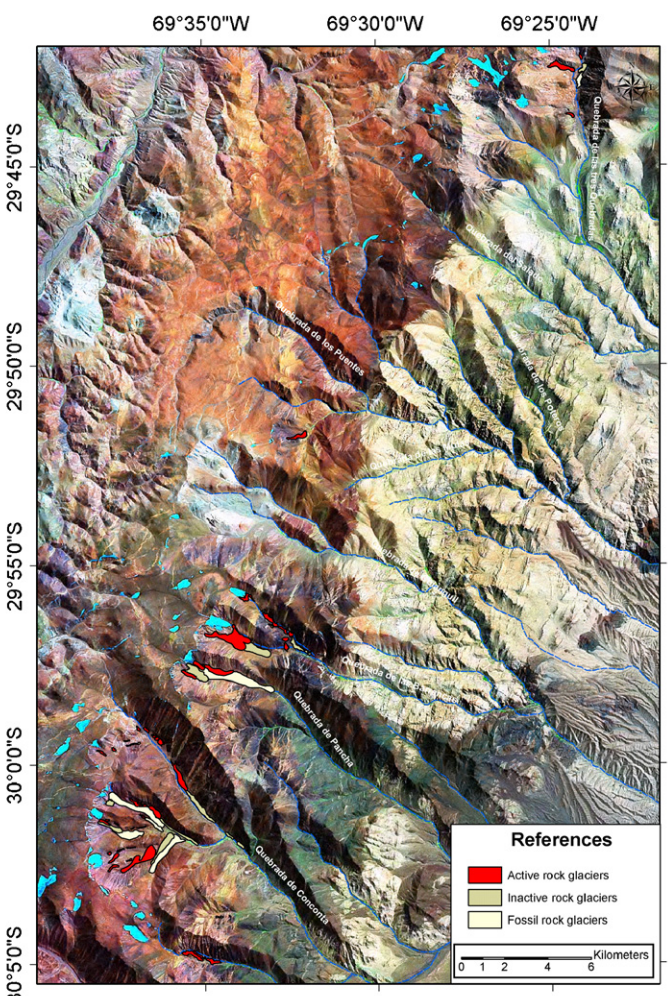

Fig. 4. Inventory map.

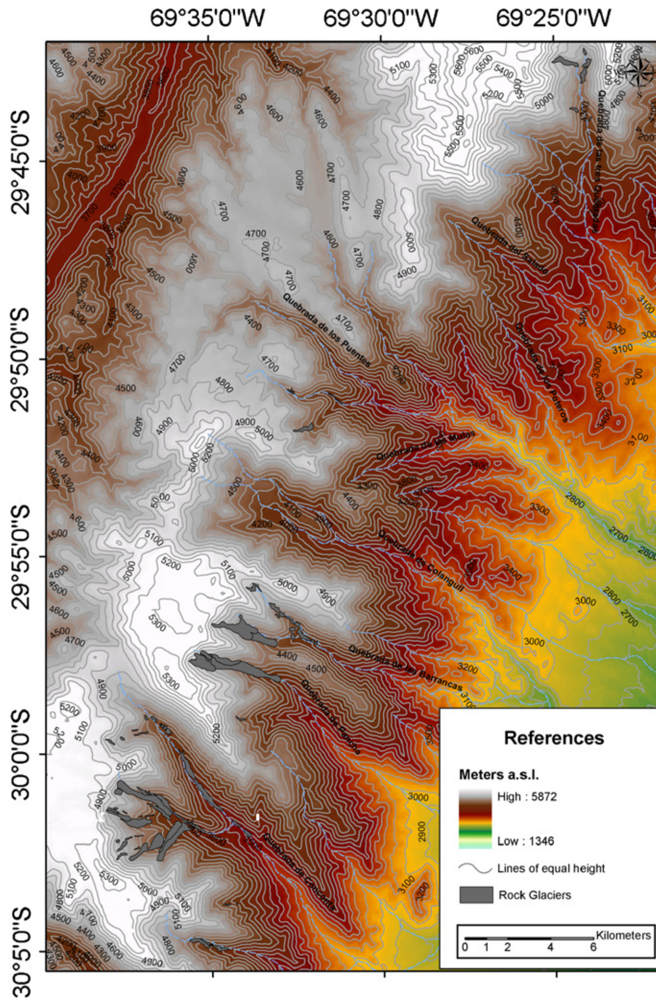

Fig. 5. Map of altitude.

(Landsat 7 TM+). The aerial photographs obtained were digitally scanned, stored on the computer, georeferenced and digitalized within a geographic information system (GIS) technology. The measured parameters for a rock glacier are the altitudes at the foot of the front, length (measured parallel to the flow line) and width (at right angles to the flow line).

Altitudes were obtained from topographic sheets published by the Instituto Geográfico Militar (Argentine Military Geographic Institute) at 1:1,00,000 scale and 50 m contour interval. On this basis, a digital elevation model (the map of altitude), in meters (Fig. 5) in GIS environment, was prepared. Minimum elevation was recorded at the base of the toe of the rock glacier. The common subdivision of rock glaciers into active, inactive and fossil based on morphological criteria (Wahrhafting and Cox, 1959; Martin and Whalley, 1987) was applied to rock glaciers in this study.

4. Results

Over 135 rock glaciers were mapped, occupying an area of 9.66 km^2. The most common periglacial features recognized in the area are talus glaciers; only 23% are tongue-shaped glaciers.

Over 77% of the rock glaciers mapped in the area are generally located along the valley wall. Thus, over 87% are located on the south-facing mountain slopes rather than on the north-facing ones, because the former are less exposed to solar radiation and contain sufficient talus for rock glacier development. On the other hand, only 3.7% appear on north-facing slopes, mainly in areas with relative low radiation.

In terms of the activity status, the three types, active, inactive and relict rock glaciers, are widely distributed over the study area. Ninety percent are active/inactive and the rest are fossil. In the group of active/inactive rock glaciers, 88 are considered active.

In the altitudinal distribution, all the rock glaciers mapped occur only from 3480 m a.s.l. (active, 3651 m a.s.l.). This elevation is thought to be the minimum necessary elevation for the development of rock glaciers.

From the 88 active rock glaciers which were inventoried, the following are particularly noteworthy:

- *Barrancas Rock Glacier* (Fig. 6) is a composite rock glacier that consists of two tongue-shaped rock glaciers, which lie side-by-side on the valley floor of the Quebrada de las Barrancas. It shows flow-like morphology characterized by well-developed longitudinal and transverse ridges and furrows. The northern active rock glacier is 170 m wide, 930 m long (measured parallel to the flow direction), and terminates at an altitude of about 4381 m a.s.l. The active frontal slope is about 46 m thick with a steep gradient of 40–45°. The surface of the southern rock glacier (inactive?) displays a less developed topography of furrows and ridges, and compared to the northern rock glacier, the frontal slope is less thick and steep. It is 145 m wide, 1489 m long and the upper part of the tongue is connected to debris talus, which controls debris supply. The Barrancas rock glacier developed on an older, bigger and simple tongue-shaped rock glacier, apparently inactive.
- *Vicuña Rock Glacier* is located on the Quebrada de la Vicuña, oriented towards the northeast. Morphologically, it is a complex spatulate rock glacier with a minor lobe on the left side. It is 2220 m long and a variable width of 90–585 m, and is characterized by well-developed transverse ridges and furrows. The front is at about 4211 m a.s.l., and the upper part is directly connected to debris talus, at 4649 m a.s.l.

Modern ice glaciers are small and few in number, and persistent snow fields are similarly small and scattered. They are restricted to areas higher than 4650 m a.s.l.

5. Discussion

In the strict sense, the activity status of rock glaciers is determined by a geodetic survey and/or permafrost investigation. However, in this study, the activity status has been assessed from visual features (cf. Wahrhafting and Cox, 1959; Martin and Whalley, 1987). Their validity is controversial because it is very difficult to prove the activity of rock glaciers only from observations using aerial photography and without having geodetic surveys. However, some indicators exist, because the appearance of these

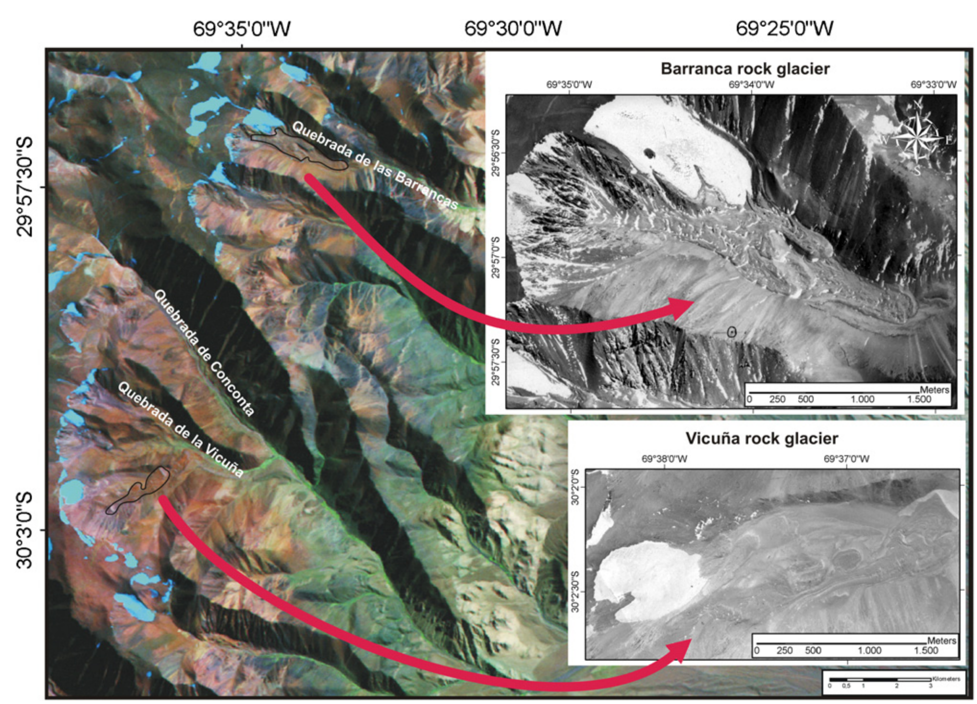

Fig. 6. Barrancas and Vicuña rock glaciers.

periglacial features can provide a reference point to evaluate the activity status. The analysis is also quite subjective since it depends on the observer's interpretation and experience.

In general, the active rock glaciers have a steep ($>35°$) frontal slope and a well-developed flow-like morphology defined by sets of parallel, curved ridges separated by long V-shaped furrows. Inactive rock glaciers show a gentler frontal slope and small deep meltwater lakes which can only be explained by the melting of ice below the debris layer. Both active and inactive rock glaciers are also distinguished by the source rockwall, which controls debris supply. Relict or fossil rock glaciers have rounded and subdued topography and several meters of subsidence have occurred by permafrost melting.

The future application of techniques of geophysical prospection, as electric resitivity tests, seismic refraction and others, will determine the boundaries of active and inactive rock glaciers that still retain ice, distinguishing them from fossil rock glaciers.

6. Conclusions

A total of 140 medium and small size rock glaciers have been identified in this portion of the Dry Andes of the Cordillera Frontal of San Juan. All are located between 3480 and 5041 m a.s.l. and cover a total surface of 9660 110.8 m^2.

According to the classification, talus rock glaciers are dominant and 77% are the tongue-shaped type. According to the activity degree of these periglacial geoforms, it was possible to identify 88 active rock glaciers (63%), 38 inactive rock glaciers (27%) and 14 fossil rock glaciers. All active forms lie above 3651 m a.s.l., and so this elevation can be recognized as the limit of "approximately discontinuous permafrost" at 30°S latitude.

The results of the present work, even though constituting a substantial advance in the knowledge of rock glaciers in this portion of the Andes, must be taken as indicative but not definitive of the high mountain hydrology.

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