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Invited review

Classification of debris-covered glaciers and rock glaciers in the Andes of central Chile

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ABSTRACT

In the Dry Andes of Chile (17 to 35° S), debris-covered glaciers and rock glaciers are differentiated from *true* glaciers based on the percentage of surface debris cover, thickness of surface debris, and ice content. Internal ice is preserved by an insulating cover of thick debris, which acts as a storage reservoir to release water during the summer and early fall. These landforms are more numerous than glaciers in the central Andes; however, the existing legislation only recognizes uncovered or semicovered glaciers as a water resource. Glaciers, debris-covered glaciers, and rock glaciers are being altered or removed by mining operations to extract valuable minerals from the mountains. In addition, agricultural expansion and population growth in this region have placed additional demands on water resources. In a warmer climate, as glaciers recede and seasonal water availability becomes condensed over the course of a snowmelt season, rock glaciers and debris-covered glaciers contribute a larger component of base flow to rivers and streams. As a result, identifying and locating these features to implement sustainable regional planning for water resources is important.

The objective of this study is to develop a classification system to identify debris-covered glaciers and rock glaciers based on the interpretation of satellite imagery and aerial photographs. The classification system is linked to field observations and measurements of ice content. Debris-covered glaciers have three subclasses: surface coverage of semi (class 1) and fully covered (class 2) glaciers differentiates the first two forms, whereas debris thickness is critical for class 3 when glaciers become buried with more than 3 m of surface debris. Based on field observations, the amount of ice decreases from more than 85%, to 65–85%, to 45–65% for semi, fully, and buried debris-covered glaciers, respectively. Rock glaciers are characterized by three stages. Class 4 rock glaciers have pronounced transverse ridges and furrows that arch across the surface, which indicates flow produced via ice. Class 5 rock glaciers have ridges and furrows that appear linear in the direction of flow, indicating reduced flow from limited internal ice; and class 6 rock glaciers have subdued surface topography because the movement of the rock glacier has ceased. Ice content decreases from 25–45%, to 10–25%, to <10% from class 4 to 6, respectively. Examples from digital imagery, aerial photographs, and field photographs are provided for each class. The classification scheme can be used to identify and map debris-covered glaciers and rock glaciers to create an inventory. This will help improve recognition of these landforms as an important water resource in the dry Andes of Chile, which will aid in sustainable planning and development in basins that hold the majority of the population and support a large share of the economic activity in Chile.

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1. Introduction

1.1. The uneven distribution of water resources

According to conventional standards, an average annual water availability of 1700 m^3/y/person is the threshold for a country to meet all of its hydrological demands. A condition of *water scarcity* occurs when water availability falls below 1000 m^3/y/person; when water availability reaches below 500 m^3/y/person, it is said to represent a condition of *absolute scarcity* (UNDP, 2006). Chile has an impressive per capita annual average of 60,000 m^3 of water availability; however, the geographical distribution of natural water availability is highly uneven (Fig. 1). The population in the northern half of the country lives under conditions of water scarcity, where water availability is <1000 m^3/y/person (Dirección General de Aguas, 1996; Universidad de Chile, 2010). The northern macro-region (17 to 34° S) covers only 50% of the total area of the country, but it contains about 74% of the total population (17 million people) and 85% of the Gross Domestic Product (GDP). In addition, the northern region is arid, yet contains the most important and most water-dependent economic activities, such as agriculture, mining, and industry (Universidad de Chile, 2010). With a population of 6 million people (about 36% of the total population of Chile), Santiago has an average water availability of 820 m^3/y/person.

Since the 1990s, sustained economic growth in Chile has been based on mining and agricultural exports, which has placed increased pressure on natural resources (Universidad de Chile, 2010). Freshwater has been impacted by the rising demand of a growing economy. About 70% of 17 million inhabitants obtain their water supply from the high Andean basins; economic activities are dependent on the same basins (Universidad de Chile, 2010). Recent mining expansion in the Andes has also placed an additional pressure on water resources and communities by increasing competition for this critical resource (Oyarzún and Oyarzún, 2011; Valdés-Pineda et al., 2014). The arid northern and semiarid central regions of the country have also been experiencing water scarcity because of higher demand and prolonged droughts (Programa Chile Sustentable, 2004). The climate of the semiarid zone has a large annual variability of precipitation (>48%), and it is prone to one drought per decade, lasting between 3 and 6 years. Precipitation during the twentieth century decreased between 40 and 50%, while agriculture and mining have expanded substantially (Ferrando, 2002). Only about 66% of domestic wastewater is treated, whereas the rest is discharged into rivers and the ocean. About 20% of the industries treat their residual waters (Universidad de Chile, 2006). In the northern region, consumptive water use and nonconsumptive water use currently exceed the available natural surface flow; therefore, the unmet demand is satisfied by the overexploitation of aquifers. Available supplies cannot meet the increasing demand, which has resulted in water scarcity and water conflicts (Larraín and Poo, 2010). This problem will become more important in the future because of global climate change: average temperatures are expected to increase, whereas available water is expected to decrease (Universidad de Chile, 2006). Between 1933 and 1992, warming rates at 33° S have been about 2 °C/decade (Rosenblüth et al., 1997). In the northern region, climate models show a projected temperature increase of 1 to 3.0 °C and a decrease in total precipitation of 10 to 25% in the next 90 years (Universidad de Chile, 2006). In central Chile, this would likely result in an increase in future runoff generation from increased melting of snow and glaciers; in the long-term, this will lead to water scarcity and decreased runoff during the summer months (Corripio et al., 2008). Accelerated water use for economic development and a growing population as well as depleted and contaminated water resources associated with climate change are important challenges for water policy in Chile.

1.2. Historical study of glaciers in the Dry Andes

The Andes are an important component of the geography of Chile; however, glaciers have only recently been systematically investigated. The majority of glaciological studies have been performed on clean-ice glaciers, often referred to as *true* glaciers, whereas less is known about debris-covered glaciers and rock glaciers. In the 1950s, Louis Lliboutry (1956) published the first comprehensive glaciological study of the central and Patagonian Andes, which provided a conceptual framework to help establish the discipline in Chile. Lliboutry (1961, 1986) mentioned the widespread existence of valley glaciers in the central Andes that had a top debris cover and discussed the evolution into rock glaciers.

During the 1960s and 1970s, Borde (1966) and Paskoff (1970) noted an abundance of rock glaciers in the western Andes, describing them as a manifestation of permafrost in the high mountain terrain. Paskoff (1970) found that solar insolation played a significant role in the distribution, with rock glaciers occurring more frequently on southern exposures. During this time, Corte (1976a,b) made the same inference for the

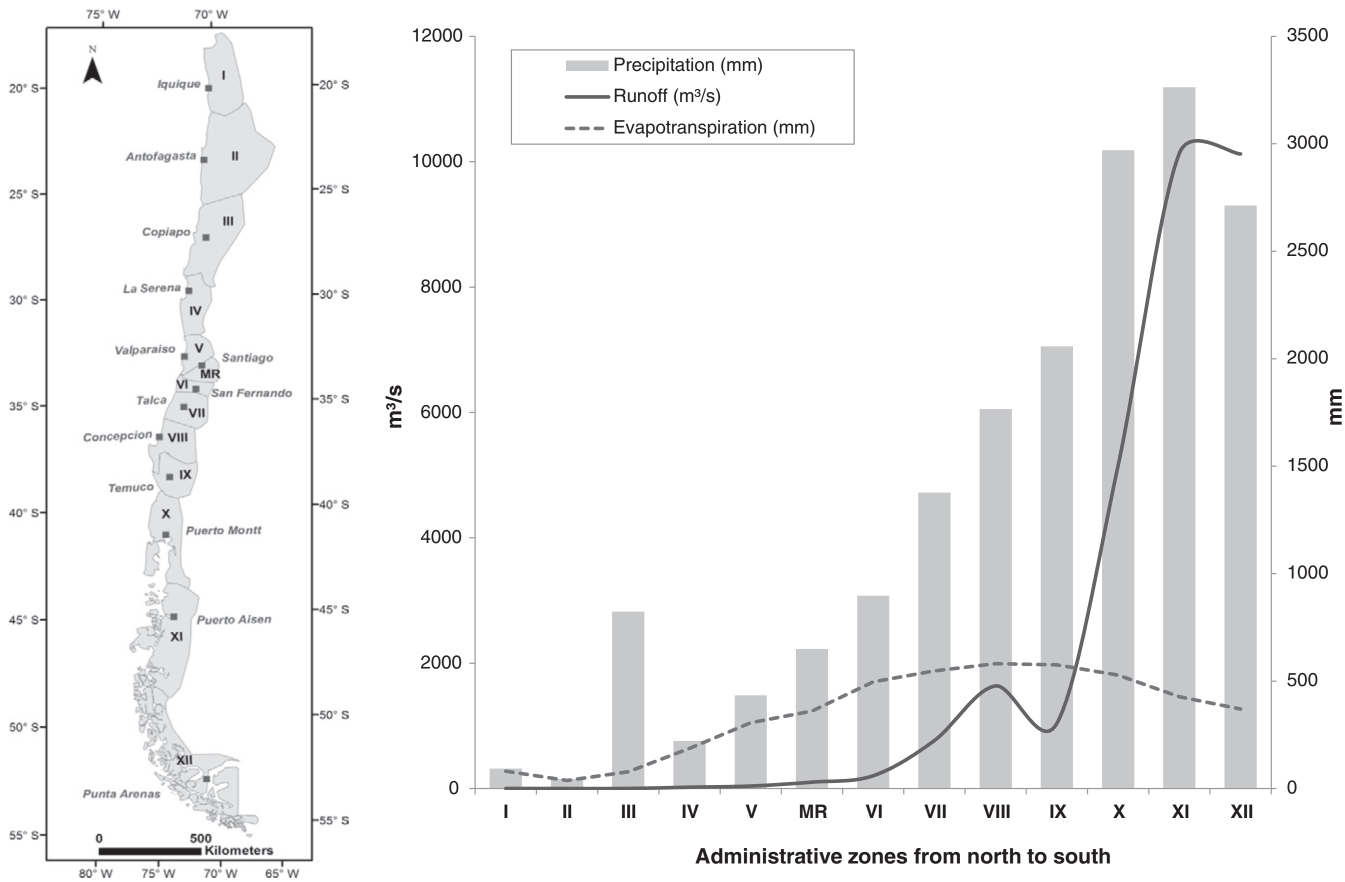

Fig. 1. The water balance of Chile is shown from north to south in terms of mean annual precipitation, streamflow, and evapotranspiration from 1951 to 1980 (Dirección General de Aguas, 1988).

eastern Andes and provided qualitative observations regarding the contribution of rock glaciers to streamflow. Marangunic (1976) produced one of the first systematic analyses of the morphology and function of rock glaciers in the Andes of central Chile, measuring horizontal displacements and discharge. These works began to highlight the importance of the contribution of rock glaciers to runoff in the Dry Andes.

Additional systematic studies were conducted during the 1990s. Schrott (1991, 1996) studied the factors that control the distribution of rock glaciers. He also provided estimates of the contribution of melting permafrost to the San Juan River in Argentina during the summer. In Chile, Ferrando (1991) highlighted the importance of rock glaciers in maintaining summer runoff in the semiarid region. These landforms, however, were omitted from national glacier inventories and water balance estimates of river basins because ice was not visible on the surface.

Most recently, the relationship between the morphology of the rock glaciers and the contribution to streamflow was estimated from the internal ice content (Soto et al., 2002; Ferrando, 2003, 2012). Others have studied the geomorphological and hydrological function of rock glaciers at a basin scale (Brenning, 2003, 2005). Still others have addressed the impact that mining operations have had on permafrost and rock glaciers in the Andean mountain environment (Brenning, 2008; Brenning and Azócar, 2010).

Besides these efforts by independent researchers, the newly created glaciological unit (Glaciología y Nieves) of the Chilean Water Directorate (hereafter referred by its Spanish acronym DGA) has commissioned two comprehensive studies of rock glaciers and periglacial environments in the semiarid region of the Andes (Instituto de Geografía, Pontificia Universidad Católica de Chile, 2010; Centro de Estudios Avanzados en Zonas Áridas, 2012). Researchers working for the Centro de Estudios Científicos (CECS) and the Centro de Estudios Avanzados en Zonas Áridas (CEAZA) have also studied debris-covered glaciers and rock glaciers (Nicholson et al., 2009; Gascoin et al., 2011; Monnier and Kinnard, 2013). In Chile and Argentina, the institutional organizations that oversee water resources and glaciers have commissioned new glacier inventories to include rock glaciers, although only a few basins have been surveyed (Bottero, 2002; Geoestudios, 2011). Most recently, geophysical and borehole drilling methods have been used to decipher the internal composition of debris-covered glaciers and rock glaciers in the Dry Andes, providing practical data about the value as a water resource (Milana and Maturano, 1999; Croce and Milana, 2002; Monnier and Kinnard, 2013).

Mining in the Andes has increased over the last 30 years; Chile is a leading copper producing country and one of the largest gold producers (Oyarzún and Oyarzún, 2011; Romero et al., 2012). Because of the expansion of open-pit mining, rock glaciers are being removed for access to copper and gold resources. Mining expansion has inadvertently contributed to the scientific knowledge pertaining to rock glaciers in the Dry Andes. Cedomir Marangunic, through his consulting firm, Geoestudios, has conducted many glaciological studies and written many technical reports for the mining industry (Geoestudios, 1998a,b, 1999, 2001, 2005; Marangunic, 2013). Unfortunately, most of these reports have not been made public, and the results remained unpublished. Current legislation requires that any mining project impacting glaciers shall gather baseline data and assess environmental impacts. The environmental impact assessment (EIA) must be submitted for government approval and be made public. The EIA provides significant information about the dynamics and internal structure of rock glaciers through prospective borehole drillings and the removal of entire rock glaciers for mining or road building by cutting across rock glaciers for mining expansion (Marangunic, 2013). Our intent is to integrate and synthesize these works to build a straightforward classification of glaciers, debris-covered glaciers, and rock glaciers for the Dry Andes and to increase awareness of these landforms as a water resource.

1.3. Existing glacier classification systems

Rock glaciers are often interpreted as debris-covered glaciers, despite having different internal ice structures and varying ice contents (Barsch and King, 1975). Genetic and morphological definitions have created confusion and debate; and in some cases, rock glaciers and debris-covered glaciers are often grouped together in a single class (Bodin et al., 2010; Berthling, 2011; Perucca and Angillieri, 2011). In different variants and adaptations, a three-tier classification has been used in the Dry Andes to describe and classify glacial landforms (Corte, 1975, 1976a,b; Soto et al., 2002; Brenning, 2003, 2005, 2008, 2010; Ferrando, 2003; Ferrando et al., 2003; Azócar and Brenning,

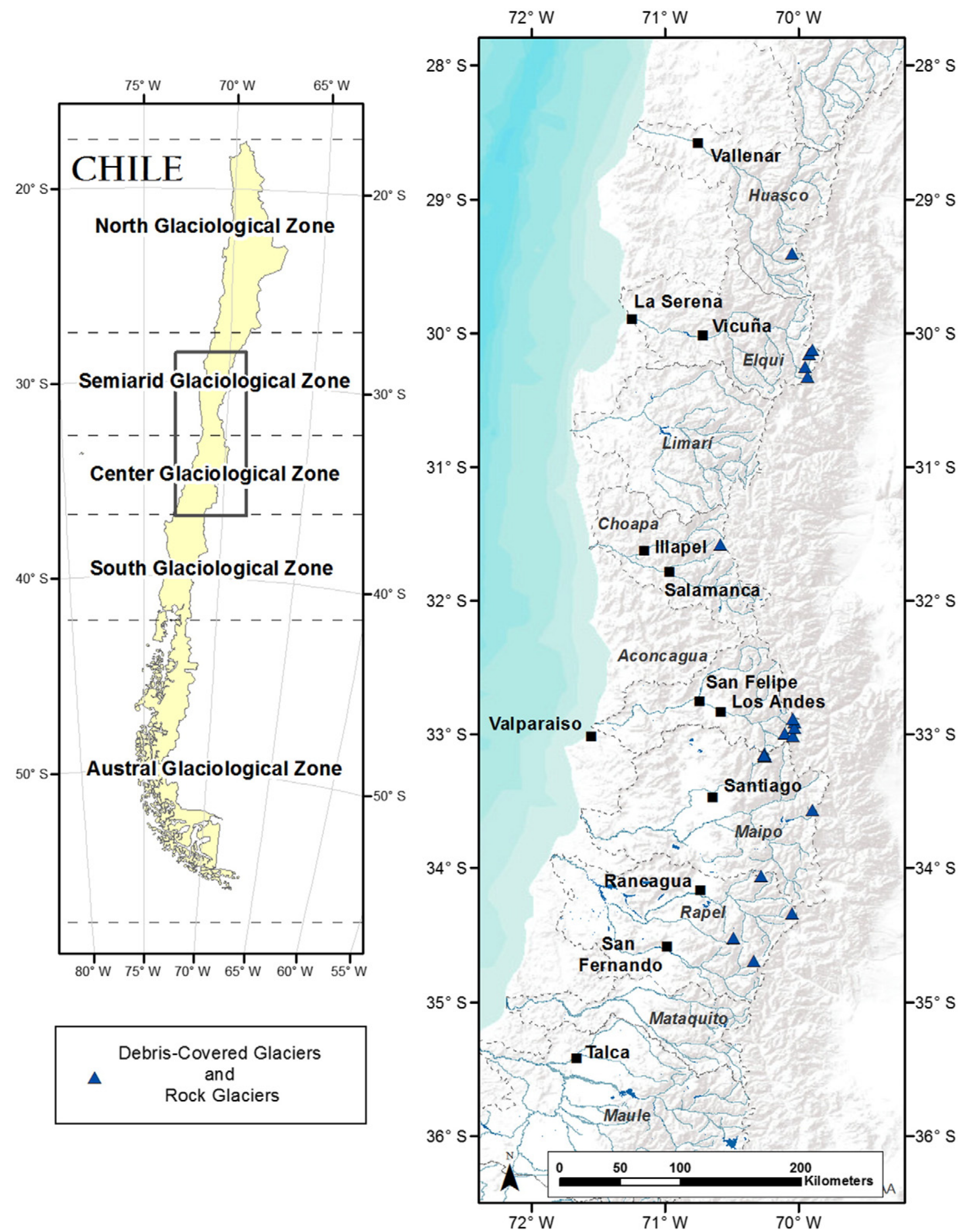

Fig. 2. The map depicts the glaciological zones of Chile with locations of debris-covered glaciers and rock glaciers used as examples in this study (see GoogleEarth© kml files). Alpine watersheds are identified.

2008; Bown et al., 2008; Geoestudios, 2008a,b; Nicholson et al., 2009; Bodin et al., 2010; Brenning and Azócar, 2010; Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), 2010; Ferrando, 2012).

In this traditional classification, the first category is the uncovered or white glacier (*glaciar descubierto* or *blanco*). Ice is clearly visible and contains very little internal/external impurities or debris. The second category, the debris-covered glacier (*glaciar cubierto*), is a glacier in which the surface is mantled with supraglacial debris that varies in coverage and thickness. Some require that 50% of the ablation zone must be covered by debris (Kirkbride, 2011). Most often the thickness of debris ranges between 0.5 and 2.0 m with increasing thickness toward the snout (Hambrey et al., 2008). Supraglacial debris is delivered by a combination of mechanisms such as avalanching, rockfall, or other mass movements; the rate of delivery of debris is high compared to ice flow (Kirkbride, 2011). In addition, englacial material is often exposed through downwasting. Depressions caused by thermokarst, or collapse features from melting ice, often show massive internal ice structures that are layered with strata containing impurities and debris. The third category is rock glaciers (*glaciar de roca*, also known as *glaciar de escombros*, *detrítico* or *rocoso*), which have a thicker surface rock layer compared to debris-covered glaciers. Underneath the surface debris, a mixture of ice and rock exists. Typically, rock glaciers have been classified by genetic or taxonomic groups (Giardino and Vitek, 1988). In Argentina and Chile, the most widely used classification is based on a combination of variables such as glacial or periglacial origin, source of debris (talus or moraine), location on a slope, surface relief, form (singular or complex), shape (tongue-shaped or lobate), or size (Corte, 1976a,b, 1987).

The Geoestudios consulting firm has proposed a slightly modified version of this classification based on the amount of rock debris present in the glacier by volume (Geoestudios, 2008b). The glaciers of central Chile can be characterized by the following typology:

- a *white* glacier (*glaciar blanco*) or a glacier that lacks debris on the surface;
- a glacier with moraines on the surface (*glaciar con morrenas en la superficie*) or a *white* glacier in which medial and lateral moraines are exposed in the ablation zone;
- a *gray* glacier (*glaciar gris*) or one that has an accumulation of debris or other impurities in the ablation zone. The top debris layer increases in thickness toward the snout of the glacier;
- a *transitional* glacier (*glaciar en transición*) or one that is evolving into a rock glacier. Definitive characteristics of this type are the occurrence of small patches of debris on the surface, a transition from *white* to *gray* after years of negative mass balance, and the development of a top layer of debris that covers almost the entire glacier; and
- rock glaciers (*glaciar de roca*), which have a thick top debris layer that covers the entire ablation and accumulation zones.

According to this classification system, rock glaciers and debris-covered glaciers are not distinguished with separate classes. In this category, the thickness of the top rock debris layer ranges from a few centimeters to a few meters. The internal ice-core contains up to 70 to 80% ice and 20 to 30% rock debris. They also have internal pockets of clear ice.

With multiple classification systems available, many different complex forms, and multiple processes of formation that result in similar landforms, confusion exists about what constitutes a glacier, debris-covered glacier, or rock glacier. Rather than developing another classification system, we build upon the existing structure and focus on another important variable: ice content and related water resources.

1.4. Water resources

In the Dry Andes, glaciers must be studied as a water resource. A general lack of knowledge occurs about water resources contained in debris-covered glaciers and rock glaciers in the Andes (Rangecroft et al., 2013). Previously, a range of values for ice content has been reported for rock glaciers. Brenning (2010) reported a range from 40 to 70%; Barsch (1996) indicated that the ice content of rock glaciers ranged from 40 to 60%; Burger et al. (1999) reported values from 50 to 70%. Recent advances in geophysical techniques and borehole drillings, that reveal the complexity of the internal structure, have allowed better estimates of ice content.

Between 27 and 33° S, rock glaciers are a more significant source of water storage compared to glaciers (Azócar and Brenning, 2010). In central Chile, the water stored in rock glaciers is about a magnitude

Table 1
Distribution of the amount of glaciated area by type of glacier for zones and selected river basins.

Glaciological zones N–S and selected river basins	Uncovered area (clean-ice glaciers)		Covered area (rock glaciers and debris-covered glaciers)		Total glaciated area		Source
	km^2	%	km^2	%	km^2	%	
North (18–27° S)	67.0	ND[a]	ND	ND	67.0	ND	Garín (1987)
Semiarid (27–32° S)							
Copiapó	23.0	ND	ND	ND	23.0	ND	Vivero (2008)[b]
Huasco	16.9	72.8	6.3	27.2	23.2	0.1	Nicholson et al. (2009)
Elqui	4.4	29.3	10.6	70.7	15.0	0.1	Favier et al. (2009)[c]
Limarí	0.0	0.0	16.8	100.0	16.8	0.1	Azócar and Brenning (2010)[d]
Choapa	0.0	0.0	18.4	100.0	18.4	0.1	Azócar and Brenning (2010)
Sub-total	44.3	46.0	52.1	54.0	96.4	0.5	
Center (32–36° S)							
Aconcagua	52.6	43.3	68.8	56.7	121.4	0.6	CECS (2008)
Maipo	204.6	54.9	168.2	45.1	372.8	1.8	Geoestudios (2011)
Rapel	225.7	82.2	48.8	17.8	274.5	1.3	Geoestudios (2011)
Mataquito	13.7	92.0	1.2	8.1	14.9	0.1	Geoestudios (2011)
Maule	18.3	81.2	4.2	18.7	22.5	0.1	Geoestudios (2011)
Sub-total	514.8	63.9	291.3	36.1	806.1	3.8	
South (36–41° S)	178.3	85.1	31.3	14.9	209.6	1.0	CECS (2009)
Austral (41–56° S)	19,653.9	99.3	141.0	0.7	19,794.9	94.4	CECS (2009)
Total	20,458.3		515.7		20,974.0	100.0	

[a] ND: no data.
[b] Vivero (2008) accounted only for uncovered glaciers.
[c] Favier et al. (2009) is a partial inventory of one upper catchment of the Elqui River basin.
[d] Azócar and Brenning (2010) is based on a statistical estimate technique, not a full inventory.

greater than the more humid Swiss Alps (Brenning, 2005; Bodin et al., 2010). This magnitude is similar to central and southern Asia as well as the southwestern USA (Azócar and Brenning, 2010). Rock glaciers are an important water component of the cryosphere; future warming will affect these landforms by increasing the contribution to streamflow (Trombotto et al., 1999; Nicholson et al., 2009). The contribution to the hydrologic system in the Dry Andes has not been well studied, but it is highly important as reserves of freshwater for summer runoff (Ferrando, 1991, 2003, 2012; Brenning, 2003, 2005). A complete inventory that addresses the contribution of debris-covered glaciers and rock glaciers to seasonal streamflow remains to be undertaken.

The classification system presented here permits differentiation of glacier categories according to the ice content to better estimate the contribution to runoff. This approach is more suitable for water planners when preparing sustainable solutions. Moreover, this classification provides important arguments to enhance the public understanding of debris-covered glaciers and rock glaciers as important reservoirs of water that may enhance preservation of these landforms (República Argentina, 2010).

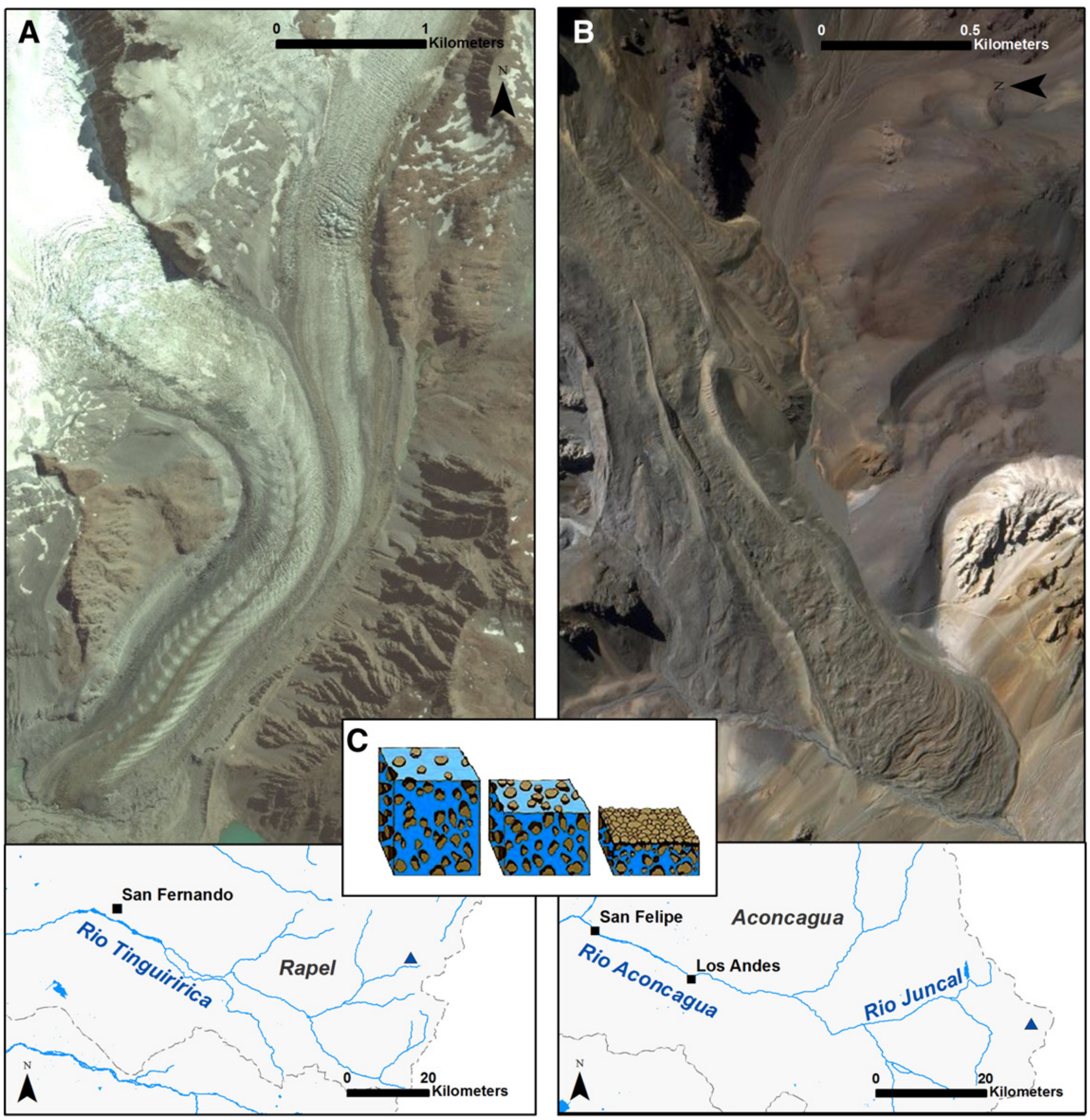

Fig. 3. An example of a debris-covered glacier (Universidad) is shown in (A) and a rock glacier is illustrated in (B). The Universidad glacier originates in two cirques that coalesce into two glacial tongues. The surface has evidence of ogives that transition into debris-covered tongues with transverse ridges and supraglacial debris. The Universidad glacier is located in the headwaters of the Cachapoal River, a subcatchment of the Rapel basin. The glacier has a total area of 27 km^2 with a maximum-recorded ice thickness of 342 m in 2012. Average ice thickness was 162 m; total estimated ice volume was 1.9 km^3, corresponding to 1.7 km^3 of water equivalent (Centro de Estudios Científicos, 2012). Between December 2010 and March 2011, a mass balance study revealed that in 98 days the glacier lost a water equivalent of 4.8 m^3/s, which translates to a yearly average water equivalent of 1.2 m^3/s. Average temperature during the summer was 4.9 °C at 2860 m (Geoestudios, 2011). The Tres Gemelos rock glacier (B) descends southwest from Los Gemelos peak (5550 m) and covers an area of 0.6 km^2. Thickness and ice estimates are not available. The valley glacier at the Los Gemelos has become disconnected from the rock glacier below, the 30-m-deep and wide lateral moraines suggest that it has transitioned into a rock glacier. The rock glacier is located in the *Estero de Navarro* (also known as the *Cajón de Navarro*), which is a subcatchment of the Río Juncal river, located in the upper section of the Aconcagua River basin. The watershed is now part of a privately owned and protected reserve. The *Estero de Navarro* has a total surface area of about 60 km^2 (Universidad de Chile, 2008). The total glaciated area of this subcatchment is 13.6 km^2 with an estimated 1.6 km^3 of water equivalent in 2014. Debris-covered glaciers and rock glaciers cover 81% of the total glaciated area and account for roughly 93% of the water stored (Bellisario et al., 2013). The evolution of a glacier to a debris-covered glacier and possibly a rock glacier is characterized by reduction of the proportion of internal ice in relation to the volume of the englacial and moraine debris (C). Location: (A) 34°41′46.0″ S, 70°19′55.5″ W; (B) 32°54′28.0″ S, 70°1′36.3″ W. Source: (A) DigitalGlobe; 30 January 2010; 0.5 m; (B) GeoEye-IKONOS; 2 April 2008; 1.0 m.

Table 2
Common characteristics of debris-covered glaciers and rock glaciers (Janke et al., 2013).

	Debris covered glaciers			Rock glaciers		
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Common name	Semi	Fully	Buried	Proper	Transitional	*Glacier* of rock
Debris coverage	~25%	~95%	100%	Fully covered	Fully covered	Fully covered
Debris thickness	<50 cm	0.5 m to 3 m	>3 m	Thickly covered	Thickly covered	Thickly covered
Ice content	>85%	65–85%	45–65%	25–45%	10–25%	<10%
Ice form	Glacial	Glacial	Glacial Interstitial ice Segregated ice	Glacial Interstitial ice Segregated ice	Interstitial ice Segregated ice	Pore ice
Visual characteristics	Debris accumulates in the ablation zone. Thicker debris is found near the toe.	The head of the glacier is often disconnected from the uncovered part.	Thermokarst is present.	Transverse ridges and furrows are pronounced arches. The front slope is steep differentiated by color and texture.	Transverse ridges and furrows are linear to flow and less pronounced. The front slope is less steep and elongated.	Surface topography is subdued, rounded, and weathered away.

2. Study area

2.1. Regional setting: glaciological zones and climatology

Chile is divided into five distinct geographical/glaciological zones with similar climatic conditions: North zone, Semiarid zone, Central zone, South zone, and Austral zone (Centro de Estudios Científicos, 2009) (Fig. 2). Precipitation increases from the North to the Austral zones, from hyperarid to very humid. Temperatures follow the reverse pattern: from hot in the North zone to moderately cold in the Austral zone. The present proposal for classification of debris-covered glaciers and rock glaciers is designed for the northern and central Andes based on examples drawn from the Semiarid and Central glaciological zones (Fig. 2). In these two areas, the majority of debris-covered glaciers and rock glaciers provide a significant source of water. Here, we provide a detailed description of the glaciological conditions in these zones (Table 1).

2.2. North zone (17 to 27° S)

The first zone (known in Chile as Norte Grande) extends from the border with Peru to the Copiapó River basin in the south. Sparse convective (tropical, from the Atlantic Ocean) precipitation occurs in the summer months north of 19° S, whereas from 19 to 27° S the climate is extremely arid and contains the Atacama Desert, one of the driest areas on Earth (Arid Diagonal). The glaciated area is only 67 km^2 (about 0.3% of the total for the country) north of 19° S; glaciers are absent in the southern area (19 to 27° S) because of the extreme aridity (Table 1) (Centro de Estudios Científicos, 2009). Glaciers are usually located on top of high massifs or volcanoes and are above the MAAT 0 °C isotherm (Sagredo and Lowell, 2012). These glaciers feed mostly ephemeral streams; the Lluta and Loa rivers are the only streams that flow into the ocean. In this zone, the Andes have a massive structure reaching over 6000 m. Continuous permafrost has been estimated at about 5600 m (Kull et al., 2002).

2.3. Semiarid zone (Norte Chico) (27 to 32° S)

The second zone extends from the Copiapó River to the Choapa River with a gradual progression from arid to semiarid conditions. Precipitation is driven by the passage of frontal systems from the Pacific Ocean during the winter. Precipitation varies between 25 and 300 mm from the coast to the Andes and increases to the south (Sagredo and Lowell, 2012). Agricultural development is restricted to valley bottoms and is supported by a combination of pluvial runoff during the winter and snowmelt and glacial runoff during the spring and summer. The

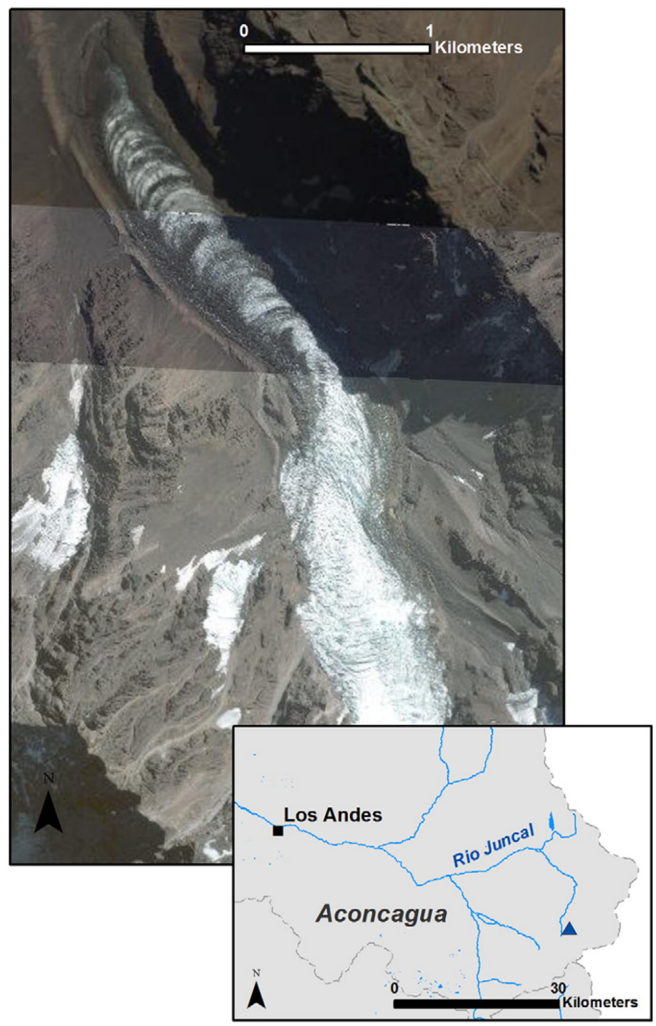

Fig. 4. The semicovered Juncal Norte glacier is shown. The total area of the glacier is ~7.22 km^2. Between 1955 and 2006, Juncal Norte glacier lost 1.5 km^2, which was mainly concentrated in the lower, debris-covered front (Rivera et al., 2002; Bown et al., 2008; Nicholson et al., 2009; Centro de Estudios Científicos, 2011). The glacier has experienced constant retreat since 1955. Between 1989 and 2010, the Juncal Norte glacier has receded at a rate of 14 m/y, the slowest recession rate of the glaciers located in central Chile. In contrast, the South Juncal glacier, a *true* glacier on the opposite southern slope, showed the greatest rate of recession in central Chile (79 m/y from 1989 to 2010) (Centro de Estudios Científicos, 2011). Location: 32°59′42.8″ S, 70°6′13.4″ W.
Source: three images listed N to S: 1) GeoEye-IKONOS; 2 April 2008; 1.0 m; 2) DigitalGlobe; 5 May 2010; 0.5 m; 3) DigitalGlobe; 12 December 2009; 0.5 m.

Fig. 5. The toe of Juncal Norte glacier depicts the thin top debris layer, dirty ice, and subglacial meltwater conduits (photo by Francisco Ferrando; date: 2 October 2014).

northern river basins of Copiapó, Huasco, and Elqui contain all *true* glaciers in this zone, covering an area of about 44 km^2 (Garín, 1987). The southern river basins of Limarí and Choapa do not have *true* glaciers (Centro de Estudios Científicos, 2009). Rock glaciers in this zone cover an area of about 83.9 km^2 (Brenning, 2010). About 553 rock glaciers exist in the river basins of Copiapó, Huasco, and Elqui (Geoestudios, 2008b). Nicholson et al. (2009) completed the only glacier inventory of a river basin in this zone (the Huasco) that included rock glaciers. Favier et al. (2009) conducted an inventory of a catchment of the Elqui basin; however, the extent of debris-covered and rock glaciers in this zone as a whole remains unknown. The Equilibrium Line Altitude (ELA) of glaciers in this region decreases southward from 5000 m at 27° S to 4500 m at 32° S (Kull et al., 2002). The 0 °C MAAT isotherm is situated between 4250 m in the northern section (29° S) and 4000 m in the southern section (32° S) (Brenning, 2005).

2.4. Central zone (32 to 36° S)

The third glaciological zone extends from the Aconcagua River basin to the Maule River in the south and covers about 10% of the total area of the country. This zone has a temperate Mediterranean climate that experiences most of its precipitation during the austral (boreal) winter, whereas the summers are dry. The runoff regime is similar to the Semiarid zone. Precipitation in the high Andes varies from 1.0 m in the north to 2.5 m in the south (Centro de Estudios Científicos, 2009). The lack of

Fig. 6. This photograph of the Juncal Norte glacier shows part of the semicovered glacier tongue with glacial tables, a supraglacial drainage channel, and ogives of cascading ice in the background (photo by Francisco Ferrando; date: 5 October 2005).

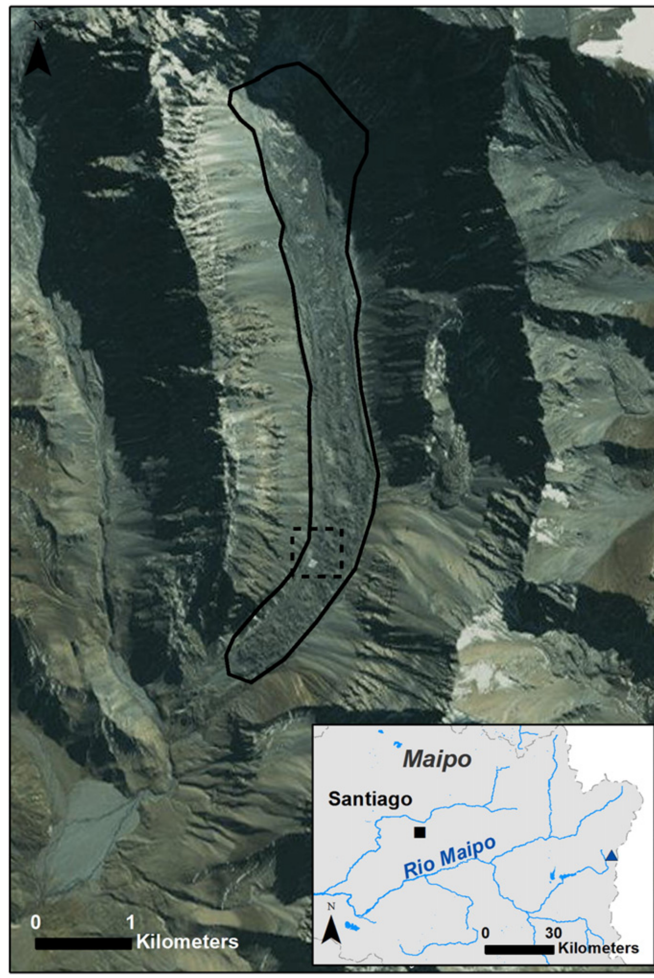

Fig. 7. Pirámide glacier is an example of a fully covered glacier, a class 2 debris-covered glacier. Two lateral moraines extend downglacier, which clearly delineate the edges of the glacier and indicate lowering of the surface of the glacier. The glacier covers an area of ~3.9 km^2. The Pirámide glacier is located in the headwaters of the Río Yeso, a subcatchment of the Maipo basin (15,380 km^2). The Maipo River has an average runoff of 93 m^3/s. After the Northern and Southern Icefields of Patagonia, the Maipo valley has the next largest glaciated area in Chile with 718 glaciers covering an area of 371 km^2. The Maipo basin has the highest hydrological demand in the country; it contains the largest population base in the Santiago metropolitan region with over 6 million people and concentrates a large share of the industry and agriculture of Chile. The Pirámide glacier has experienced a small loss of area compared to other glaciers in the central glaciological zone (Centro de Estudios Científicos, 2011). Ferrando (2012) calculated an average thickness of 54 m, which corresponds to a water equivalent of 135,000 m^3. On this class 2 glacier, thermokarst collapse features and the intensification of melting and downthinning imply a negative mass balance, which might be related to La Niña conditions (dry phase of El Niño–Southern Oscillation, ENSO) since 2009. A granulometric analysis of the internal stratified structure of this glacier suggests that most of the surface debris materials are englacial that have become exposed through ice downwasting (Ferrando, 2012). The dashed square shows the location of Fig. 8. Location: 33°33′33.2″ S, 69°53′35.1″ W. Source: DigitalGlobe; 26 March 2010; 0.5 m.

rain during the summer months creates water stress for the natural vegetation.

The glaciers in the Andes play a fundamental role in the availability of water for irrigated agriculture and human settlements. At the end of the summer (February and March), glacier discharge is small (19% of the total river runoff); however, during dry years, it can be as high as 34% of the total discharge. During years of drought, such as the summers of 1968 and 1969, glacier discharge was 67% of the total river discharge (Peña and Nazarala, 1987). This zone holds the largest glaciated area outside Patagonia at 806 km^2. About 36% of the total glacier area corresponds to debris-covered glaciers and rock glaciers. In the high Andes, the mean monthly temperature ranges from 5 °C in the summer (December through March) to −5 °C in the winter (June through August) (Sagredo and Lowell, 2012). The altitude of the Andes descends from about 6500 m in the north to 3800 m in the south of this zone (Centro de Estudios Científicos, 2009). Glaciers of central Chile do not have ELA data (Casassa et al., 2003). The snow line decreases longitudinally from about 5000 m in the north to 3000 m in the south (Centro de Estudios Científicos, 2009). Precipitation (caused by westerly winds), snow cover, and glacier mass balances are highly influenced by the El Niño–Southern Oscillation (ENSO) (Escobar and Aceituno, 1998). Wet El Niño events have brought positive mass balance years, but dry La Niña years have caused negative mass balances (Escobar et al., 1995).

2.5. South zone (36 to 41° S)

The fourth glaciological zone extends from the Itata River in the north to the Bueno River in the south. This region has more abundant rainfall with larger and more numerous rivers; discharge is created from a combination of rain and snowmelt. The Andes descends from about 3000 m in the north to about 2000 m in the south. Therefore, altitude is the limiting factor for glaciers; they only occur on volcanoes of high altitude. The snow line descends longitudinally from 3000 to 1800 m (27 to 32° S). Annual precipitation varies from 1.0 m in the north to 3.0 m in the south (Centro de Estudios Científicos, 2009). Glaciers in this zone cover an area of about 209 km^2 or almost 1% of the total glacial area of the country. Most of the glaciers are uncovered or free of surface debris (Sagredo and Lowell, 2012).

2.6. Austral zone (41 to 56° S)

The fifth glaciological zone comprises Patagonia and extends from the Bueno River in the north to the Cabo de Hornos. This zone has a very high annual average precipitation and the largest water surplus in the country. The Northern and Southern Icefields are the largest glaciated areas in the country and hold most of the water resources. Glaciers in this zone cover an area of about 19,448 km^2 or about 94% of the total glacial area in the country (Centro de Estudios Científicos, 2009). The majority of glaciers are uncovered.

Fig. 9. The photograph provides an example of the sometimes discontinuous rock layer on the surface of a class 2 debris-covered glacier. The largest axis of the debris ranges from 0.01 to 0.1 m (photo by Francisco Ferrando; date: 15 December 2009).

3. Classification system

3.1. Common characteristics of debris-covered glaciers and rock glaciers in the Andes

Distinctive formation mechanisms have been recognized related to glacial, periglacial, or a combination of these processes (Janke et al., 2013). In a glacial model, rock glaciers are seen as remnants of the last ice age, an expression of a permanently negative glacial mass balance for thousands of years. They often have an ice-cored internal structure. Periglacial rock glaciers develop at the foot of slopes in cold mountain environments by the percolation and accumulation of meltwater that freezes and forms an ice-cemented structure of rock and ice (Janke et al., 2013). Moreover, the evolutionary dynamics of rock glaciers of periglacial origin are often associated with climatic conditions that do not necessarily coincide with the last glacial period.

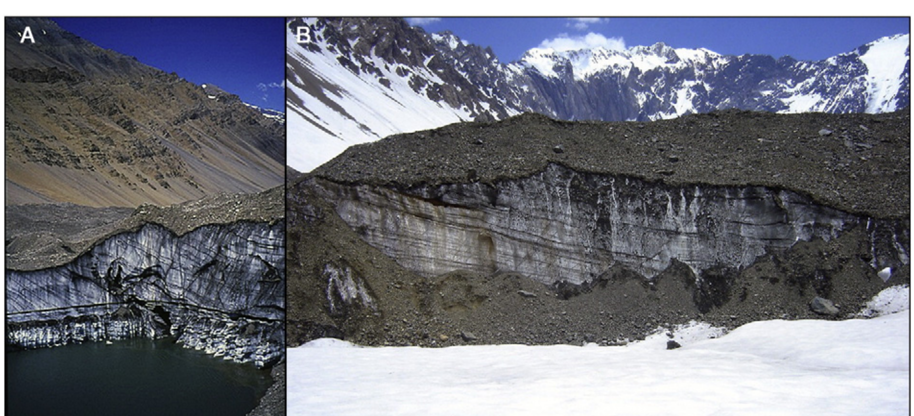

Fig. 8. These photographs illustrate an ~100- by 100-m collapse feature near the toe of Pirámide glacier. The escarpment reveals the presence of icy-debris layers that range in thickness from 0.2 to 0.3 m. The total thickness of the debris cover typically ranges from 1 to 2 m at the head, but has been reduced to 0.2 to 1 m because of collapse and transport at this location. Water movement transports sediment that ranges in size from fine glacial flour to larger rocks within the top debris layer, making the ice appear impure with vertical streaks of debris (photos by Francisco Ferrando; date: 15 December 2009).

In the Andes, the following characteristics are common to debris-covered glaciers and rock glaciers: (i) a reduced accumulation zone; (ii) a tongue-shaped form of varying lengths, widths, and thicknesses; (iii) a debris mantle of varying thicknesses and extent of coverage derived from complex assemblage of colluvium, moraines, or exposed englacial material through melting. Low solar radiation is important for the occurrence of rock glaciers and debris-covered glaciers (Schrott, 1996; Brenning and Trombotto, 2006). Rock glaciers and debris-covered glaciers can extend below the 0 °C MAAT isotherm because of unique climatic variables and topography in glacial valleys (Brenning, 2005; Martini et al., 2013). In other mountain ranges, these landforms exist where MAAT isotherms range from −1 to −2 °C (Barsch, 1996). Rock glaciers in the Dry Andes of central Chile develop in specific areas that have at least two main characteristics (Geoestudios, 2008b). First, they occur in areas of steep topography that are highly prone to avalanches that contain 2 to 3% of debris material. When the snow melts, a debris mantle remains on top of the glacier. For instance, an avalanche of 15-m thickness (common in the high Andes) with about 2% debris content will leave 0.25 m of debris on the glacier surface, if the snow fully melts during the summer. Second, rock glaciers are located at the foot of high and almost vertical rockwalls that are subjected to frost shattering (Geoestudios, 2008b). In the Andes, the major form of periglacial rock glaciers is lobate, whereas glacially derived rock glaciers are tongue-shaped remnants of valley glaciers.

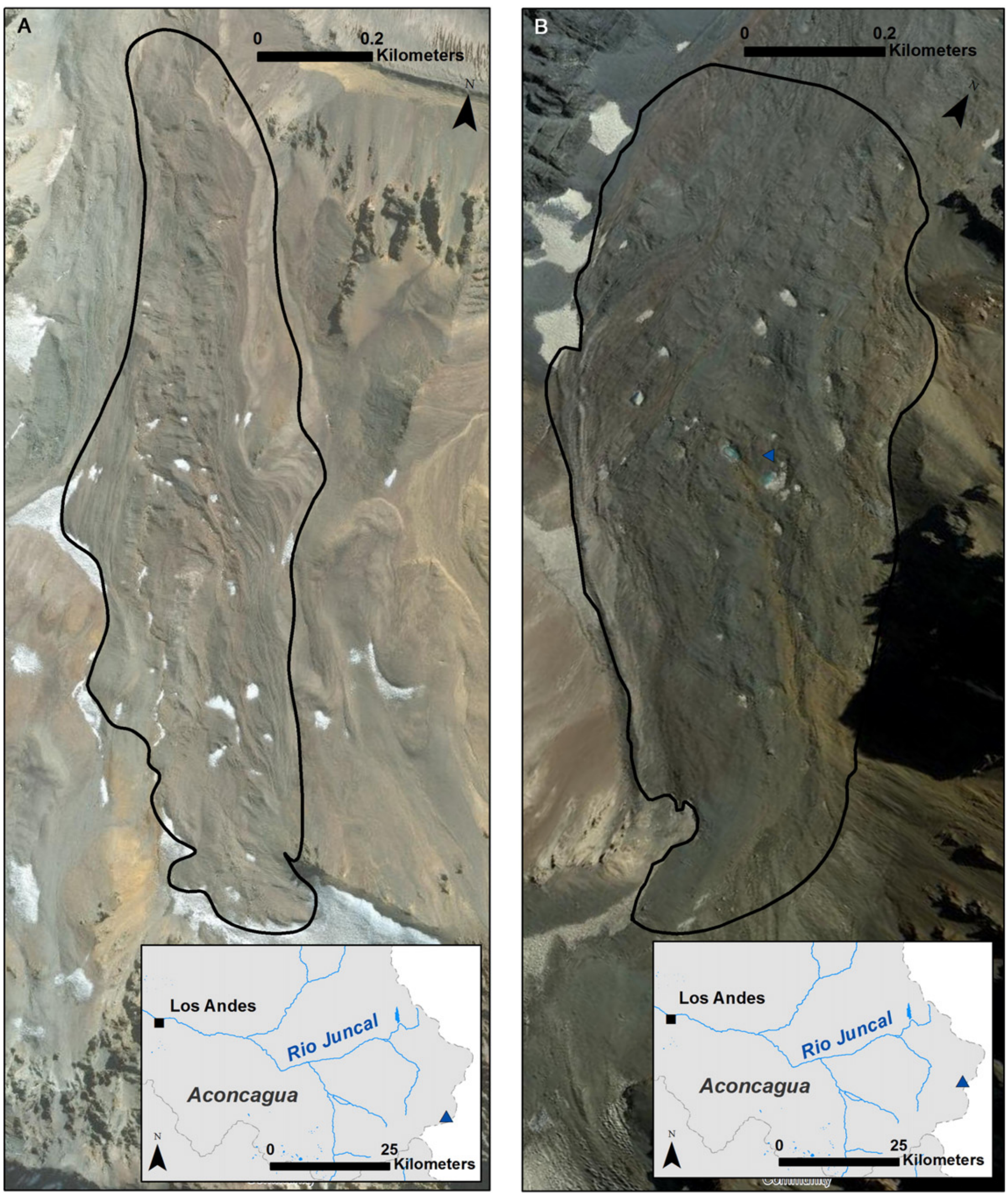

Fig. 10. Examples of class 3 (buried) glaciers are provided. Note the appearance of thermokarst (depressions are filled with either snow or water, creating pockmarks on the surface) and weak development of ridges on the surface of each. The class 3 glacier shown in (A) is 0.4 km^2, and the glacier in (B) covers 0.5 km^2. Location: (A) 33°0′41.1″ S, 70°2′25.7″ W; (B) 32°57′7.9″ S, 70°1′54.8″ W.
Source: (A) DigitalGlobe; 23 December 2009; 0.5 m; (B) GeoEye-IKONOS; 2 April 2008; 1.0 m.

3.2. The continuum

In this work, we build upon the existing classifications to propose a more specific categorization of debris-covered glaciers and rock glaciers as a progression of diminishing ice content. The debris-covered glaciers and rock glaciers discussed are derived from *true* glaciers and the evolution can be envisioned as part of a continuum of landforms as they degrade from valley glaciers to debris-covered glaciers and eventually to rock glaciers (Giardino and Vitek, 1988). Currently, a classification system that represents the unique glaciogenic conditions of the Dry Andes of central Chile does not exist. Therefore, the fundamental objective of this work is to provide a systematic taxonomy to classify debris-covered glaciers and rock glaciers based on high-resolution imagery so that an inventory can be conducted. Through field observation by the authors (in particular Francisco Ferrando) and coring data, surface morphology is related to internal composition of ice and rock, an important indicator of available water resources.

The visual classification is based on common features that relate thickness and extent of debris coverage, which affect the ratio of ice to rock. Two main classes exist: debris-covered glaciers and rock glaciers. For each class, three (3) subclasses exist that are related to the transition of debris-covered glaciers to rock glaciers. Debris-covered glaciers are landforms that progressively develop a top layer of rock material that eventually serves as an insulating layer for the underlying ice. The extent of debris coverage and the thicknesses of the layer of debris are used to differentiate the stages in the evolution toward the form of a rock glacier. They show signs of persistent and relatively fast movement. The thickness of the insulating layer is directly connected with the degree of heat-insulation transmission; therefore, it reduces ablation, thus preserving a former glacier beneath. On the surface, debris-covered glaciers often show thermokarst, which suggests an imbalance in that the accumulation of debris has not established sufficient thickness to preserve an internal ice-core. Rock glaciers have reached sufficient surface accumulation to maintain internal ice. They are identified by the surface morphology of the glacier such as arched ridges that indicate flow, albeit much reduced in comparison with most debris-covered glaciers (Fig. 3; Table 2).

3.3. Class 1 — semicovered

Class 1 debris-covered glaciers are characterized by the development of a thin layer of debris in the ablation zone that gradually thickens and covers the ice tongue near the glacial terminus (Figs. 3A, 4). Debris thickness is no more than 0.5 m, but varies considerably. The accumulation zone lacks debris cover; it receives enough annual snow accumulation to maintain ice. Reduced insolation (headwall shading) and a greater elevation allow ice to exist near the head, whereas the toe of the glacier rests on the valley floor under thermal conditions that promote melting and debris accumulation. The toe of a glacier contains *dirty* or *black* ice in most of its exposed front, as well as englacial and subglacial conduits that vary considerably in terms of discharge and turbidity (Fig. 5). Greater than 75% of ice is visible on the surface, and it contains more than 85% ice internally (Table 2).

Semicovered glaciers experience diurnal supra-glacial water flows in the warm season, in which crevasses (0.5 m wide or more) as well as moulins form (Fig. 5). Beneath the ELA, in the upper section of the ablation zone, curved ogives often form transverse to the direction of flow. Despite the flow, this section has minimal impact on the lower section of the toe, where minimal or no horizontal movement occurs; however, displacement may be offset by the ice depletion

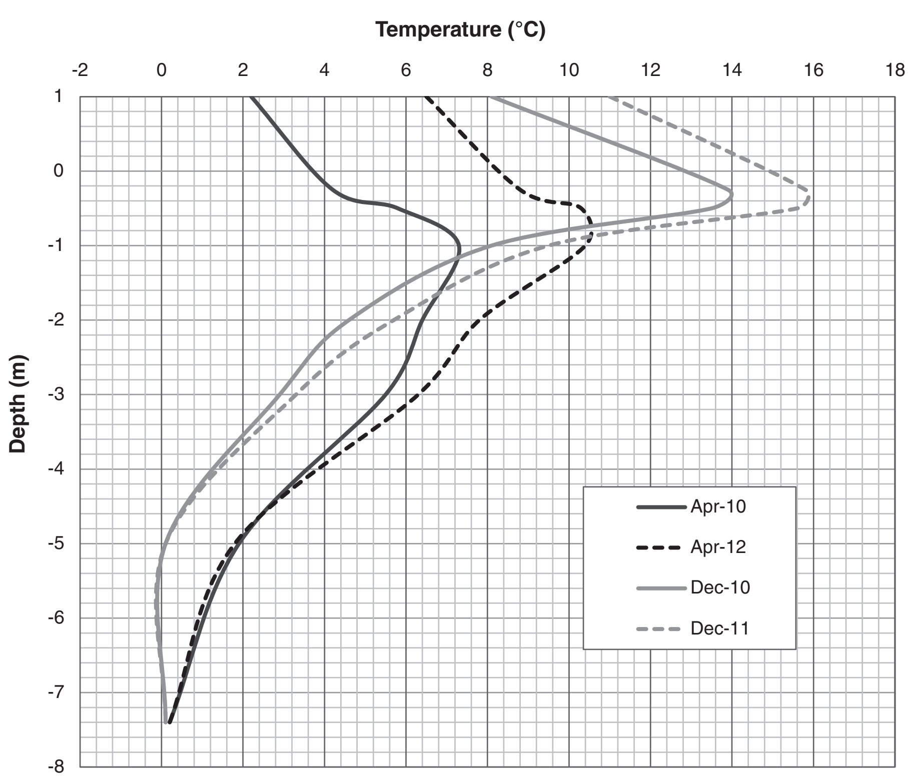

Fig. 11. Temperature plots at Llano de Las Liebres (4050 m) are shown for April 2010 and 2012 as well as December 2010 and 2011. Note that the seasonal air temperatures penetrate to a depth of about 0.5 to 1.0 m at which the line inverts as cooling begins. Seasonal variations show a range of ground temperatures. The temperature at a maximum depth (7.4 m) remained at 0.2 °C in April 2010 and 2012. The Llano de las Liebres glacier is located in the headwaters of the Elqui basin in the catchment Río La Laguna. The active layer is about 3 m deep in the mid-section and deeper than 8 m near the toe (shown here). The periglacial environment is dry; the ELA of glaciers in this region is over 5000 m; the 0 °C MAAT isotherm is situated at about 4000 m. The lower limit of intact rock glaciers occurs at about 3800 m, which represents the lower limit of the discontinuous mountain permafrost (Instituto de Geografía, Pontificia Universidad Católica de Chile, 2010; Centro de Estudios Avanzados en Zonas Áridas, 2012).

and wastage (as observed on the Juncal Norte glacier). Semicovered glaciers might also display frost-shattered debris, dirt cones, and glacial tables that protect ice from ablation beneath a large rock (Fig. 6).

3.4. Class 2 — fully covered

Class 2 debris-covered glaciers are fully covered (about 95% of the surface) with thicknesses that range from 0.5 to <3.0 m (Fig. 7). Based on coring data, ice content ranges from 65 to 85% (Ferrando, 2012; Marangunic, 2013). Ferrando (2012) estimated the internal composition of ice for this class on the Pirámide glacier, where internal collapses have exposed more than 20 m of the internal profile of the glacier (Fig. 8). The surfaces of fully covered glaciers have a chaotic morphology with no signs of flow or arched ridges. No clear differentiation occurs between the accumulation and ablation zones. Some sections may be sparsely covered with rock debris that has been refrozen to the surface of the glacier (Fig. 9). Typically, ice is exposed at the head of the glacier. Debris thickness increases toward the toe as end moraines develop. On the Pirámide glacier, debris thickness varies from 0.3 to 1 m (Ferrando, 2012). In regions where the top debris layer ranged from 0.2 to 0.3 m, sufficient heat transmission occurs to produce superficial ice melting throughout

Fig. 12. Class 4 rock glaciers are shown. Note the formation of transverse ridges and furrows as well as a longitudinal furrow extending down the center of the rock glacier (A). Transverse ridges grade into longitudinal ridges on the rock glacier shown in (B). The front slope consists of unstable material, which is differentiated from the surface of the toe by different hues and tones. The area of the Llano de las Liebres rock glacier shown in (A) is 0.21 km^2, and the area of the rock glacier shown in (B) is 0.75 km^2. From April 2010 to April 2012, Llano de las Liebres rock glacier had a horizontal velocity of 85 ± 34 cm/y, whereas vertical thinning was calculated to be 19 ± 13 cm/y (Instituto de Geografía, Pontificia Universidad Católica de Chile, 2010; Centro de Estudios Avanzados en Zonas Áridas, 2012). Location: (A) 30°14′59.9″ S, 69°56′52.9″ W; (B) 30°19′28.2″ S, 69°56′4.2″ W.
Source: (A) GeoEye-IKONOS; 19 April 2008; 1.0 m; (B) GeoEye-IKONOS; 19 April 2008; 1.0 m.

the day (Ferrando, 2012). As a result, the top debris layer allows the downward transmission of absorbed heat to the ice beneath. The debris has not accumulated to an adequate thickness (>3 m) to insulate the ice beneath. As a result, the debris effectively responds as an active layer that seasonally as well as diurnally freezes and thaws. Frost sorting and meltwater transport fine sediments deeper in the debris profile.

In some instances, the debris-covered glacier may become detached from the main valley glacier (Fig. 8). This typically occurs when the glacier is in a state of transition to class 3. The wall of the cirque at the head of the glacier lacks a connection with the body of the debris-covered glacier, despite the occurrence of avalanches or calving of ice blocks from hanging glaciarettes on the cirque wall. The imbalance is noted by pockmarks of thermokarst on the surface near the head of the fully covered glacier (Fig. 7). Collapse features on the surface of the fully covered glacier reveal internal water circulation channels. Large depressions formed by the collapse of *ice ceilings* are usually filled with water that diurnally freezes and thaws.

3.5. Class 3 — buried glacier

Class 3 debris-covered glaciers are fully covered but are distinguished by a thicker top layer of debris (generally 3 to 5 m). The

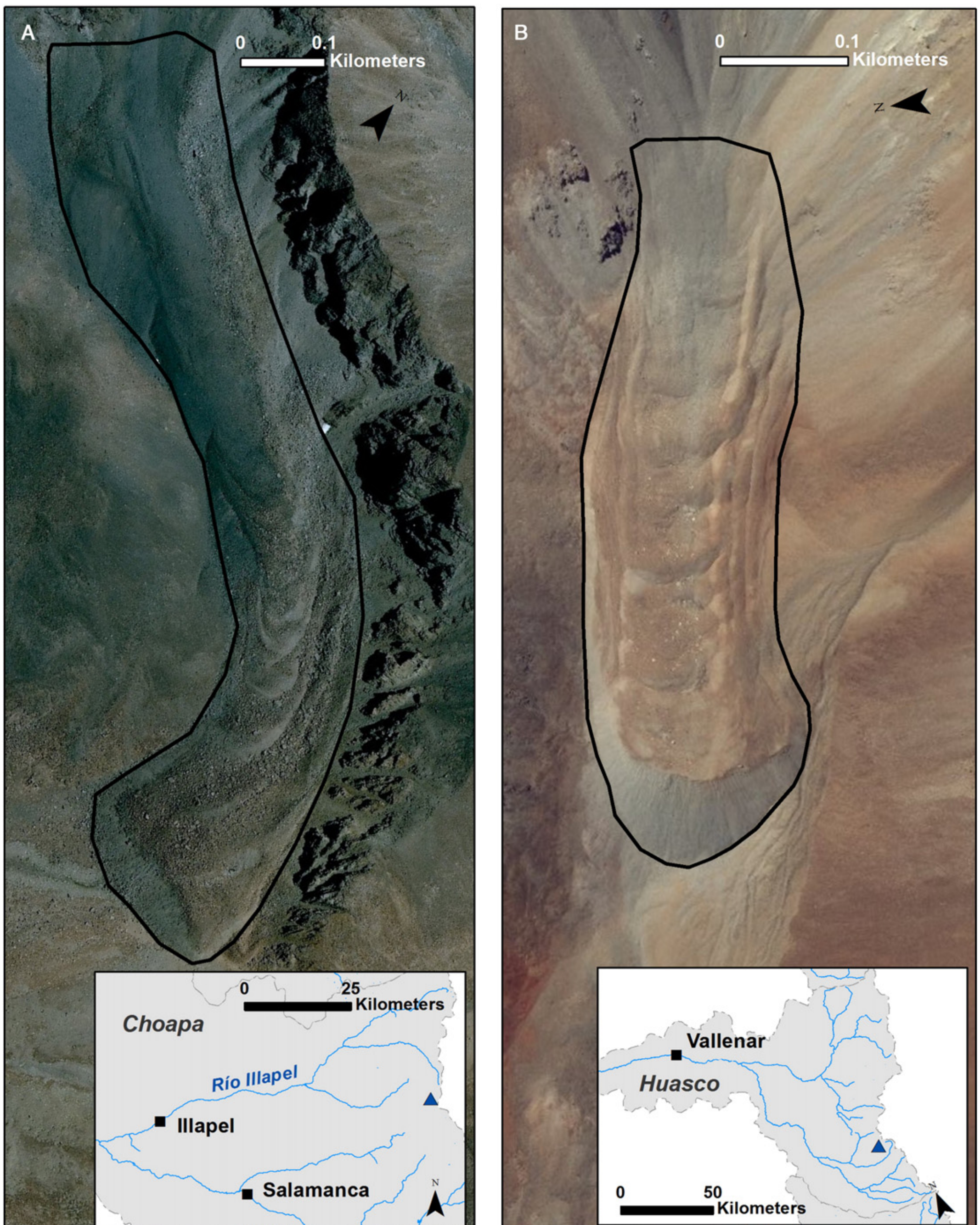

Fig. 13. Class 5 rock glaciers are depicted. The area of the rock glacier shown in (A) is 0.2 km^2, whereas the rock glacier shown in (B) is 0.1 km^2. Transition to the front slope is gradual, and the surface is more subdued. The rock glacier shown in (A) has larger rocks on the surface, indicating removal of finer material. The rock glacier also has a rounded toe to front slope transition. The ridges in (B) are linear, indicating reduced rates of flow; the front slope is gentler and extends a greater distance downslope. Location: (A) 31°34′58.8″ S, 70°34′53.5″ W; (B) 29°24′26.2″ S, 70°2′47.6″ W.
Source: (A) DigitalGlobe; 6 February 2008; 0.6 m; (B) DigitalGlobe; 9 September 2010; 0.5 m.

thickness of the top layer can exceed five (5) or more meters in areas where moraines have been built or rates of talus supply are high. The thicker cover permits thermal insulation of ice, which helps maintain the integrity of the glacier. Ice is sometimes visible in crevasses or in collapse features. Class 3 buried glaciers show weak development of arched rolls, indicating flow (Fig. 10). Based on field measurements, ice content ranges from 45 to 65%. On a class 3 section of the Cerro Tapado glacier complex, ground penetrating radar (GPR) measurements revealed 80 m of buried ice. Frequent and massive exposures of ice were made visible through thermokarst collapse (Monnier et al., 2014).

Heat transfers to about a depth of 0.5 to 1.0 m through the debris cover; after this depth, temperatures decrease with depth and the debris cover acts as an insulator (Fig. 11) (Humlum et al., 2005). An intricate relationship exists among seasonal change, long-term climate change, and debris thickness. The depth of the active layer and the depth at which temperatures remain at or below 0 °C can fluctuate dramatically in the Andes. For example, according to borehole temperature measurements at a buried class 3 section of Llano de Las Liebres rock glacier, ground temperatures between 2 and 5 m depth are affected by seasonal variation of air temperature in addition to rising annual temperatures (Fig. 11). Balch ventilation has minimal effect on these

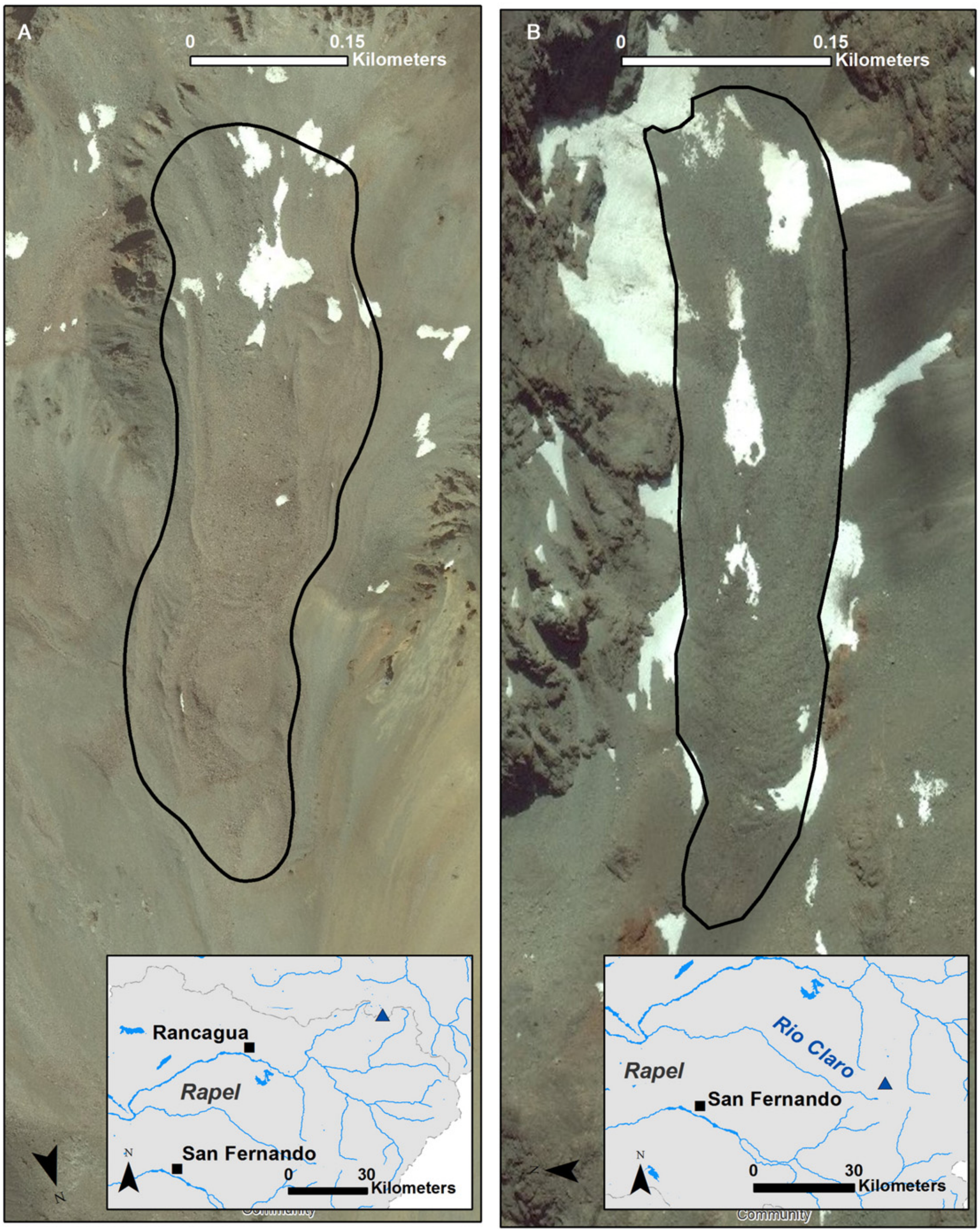

Fig. 14. Examples of Class 6 rock glaciers are shown. The surface topography has been weathered and reworked, but the basic form of the rock glacier still exists. Snow accumulates in depressions created by the melting of internal ice near the head of the rock glacier (perhaps remnants of an ice-core). The front slope of the rock glaciers is not visible; they blend with the surface of the rock glacier. The area of the rock glacier shown in (A) is 0.1 km^2 and the area of the rock glacier shown in (B) is <0.1 km^2. Location: (A) 34°3′27.1″ S, 70°16′41.2″ W; (B) 34°31′32.0″ S, 70°29′15.9″ W.
Source: (A) DigitalGlobe; 30 January 2010; 0.5 m; (B) DigitalGlobe; 30 January 2010; 0.5 m.

debris-covered glaciers and rock glaciers because the surface material is not coarse enough to trap cold air (Barsch and King, 1975). Percolating water from seasonal snowmelt can help maintain the ice mass by refreezing on the ice-core; however, debris must reach sufficient thickness to insulate and reduce ablation to protect the ice against seasonal and long-term warming. Class 3 buried glaciers are often transitioning to rock glaciers (class 4), but first must stabilize to maintain the ice structure. This is accomplished by the gradual thinning of the ice structure to expose englacial material that effectively thickens the surface coverage.

3.6. Class 4: rock glacier proper

Rock glaciers are characterized by the gradual but continuous reduction of internal ice and the accumulation of surface debris as englacial material is exposed through downwasting of internal ice (Figs. 3B, 12). The amount of internal debris gradually becomes proportional to the amount of ice. Class 4 rock glaciers are completely covered by debris, no ice is visible on the surface, and they typically contain 25 to 45% ice; others have reported values as high as 50% (Brenning, 2005; Azócar and Brenning, 2010). Internal ice consists of a matrix of an ice-core from a former glacier, segregated ice, and interstitial ice. The GPR soundings revealed massive ice lenses on a class 4 section of the Cerro Tapado glacier complex. The internal structure is more heterogeneous in comparison to the class 3 sections of the glacier. In Argentina, Croce and Milana (2002) used refraction and other geophysical methods to determine the existence of layers that consisted of dry debris, a watery debris mixture, an ice/debris mix, and a wet base layer of debris. In the Andes, rock glaciers accumulate meltwater that refreezes as ice on the frozen ice/debris mixture, which is later released during the summer (Corte, 1988).

Several features are predominant on class 4 rock glaciers. Thermokarst depressions created by collapse and the formation of small ponds are less common than on class 3 buried glaciers. Transverse ridges and furrows develop because of compression produced by flow, overlapping shear planes, differential movement of layers, or changes in debris content or supply (Janke et al., 2013). The ridges and furrows are pronounced and are formed perpendicular to the direction of flow. Longitudinal ridges form at the edges of the rock glacier, parallel to the direction of flow. They are the result of extensional flow, resistance to flow, or are lateral moraines that have become incorporated into the rock glacier. Meandering, longitudinal furrows may be present and form from drainage or the reduction of an ice-core. The front slope of the rock glacier is at the angle of repose, indicating forward advancement. The junction angle between the gently sloping surface and the front slope is sharp (Janke et al., 2013). The materials on the front slope appear *fresher*, usually a lighter color, because of the constant supply from the surface. As the climate warms, the ice is continuously reduced below the surface; this slows movement and reduces the capacity as a water resource.

3.7. Class 5 rock glacier

Rock glaciers in this class contain 10 to 25% internal ice. The majority of ice is either segregated or interstitial; as a result, flow is diminished. The surface of the rock glacier appears more rounded; ridges and furrows are less distinct (Fig. 13). In addition, the transverse ridges appear linear with less of a bowed appearance. Because of snowmelt and minimal movement, finer material is washed deeper into the vertical profile or flushed from the rock glacier. The surface material has been reworked, which results from rounding of topography. For example, the front slope appears less steep and elongated; the junction angle between the surface and front slope appears curved rather than distinct. A borehole may be needed to distinguish this category. Two boreholes were drilled to 20 and 25 m on what is believed to be a class 5 rock glacier (Monnier and Kinnard, 2013). Mining operations, road building, and tailing deposits make it difficult to classify this rock glacier based on recent and historical imagery; however, an ice/rock mixture was encountered with about 10 to 30% ice content. In this area, about 7 rock glaciers occur in the upper catchment of the Choapa basin that appears morphologically similar to class 5 rock glaciers.

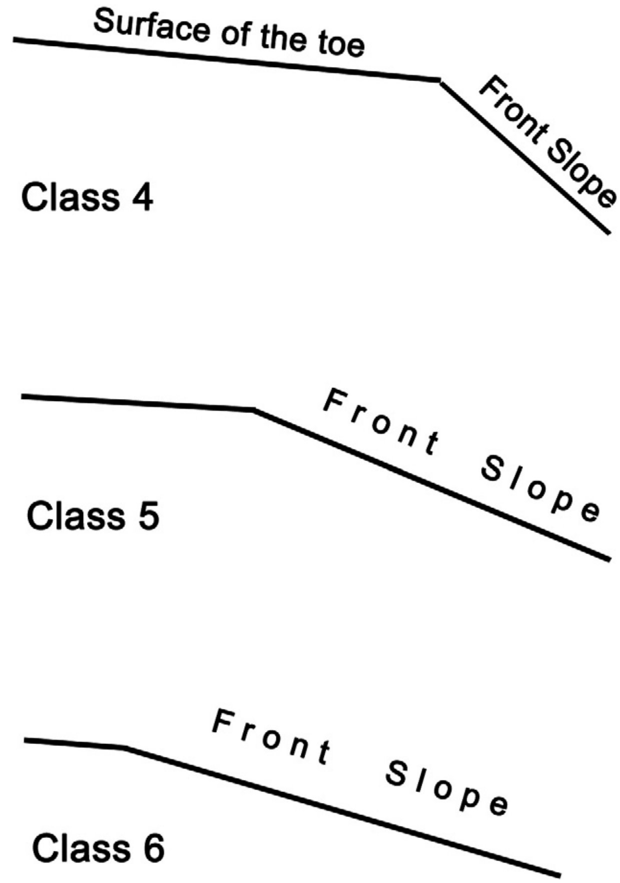

Fig. 15. The front slope for class 4 rock glaciers is steep and pronounced when viewed from the oblique. As rock glaciers evolve, ice content decreases, which limits flow. The surface elevation is reduced and the front slope becomes elongated, reducing the junction angle.

3.8. Class 6 rock glaciers

Class 6 rock glaciers have <10% ice content. The rock glacier consists of mainly morainal debris; however, the shape of the ice tongue is maintained. Ice occurs as small, isolated nuclei (pore ice) within the rock

Table 3
General stratigraphic characteristics of the borehole drillings are provided by Marangunic (2013).

Layer	Characteristics
Top debris	Thickness ranges from 0.5 m in the head to greater than 3 in the toe. Material consists of fine and coarse loosely assembled angular gravels. Fine material is absent and sand is scarce. Permeability and porosity are high.
Body	Thickness averaged 59 m, reaching a minimum of 8 m and a maximum of 125 m. The body consisted of a debris–ice mixture that was rich in ice (greater than 70% ice).
Basal moraine	Thickness averaged 1 m, reaching a maximum of 8 m. Material consisted of an equal mixture of ice and debris.
Bottom moraine (glacial till)	Thickness reached a maximum of 2.5 m. The layer consisted of about 10–20% of fine material, 30–40% sands, and 50–60% gravel. Materials are water saturated from the above layer of ice.

glacier. In localized areas, subsidence of the rock material occurs because of water movement, gravitational settling, or in some instances, earthquake activity. Fine material has been removed by snowmelt. The surface has an erratic, chaotic appearance of superficial debris characterized by irregular, small hills and boulders. The coarser debris on the surface has not moved in a significant amount of time. Mechanical and chemical weathering processes have altered the exposed surfaces of boulders. The front slope of the rock glacier has been removed; a clear transition from the surface of the toe to the front slope is no longer visible (Figs. 14, 15).

4. Borehole drillings

During 1997–1998, 88 boreholes were drilled (using the ODEX Percussion Down-The-Hole Hammer technique and metal casing of 0.15 m), surrounding the open pit copper mine, Andina, located in the Andean highlands of the Blanco River, an upper catchment of the Aconcagua River (32° S) (Marangunic, 2013). The open pit is surrounded to the south and east by a system of debris-covered glaciers, rock glaciers, and ice-rich permafrost—many of which have been disturbed by road construction and mining tailing deposits and even partly removed by the development of the pit since the early 1980s (these modifications predate the field measurements). The Chilean government-owned Copper Mining Corporation, CODELCO, conducted the drillings to assess the internal structure (in terms of thickness and ice content) of rock glaciers and the mineral content of the bedrock to develop a plan for the expansion of the mining operation. The data provided in this section are from the EIA of CODELCO's mining expansion project, Andina 244. The consulting firm, Gestión Ambiental Consultores S.A., was responsible for the overall EIA report; Cedomir Marangunic was the lead author for the baseline and glacier impact chapter. Hereafter, we use Marangunic (2013) for reference purposes. We should note that the consulting companies conducting the EIA for large mining development in the Andes might not have full autonomy in presenting their findings. The

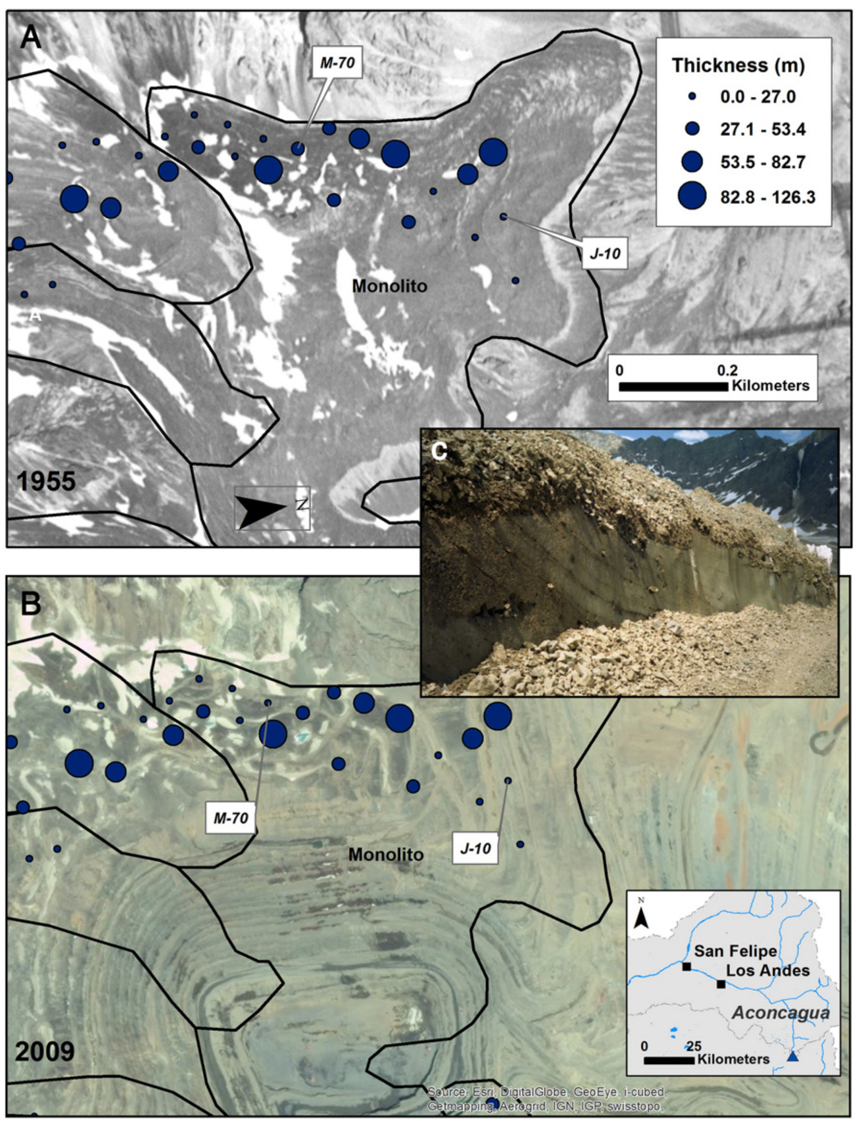

Fig. 16. The class 2 Monolito debris-covered glacier is shown. The drillings (A) were conducted in 1998 to measure the thickness and ice content of the glaciers. Two examples of borehole measurements are provided in Table 4. In (A), the extent of the glaciers from 1955 is outlined. Large portions of glaciers have been removed by 2009 (B). The exposure shown in (C) is the result of a road cut through the side of the rock glacier to provide access to mineral resources, revealing the thin surface coverage and ice-core beneath. Location: (A/B) 33°9′49.7″ S, 70°15′14.6″ W.
Source: (A) Aerial photo 4301, Hycon flight 23, Instituto Geográfico Militar (IGM); 23 February 1955; resampled to 1 m; (B) DigitalGlobe; 23 December 2009; 0.5 m (photo by Cedomir Marangunic; date: not available).

Table 4
Depth and ice content for selected corings are provided by Marangunic (2013) (locations are illustrated in Fig. 16); the thin surface debris cover and high ice content at depth are common characteristics associated with class 2 debris-covered glaciers.

Location	Depth (m)	Thickness (m)	Ice content (%)
Drilling ID: J-10	0–1	1	0
Elevation: 4043 m	1–3	2	70
	3–8	5	50
	8–10	2	70
	10–14	4	50
	14–15	1	70
	15–17	2	94
	17–20	3	50
Drilling ID: M-70	0–1	1	0
Elevation: 4194 m	1–12	11	94
	12–18	6	100
	18–20	2	94
	20–24	4	70
	24–26	2	94
	26–30	4	70
	30–37	7	94
	37–42	5	70

mining companies pay these consulting companies; approval of mining developments depends partly on the outcomes of the glaciological impact assessment. The drilling raw data used in this work was generated by CODELCO, and the publication of this data was carried out by the consulting firm.

The EIA of CODELCO's mining expansion project, Andina 244, provided the total thickness of rock glaciers and the location of the drillings for 81 boreholes. From these, the full stratigraphy had been fully recorded for only 21 drillings. Furthermore, from these 21 measurements, we selected those corings that had been performed in areas less disturbed by mining tailing deposits. These drillings provide insightful, unique information on the thickness, stratigraphy, and ice-debris structure of a system of Andean debris-covered glaciers and rock glaciers (Table 3). The percentages of ice found in the borehole drillings were categorized with the following ice contents: 50, 70, 94, and 100%. For simplicity purposes, we consolidated the 94 and 100% categories into a single class.

4.1. Monolito (class 2) debris-covered glacier

The Monolito (class 2) debris-covered glacier is shown in Fig. 16. Selected coring data are provided in Table 4. The glacier is part of a larger system that extends toward the west. The debris-covered glacier has a thin surface debris and minimal development of ridges and furrows (Table 4; Fig. 17). When the coring data were obtained, casings were solidified in the bedrock underneath the rock glacier and were marked level with the surface. Since 1998, the casings at the surface have been exposed and an average vertical loss of about 17 cm/y was calculated (Table 5).

4.2. Characteristics of rock glaciers revealed through borehole drillings

According to the borehole information and total or partial removal of rock glaciers, the following general stratigraphic characteristics of rock glaciers in the Dry Andes of Chile can be inferred. Most of the lower sections of the rock glaciers in the Blanco system (where the drillings were conducted) are covered by a thick layer of mining tailings, which makes it difficult to distinguish from the top debris layer. The rock glaciers that are free of tailings have significant movement as indicated by areas of compression with arched ridges in the ablation zone. The nucleus or body of the rock glacier contains ice-rich strata that seldom contain less than 70% ice content. All rock glaciers have ~0.1- to 1.0-m-thick basal moraine in the ablation zone with a 50–50% debris–ice mixture. The layer has a high level of cohesion of the debris (100 kg/cm^2), and the materials have a high angle of internal friction (38°). The basal moraine does not exist in the accumulation zone. It extends under the totality of the ablation zone as long as the gradient of the slope of the bedrock does not exceed 19%; it is progressively reduced as the slope of the bedrock increases. Under the basal moraine, the bottom moraine exists, a debris layer without ice. It consists of abundant fine material that has been transported and deposited beneath the glacier. For rock glaciers

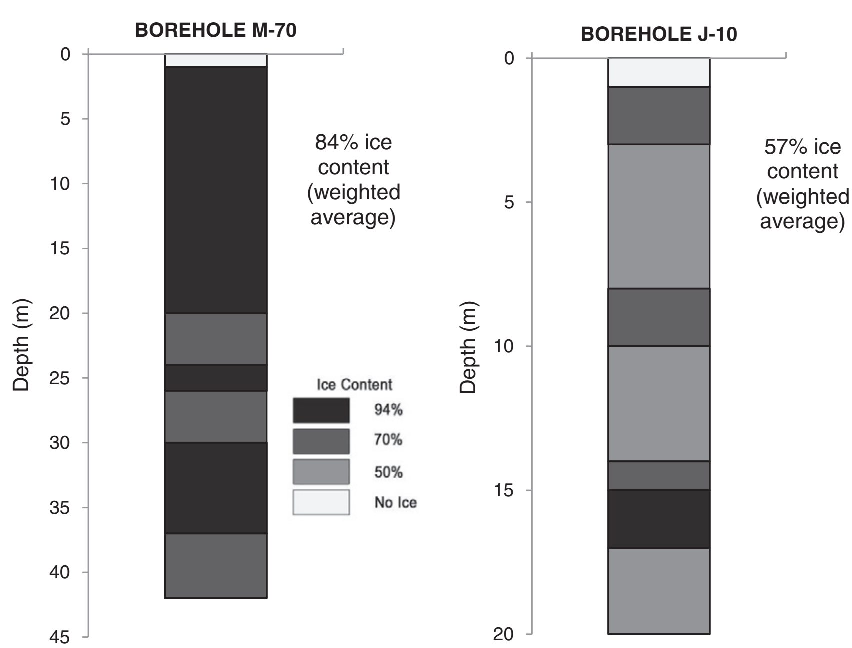

Fig. 17. The vertical profile of ice content for drillings on the Monolito debris-covered glacier is shown.

Table 5
Reduction of surface elevations of the debris-covered Monolito glacier (class 2) between February 1998 and April 2006; insufficient thickness of debris (<3 m), removal and redistribution of mine tailings, or a warming climate have likely caused thinning of ice (Marangunic, 2013).

ar	Vertical change (cm)	Rate (cm/yr)
KL-160	−149	−18.3
N-150	−154	−18.9
LM-140	−76	−9.3
NO-140	−88	−10.8
L-130	−152	−18.6
MN-120	−140	−17.2
M-110[a]	−399	−48.9
N-110	−92	−11.3
MN-100	−91	−11.1
NO-100	−48	−5.9
M-90	−192	−23.5
N-90	−78	−9.6
LM-80	−198	−24.2
MN-80	−125	−15.3
M-70	−58	−7.1
KL-60[a]	−305	−37.5
K-50	−125	−15.3
KL-20	−78	−9.5
H-10	−76	−9.3
J-10	−162	−19.7
L-10	−125	−15.2
Average	*−139*	*−17.0*

[a] These high rates of loss are found in an area of horizontal extension causing collapse of the glacier surface.

with greater displacement, the bottom moraine consists of loose material with very low-level cohesion (0.1 kg/cm^2) with a low angle of internal friction (11°) because they are in constant deformation. Like the basal moraine, these layers are also prominent below the equilibrium line. The thickness of the bottom moraine ranges from a few decimeters up to 2 m.

4.2.1. Rio Blanco rock glacier chain

The Rio Blanco system consists of a chain of 7 rock glaciers. Transverse ridges and furrows distinguish these as class 4 rock glaciers. The length of the rock glaciers ranged from about 0.5 to 1.0 km (Fig. 18). Approximately 44 boreholes were drilled on the rock glaciers in 1998. Table 6 and Fig. 19 provide coring data for three sites on Rio Blanco #5 rock glacier.

Table 6
Thickness and ice content of selected boreholes on Rio Blanco #5 rock glacier are provided; note the thicker top layer of surface coverage of rock glaciers contains no ice; some deposits may have been overlain with tailings; nevertheless, ice is being preserved at depth (Marangunic, 2013).

Location	Depth (m)	Thickness (m)	Ice content (%)
Drilling ID: YY-50	0–6	6	0
Elevation: 3994 m	6–57	51	94
	57–81	24	0
Drilling ID: VVWW-60	0–22	22	0
Elevation: 4033 m	22–24	2	70
	24–39	15	94
	39–48	9	100
	48–59	11	94
	59–63	4	70
	63–70	7	94
	70–76	6	100
Drilling ID: TTUU-80	0–47	47	0
Elevation: 4068 m	47–54	7	50
	54–61	7	70
	61–66	5	50
	66–70	4	94
	70–74	4	100
	74–75	1	94
	75–79	4	100
	79–	NA	94

4.2.2. Cerro Negro rock glacier #2

About eight rock glaciers occur in the Cerro Negro system. Drillings were conducted on rock glacier #2 (Fig. 20). Drilling #1 was performed at the glacier terminus. This borehole contained a 9-m layer of ice (Table 7). The thickness measured at this point is not representative of the average and maximum thickness of this rock glacier. In this location, the surface has shown minimal horizontal movement and compression. A geodesic mark placed at this point showed horizontal movement in the order of few centimeters over several years. Drilling #2 was performed in the front section of this rock glacier with arched ridges, indicating greater displacement. The thickness of the internal ice layer was measured at 20 m. Drilling #3 was performed at the edge of the rock glacier; therefore, it does not represent the true thickness of the ice layer in this rock glacier.

In 2006, a new drilling was performed. Bedrock was encountered at 45 m. In the same year, a transverse GPR was performed 250 m above the 1998 and 2006 drillings, which revealed a thickness of up to 78 m. The ice layer has a maximum thickness of 20 to 23 m. The lack of ice obtained in the deep debris layer may be because of a procedural problem

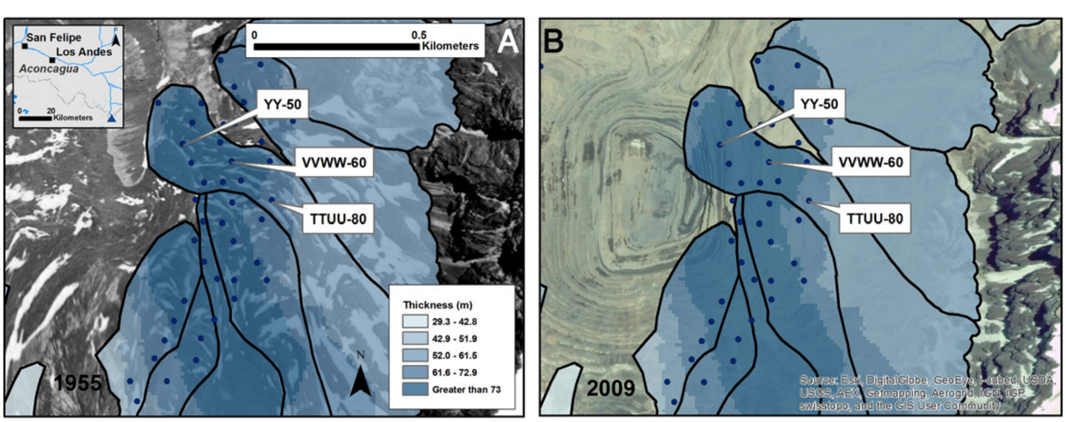

Fig. 18. The Rio Blanco chain of rock glaciers is shown. Thickness was interpolated using kriging. Some of the thicker sections of the rock glacier were removed from 1955 to 2009. Profiles of selected boreholes are provided in Table 6. Location: (A/B) 33°9′57.1″ S, 70°14′56.9″ W.
Source: (A) Aerial photo 4301, Hycon flight 23, Instituto Geográfico Militar (IGM); 23 February 1955; resampled to 1 m; (B) DigitalGlobe; 23 December 2009; 0.5 m.

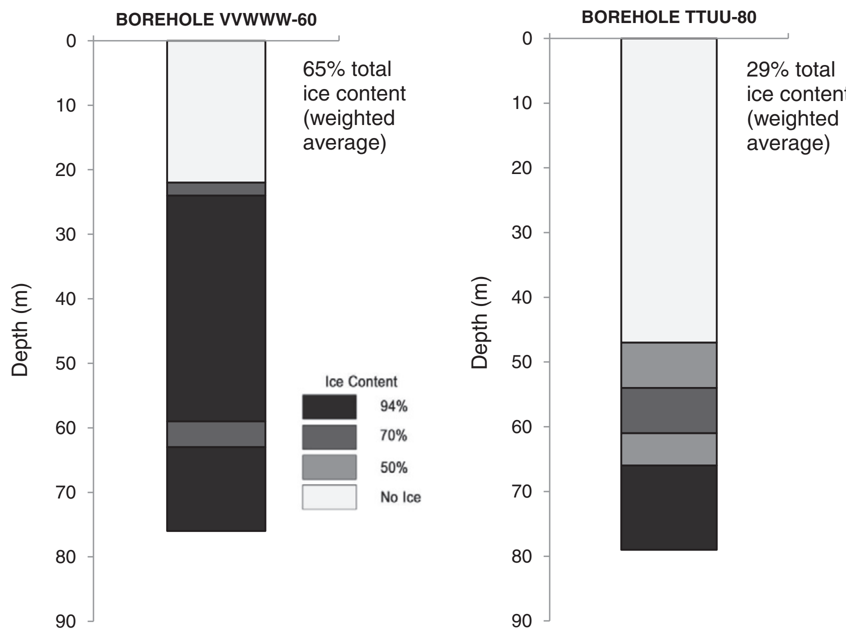

Fig. 19. The vertical profile of ice content for drillings on the Rio Blanco #5 rock glacier is shown.

in that the ice may have melted during the drilling (Marangunic, 2013) (Table 7).

5. Complex debris-covered/rock glacier systems

Although we have divided debris-covered glaciers and rock glaciers into six distinct classes, it is often difficult to assign one class to a single landform because of the complexity of the alpine terrain and interaction of factors such as snowfall, available debris, and temperature that affect glacial and periglacial processes. For example, a complex debris-covered glacier system is illustrated in Fig. 21A. A class 1 semicovered glacier grades into a fully covered class 2 glacier in which some surface ice is visible. An additional class 2 debris-covered glacier from a different headwall source (noted by a lighter tone) merges with the aforementioned class 2 glacier. The class 2 glacier eventually becomes a class 3 glacier marked with thermokarst depressions as the debris thickens. The buried class 3 glacier also has remnants of a debris flow superimposed on its surface.

An example of a transition from glacier to class 3 buried glacier is shown in Fig. 21B. A glacier transitions into a semicovered debris-covered glacier (class 1), into a fully covered glacier (class 2), and eventually into a buried glacier (class 3). Between classes 2 and 3, a class 4 rock glacier has developed from an additional glacial lobe and source of talus. The rock glacier has pronounced ridges and furrows, which distinguishes it from other sections of the debris-covered glacier classes.

Another example of a complex debris-covered glacier and rock glacier system is shown in Fig. 22. The class 3 buried glaciers originate from two different lobes of the glacier El Tapado. The larger lobe is marked by thermokarst pockets filled with water. Two distinct lobes, considered class 4 and class 5 rock glaciers, exist at the base of the class 3 glacier section. The class 4 and class 5 rock glaciers were constructed in different episodes; they are not part of a continuum

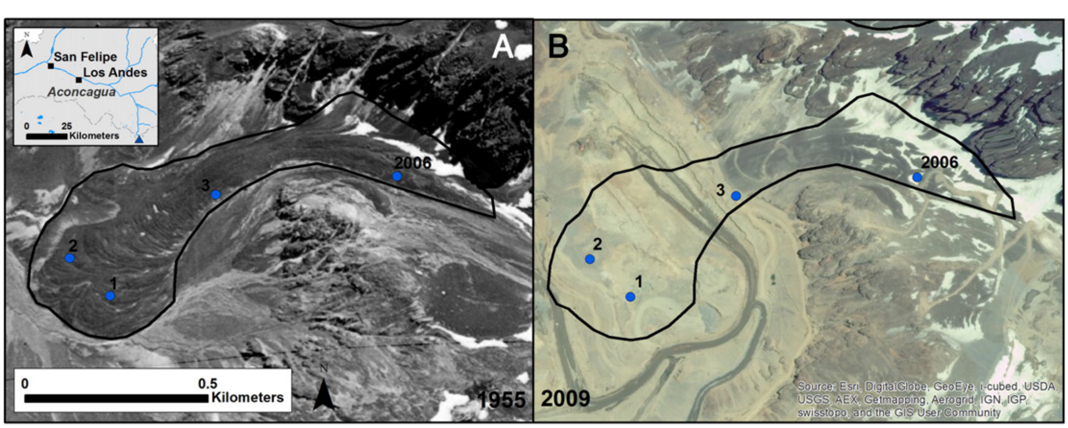

Fig. 20. Cerro Negro #2 class 4 rock glacier is shown with borehole locations. Polygons represent the extent in 2003. Borehole characteristics are provided in Table 7. Location: 33°8′35.3″ S, 70°14′56.7″ W.
Source: (A) Aerial photo 4301, Hycon flight 23, Instituto Geográfico Militar (IGM); 23 February 1955; resampled to 1 m; (B) DigitalGlobe; 23 December 2009; 0.5 m.

Table 7
Characteristics of borehole drillings through the Cerro Negro #2 class 4 rock glacier are provided (Marangunic, 2013).

Vertical structure	Drilling 1		Drilling 2		Drilling 3	
	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)
Top debris layer, loose material without ice	0–6	6	0–2	2	0–2	2
Massive ice with very little debris: average > 95% of ice	6–15	9	2–22	20	2–15	13
Active basal moraine of rock glacier	15–17	2	22–25	3	15–18	3
Only debris no ice. Probably, an old moraine of a pre-existing hanging glacier	17–39	22	25–43	18	18–48	30
Only debris with abundant fine material. Probably, an inactive old bottom moraine from a pre-existing glacier	39–46	7	43–45	2	48–51	3
Bedrock	>46	NA	>45	NA	>51	NA

(Monnier et al., 2014). Rates of flow associated with each section are listed in Table 8. The horizontal velocity of the buried section is about half of the class 4 section. The class 5 rock glacier shows small horizontal and vertical velocities as the rock glacier has lost a significant portion of its ice. The class 5 rock glacier transitions into what appears to be a class 6 rock glacier. Monnier et al. (2014) referred to as a morainal complex. The surface has been eroded by meltwater and has a dark drainage pit from which a small stream emerges. An additional class 4 rock glacier (Llano de Las Liebras) exists to the east of the main Del Tapado system. Another debris-covered glacier

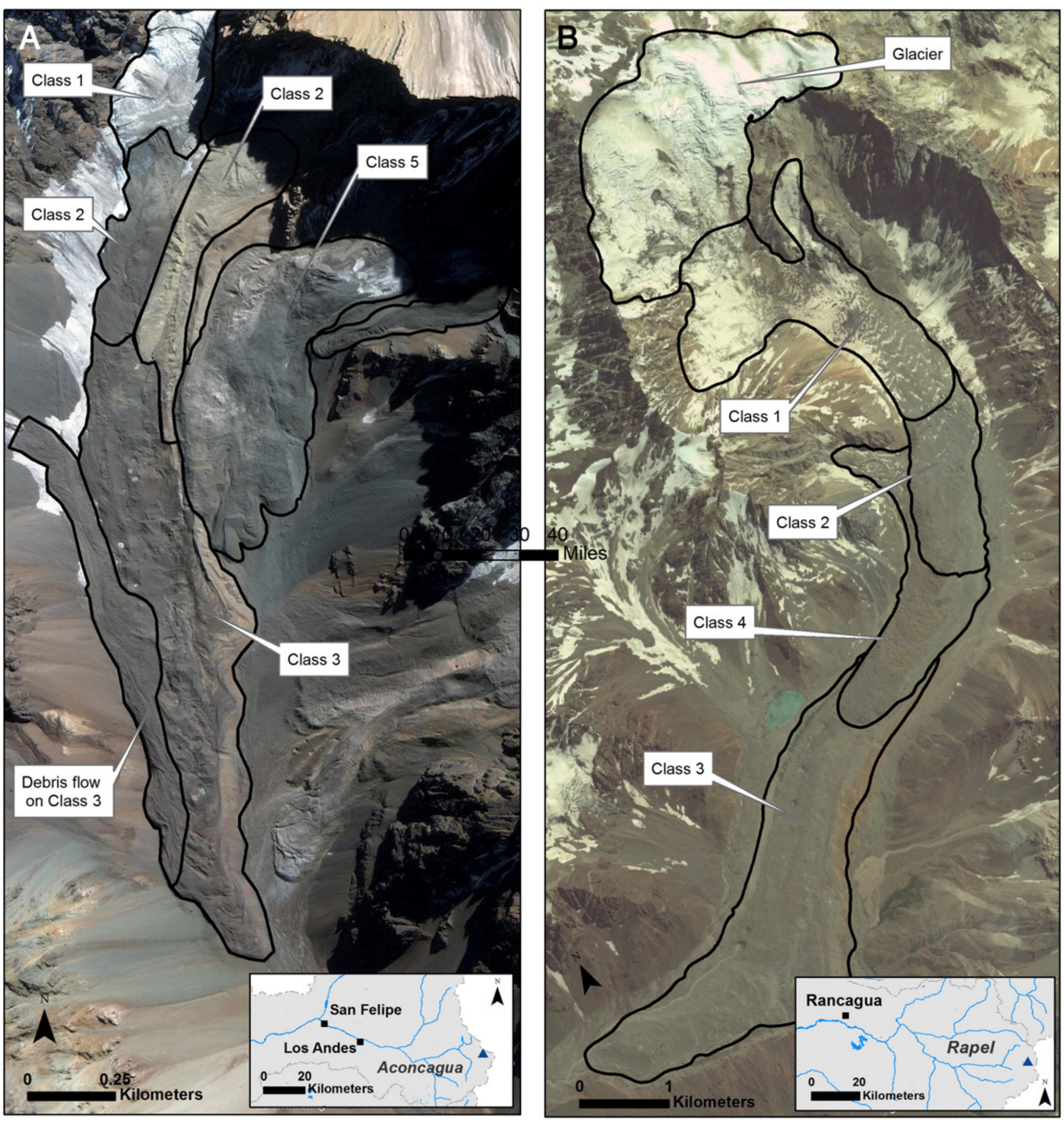

Fig. 21. Examples of complex debris-covered glaciers and rock glaciers are provided in (A) and (B). The system shown in (A) is located in the Navarro subcatchment of the larger Juncal catchment in the Aconcagua basin. The system shown in (B) is located on the Colina Mountain in the headwaters of the Maipo basin, bordering with Argentina. Location: (A) 32°53′4.1″ S, 70°2′31.1″ W; (B) 34°20′34.2″ S, 70°2′57.3″ W.
Source: (A) GeoEye: IKONOS; 2 April 2008; 1.0 m; (B) DigitalGlobe; 30 January 2010; 0.5 m.

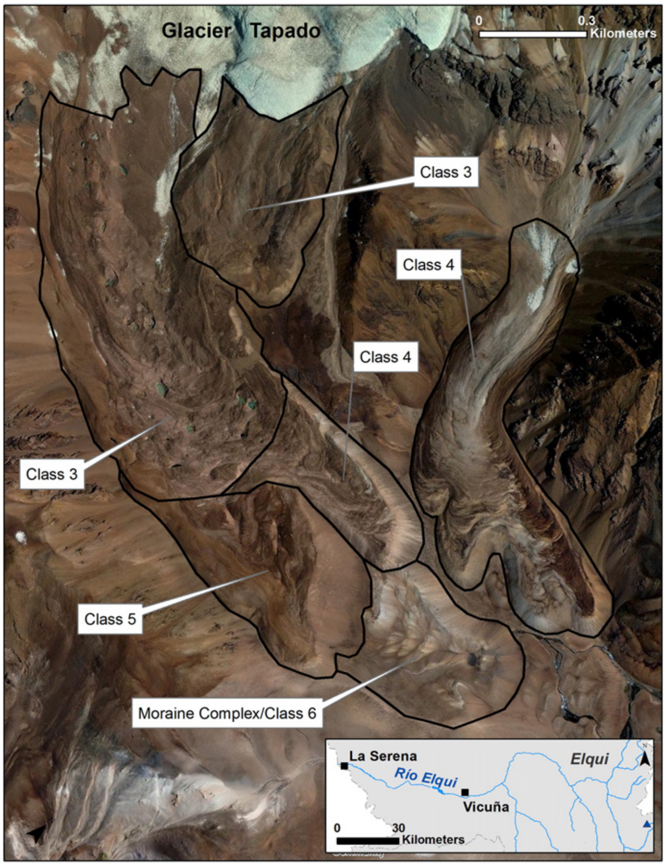

Fig. 22. This system is located in the Río La Laguna, a small catchment in the Río Elqui basin. The catchment contains 2.3 km^2 of debris-covered glaciers and rock glaciers; the El Tapado glacier covers 1.2 km^2 (almost a 2:1 ratio). The El Tapado glacier, a hanging glacier, is considered the only *true* glacier flowing in the upper mountains of this semiarid region. The adjacent mountains, even though at higher elevations, have only small remains of glaciers or snowfields (Ginot et al., 2002). From 1955 to 2005, El Tapado glacier receded from 3.6 to 1.2 km^2 (Centro de Estudios Científicos, 2011). Iribarren (2008) measured runoff from these two catchments at the end of the summer and calculated that the specific contribution of rock glaciers in the catchment was 355 l/s/km^2, which was just as important as *true* glaciers. To the south of the Elqui basin, in the Limarí and Choapa River basins, no *true* glaciers exist, but many rock glaciers occur that maintain river runoff. Location: 30°9′16.9″ S; 69°55′4.6″ W.
Source: GeoEye: IKONOS; 15 March 2007; 1.0 m.

and rock glacier system (Tres Lenguas) located in the same subbasin of El Tapado is described in Fig. 23.

6. Conclusions

Debris-covered glaciers and rock glaciers must be recognized as an important water resource. The classification presented here utilizes surface morphology, field observation, and coring data to estimate the ice content of debris-covered glaciers and rock glaciers. For debris-covered glaciers, surface coverage of semi (class 1) and fully covered (class 2) glaciers increases from 25 to 95%, respectively. Debris thickness gradually increases as glaciers become buried (class 3) with more than 3 m of surface debris. The ice content of debris-covered glaciers is high, gradually decreasing from more than 85%, to 65–85%, to 45–65% for semi, fully, and buried debris-covered glaciers, respectively. Rock glaciers are characterized by three stages. Class 4 rock glaciers have pronounced transverse ridges and furrows that indicate flow produced from ice content that varies from 25–45%. Class 5 rock glaciers have surface features that indicate decreasing rates of flow as ice content decreases to 10–25%. Class 6 rock glaciers have subdued surface topography because the rock glacier movement has ceased. Ice content has decreased to <10%.

Recent mining expansion in the high Andes has increasingly affected glaciers. Because ice is often not evident, debris-covered glaciers and rock glaciers are often confused with other landforms. In other instances, the presence of rock glaciers is recognized, but the internal ice content is underrepresented. Class 4 rock glaciers are incorrectly assigned to class 5 or class 6 categories, which have lower percentages of ice content. At some mining operations, tailings are piled on rock glaciers. This accumulation acts as an insulator that helps build internal ice, which causes horizontal movement to accelerate. In this paper, examples of each class were provided so that these landforms can correctly be identified on high-resolution imagery. As a result, debris-covered glaciers and rock glaciers should not be confused with moraines, talus, block fields, or other landforms that often do not contain as much ice.

The inventory of glaciers in Chile is incomplete. The majority of the inventories have accounted for only *true* glaciers with clean ice, despite early knowledge that rock glaciers and debris-covered glaciers were abundant in the Dry Andes. Recent efforts have begun to upgrade the glacier cadaster with geographic information system (GIS) technologies and high-resolution imagery. In the Semiarid zone, debris-covered and rock glaciers have not been inventoried at the basin level. Azócar and Brenning (2010) conducted a statistical assessment in the semiarid north (27 to 32° S), concluding that the area covered by rock glaciers is larger than the area covered by glaciers by at least a factor of two. The only complete glacier inventory at the basin level in the Semiarid zone found that debris-covered glaciers and rock glaciers in the Huasco River covered 27% of the total glacier area (Nicholson et al., 2009). In the Copiapó and Elqui river basins, debris-covered glaciers and rock glaciers have not been inventoried (Vivero, 2008; Favier et al., 2009). The Limarí and Choapa River basins have minimal *true* glaciers, but they contain debris-covered and rock glaciers, although the full extent is unknown (Marangunic, 2013). The most recent published inventory in the Aconcagua basin (32° S) described only the magnitude of uncovered glaciers and debris-covered glaciers (Bown et al., 2008). Recent efforts have been commissioned by the Chilean Water Directorate (DGA) to upgrade the glacier inventory in the Central zone (CECS, 2008; Geoestudios, 2011). These technical reports note that in the two most important basins in the Central zone, the Aconcagua and the Maipo basins, rock glaciers outnumbered uncovered glaciers by a ratio of 2.3:1 (CECS, 2008; Geoestudios, 2011).

As inventories are updated and refined, the classification system presented here should be considered for implementation. Surface features common to each class of debris-covered glaciers or rock glaciers are visible on high-resolution imagery or aerial photographs. This system can be used to digitize and assign attributes in a GIS environment. Brenning (2005) used an empirical rule that related area to thickness. Volume was adjusted for ice content and the density of ice to estimate water equivalent. This formula can easily be altered to account for the varying degrees of ice content presented here. Utilizing the functionality of a GIS and associated classified attributes, planners can efficiently calculate water equivalents for individual landforms or a variety of subcatchment, catchment, or basin scales.

Table 8
Average horizontal and vertical velocities on sections of the El Tapado debris-covered glacier and rock glacier system and nearby Llano de Las Liebras rock glacier (Instituto de Geografía, Pontificia Universidad Católica de Chile, 2010; Centro de Estudios Avanzados en Zonas Áridas, 2012).

April 2010 to April 2012			Horizontal	Vertical
Llano de las Liebres	Class 4	Ave. (cm/y)	85	−19
		St. dev.	±34	±13
Del Tapado	Buried	Ave. (cm/y)	42	−29
		St. dev.	±43	±42
	Class 4	Ave. (cm/y)	85	−28
		St. dev.	±30	±10
	Class 5	Ave. (cm/y)	18	−5
		St. dev.	±8	±2

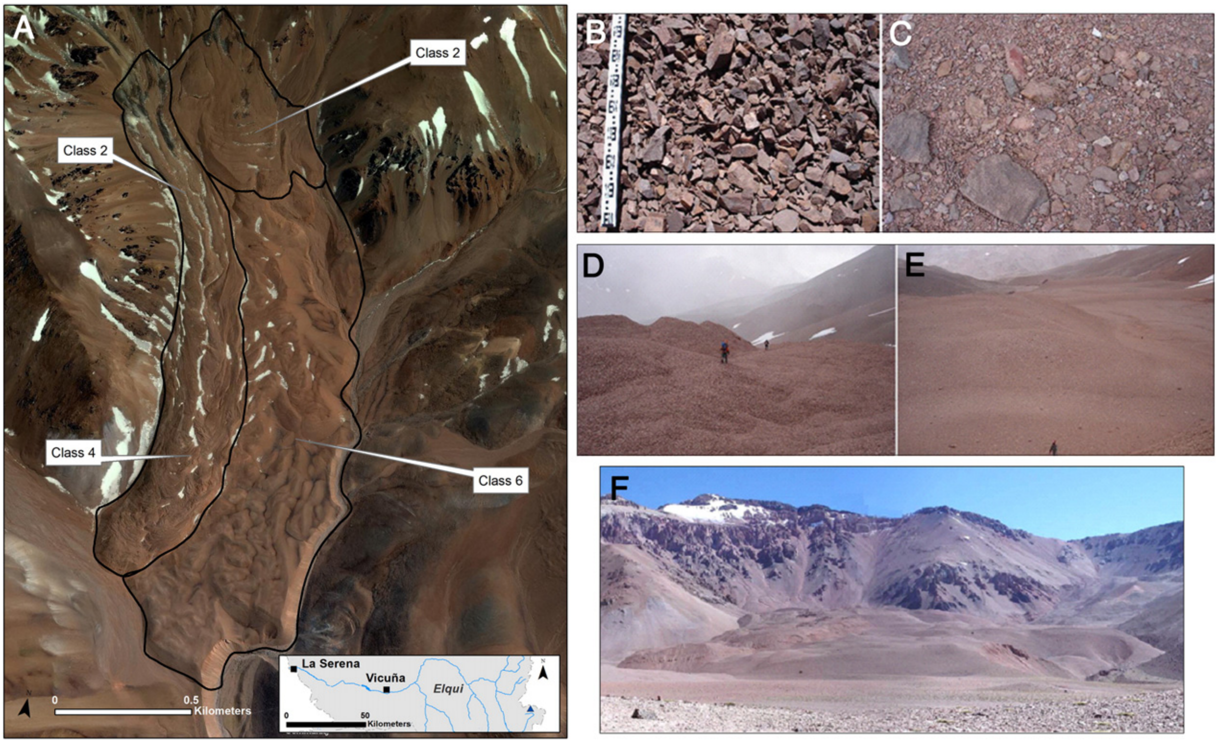

Fig. 23. The Tres Lenguas system consists of an assemblage of class 2 fully covered glaciers as well as class 4 and class 6 rock glaciers (A). The class 4 section of the rock glacier (B) shows frost-shattered material that is loosely assembled because of slow but persistent flow. Fines have been removed (B); however, fines have accumulated in the matrix of a section of the class 6 rock glacier shown in (C) giving the surface a compacted, stable appearance. The class 4 section of the rock glacier has sharper angularity and less stability of slopes produced from flow (D) compared to the more rounded, weathered, and subdued section of the class 6 rock glacier (E). The terrestrial photo (F) shows a steep front slope on the class 4 section of the rock glacier (left), which is more pronounced in comparison to the class 6 section of the rock glacier (right). Location: (A) 30°7′35.9″ S, 69°53′46.1″ W.
Source: (A) GeoEye: IKONOS; 23 December 2006; 1.0 m (photos by Pablo Iribarren; date: 6 March 2007).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geomorph.2015.03.034. These data include Google map of the most important areas described in this article.

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