Geomorphology 238 (2015) 47–55

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Reconsidering the glacier to rock glacier transformation problem: New insights from the central Andes of Chile

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ARTICLE INFO

Article history:
Received 14 October 2014
Received in revised form 24 February 2015
Accepted 25 February 2015
Available online 6 March 2015

Keywords:
Rock glacier
Debris-covered glacier
Shifting landscapes
Permafrost
Ice ablation
Sediment store

ABSTRACT

The glacier to rock glacier transformation problem is revisited from a previously unseen angle. A striking case in the Juncal Massif (located in the upper Aconcagua Valley, Chilean central Andes) is documented. There, the Presenteseracae debris-covered glacier has advanced several tens of metres and has developed a rock glacier morphology in its lower part over the last 60 years. The conditions for a theoretically valid glacier to rock glacier transformation are discussed and tested. Permafrost probability in the area of the studied feature is highlighted by regional-scale spatial modelling together with on-site shallow ground temperature records. Two different methods are used to estimate the mean surface temperature during the summer of 2014, and the sub-debris ice ablation rates are calculated as ranging between 0.05 and 0.19 cm d^{-1}, i.e., 0.04 and 0.17 m over the summer. These low ablation rates are consistent with the development of a coherent surface morphology over the last 60 years. Furthermore, the rates of rock wall retreat required for covering the former glacier at Presenteseracae lie within the common 0.1–2 mm y^{-1} range, assuming an average debris thickness and a range of debris-covering time intervals. The integration of the geomorphological observations with the numerical results confirms that the studied debris-covered glacier is evolving into a rock glacier.

1. Introduction

Rock glaciers are ice–rock mixtures in permafrost conditions moving downslope by a few centimetres to a few metres per year and that exhibit viscous flow morphology, i.e., overall tongue shape, steep margins, and ridge-and-furrow patterns on the surface (Barsch, 1996; Haeberli et al., 2006; Berthling, 2011). In most cases, the heterogeneous core of rock glaciers is invisible from the surface because it is covered with an ice-free, clastic-blocky superficial layer a few metres-thick that seasonally thaws every summer (active layer). Although rock glaciers are not generally considered as a type of glacier (e.g., Haeberli et al., 2006; Degenhardt, 2009; Kääb, 2013), some glaciological classifications may include them (Rau et al., 2005). Rock glaciers differ from debris-covered glaciers; the latter are glaciers covered with a thin and discontinuous debris mantle devoid of viscous flow morphology, with distinct flow dynamics and no need of permafrost for their development (Nakawo et al., 2000; Berthling, 2011).

Nevertheless, the relationships that rock glaciers may have with glaciers in structure and origin have constituted the main rock glacier controversy since the 1970s (Potter, 1972; Johnson, 1980; Barsch, 1987, 1992, 1996; Humlum, 1988, 1996; Whalley and Martin, 1992; Clark et al., 1994a,b, 1998; Jakob, 1994; Whalley et al., 1994, 1995; Potter et al., 1998; Whalley and Palmer, 1998; Haeberli, 2000; Krainer and Mostler, 2000; Fukui et al., 2008; Milana and Güell, 2008; Krainer et al., 2010). This controversy has been between the *continuum school* vs. the *permafrost school* as summarised and extensively discussed by Berthling (2011). The continuum school has defended the possibility of rock glaciers deriving from glaciers, a concept that includes terminological variants such as *ice-cored rock glaciers* (Potter, 1972), *glacier ice-cored rock glaciers* (Johnson, 1980), or *glacier-derived rock glaciers* (Humlum, 1996). The permafrost school has refuted the latter possibility and has progressively gained weight and credibility since the 1980s (e.g., Haeberli, 2000; Haeberli et al., 2010; Berthling, 2011).

In spite of this dichotomy, the works defending or challenging glacial origins for rock glaciers have always been based on already well-developed features, mostly in mid-latitude mountain ranges (Alps and Rockies). There has been a critical lack of discussion on cases where rock glacier morphology is *currently developing* at the front of debris-covered glaciers, which potentially represent ongoing glacier to rock glacier transformations. Only one study by Schroder et al. (2000) in the Himalayas reported the case of a rock glacier appearing from a glacier within the human life time scale.

The upsurge of free and potent remote sensing tools, such as Google Earth, has considerably transformed field exploration in geomorphology and makes extensive landform recognition in remote and poorly accessible areas fast and easy. As such, it is possible to see many cases of debris-covered glaciers in the dry Andes and Himalayas exhibiting

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http://dx.doi.org/10.1016/j.geomorph.2015.02.025
0169-555X/

rock glacier morphology (ridges and furrows, steep front, and lateral margins) in their termini. In such cases, the rock glacier morphology is in complete continuity with the upper debris-covered glacier and does not represent a permafrost zone overridden by readvancing glaciers, a topic abundantly studied (e.g., Haeberli, 2005).

In this paper, we want to reconsider the glacier to rock glacier transformation problem. We do not place the issue in a dichotomous debate, in which it would have to be presented as an alternative to the permafrost model. Instead, we assume that rock glaciers as creeping permafrost features can originate either from periglacial processes (e.g., ground ice forming into talus or moraines) or from glacial processes (debris-covered glaciers). We see the glacier to rock glacier issue as a potential and conspicuous illustration of the geodynamic relays that can occur in shifting mountain landscapes as the climate changes: i.e., in this case a progressive shift from the glacial realm to the periglacial realm.

Berthling (2011) gave four criteria for a glacier to rock glacier model to apply: (i) the presence of permafrost; (ii) melting of the ice core at a rate sufficiently low for a coherent surface morphology to be maintained and developed; (iii) an age of the feature compatible with known periods of glacial advance and subsequent retreat; and (iv) rates of rock wall retreat matching the time required for the constitution of the sediment store in the feature. In the present work we test and discuss these criteria on the basis of features observed in the central Andes of Chile. More particularly, we focus on the case of Presenteseracae (upper Aconcagua River catchment, 32.88° S, 70.03° W), which is a small debris-covered glacier with rock glacier morphology in its lower part. This debris-covered glacier is difficult to access (~10 km of tough itinerary off trail or on bad paths) and has not been extensively instrumented (e.g., borehole, complete meteorological apparatus). Our goal in the present study is to bring preliminary, yet valuable insights into the recent and ongoing development of the landform based on in situ observations and measurements, remote sensing, and numerical calculations.

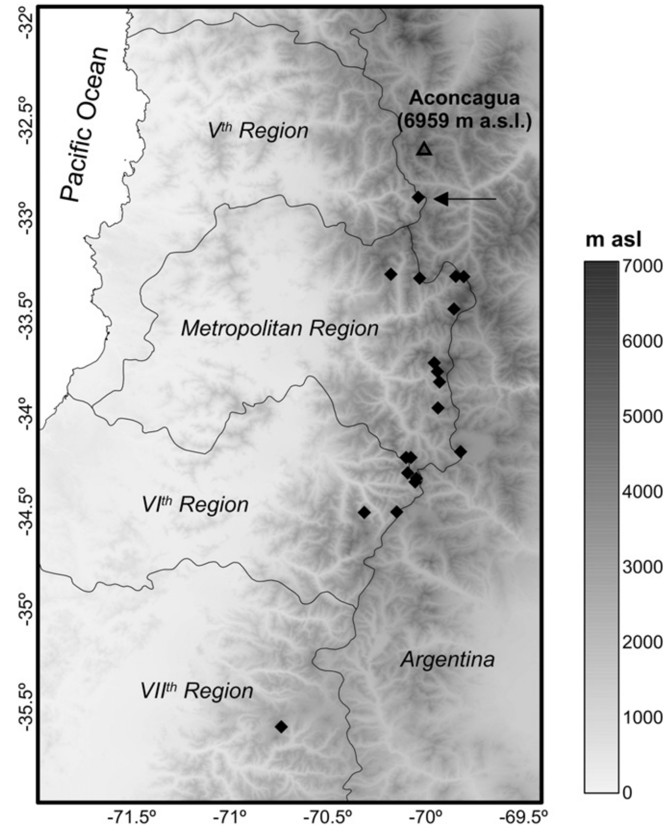

Fig. 1. Debris-covered glaciers with rock glacier morphology in their lower part, in the central Andes of Chile. The arrow indicates the position of the Presenteseracae debris-covered glacier. Elevation data from ASTER DEM.

2. Study area

The studied area is the semiarid Chilean central Andes (30–35° S) (Fig. 1). This is the highest part of the Andes, with the Cerro Aconcagua culminating at 6959 m above sea level (asl) on the Argentinean side (a few kilometres from the international border). Various other summits exceed 6000 m asl on the Chilean side. In this area, as summarised by Brenning (2005) and Azócar and Brenning (2010), precipitations above 3000 m asl range from ~200 mm y^{-1} (north) to 700–800 mm y^{-1} (south); the 0 °C isotherm of mean annual air temperature (MAAT) is located between ~3700 m asl (south) and 4000 m asl (north). The central Andes of Chile have been increasingly studied over the last 10 years owing to abundant peculiar cases of rock glaciers (Brenning, 2005; Brenning and Trombotto, 2006; Milana and Güell, 2008; Brenning and Azócar, 2009; Azócar and Brenning, 2010; Bodin et al., 2010; Monnier and Kinnard, 2013; Monnier et al., 2014). The glacier–rock glacier relationship issue was addressed in the case of the Tapado glacier foreland by Milana and Güell (2008), Monnier et al. (2014), and Pourrier et al. (2014). The foremost of the above authors interpreted the rock glacier as derived from the upper debris-covered glacier (*glacigenic rock glacier*) whilst the latter two interpreted the rock glacier as overlapped by the debris-covered glacier after the Little Ice Age (LIA) advance.

The study area was surveyed between 32.8 and 35.6° S using Google Earth where about 20 cases of debris-covered glaciers exhibiting rock glacier morphology at their termini were identified (Fig. 1). These sites are unfortunately always remote (up to more than 25 km hiking with no or poor track) and/or located in private areas with restricted or no right of access. We focus here on the logistically 'least worst case scenario' of the Presenteseracae debris-covered glacier. This site is located in the Juncal River catchment (upper Aconcagua River catchment, Fifth Region of Chile). The Juncal catchment (~109 km^2) has a large elevation range (~1400–6110 m asl). The glacierization is moderate (14% according to Bown et al., 2008; Ragettli and Pellicciotti, 2012) with most glaciers being found in the southern extremity of the catchment. Using common criteria (Barsch, 1996) and 2010–2014 Google Earth images, we identified 55 active rock glaciers in the catchment. They cover 8.34 km^2, i.e., almost 8% of the catchment area. They exhibit a large range of size (from ~100 m to more than 3 km long) and exist in a variety of topoclimatic conditions.

The Presenteseracae debris-covered glacier (32.88° S, 70.03° W) is located in a deep, narrow, SW-facing cirque below the Presenteseracae Peak (4875 m asl; Fig. 2), the northwesternmost peak of a prominent range with multiple summits called 'Cerros Tres Gemellos', in the north-eastern part of the Juncal River catchment. The debris-covered glacier is located between 4075 and 3800 m asl and entirely fills the floor of the cirque. Although it is small (~600 m long and 300 m wide), this does not call into question the use of the term *glacier* according to recent common definitions (Cogley et al., 2011) and to the presence of flow-related arcuate structures on former bare ice areas (Fig. 3). The rock walls above the debris-covered glacier are composed of densely fractured andesitic breccias and conglomerates (upper Cretaceous) and sandstones and limestones (upper Jurassic). The foreland of the debris-covered glacier exhibits various lateral or median morainic ridges (the uppermost of which are overridden by the Presenteseracae debris-covered glacier), two degraded rock glacier lobes, and gullies carved by water and debris flows (Fig. 2). The degraded rock glacier lobes may have been overridden and degraded by glacial advance. On the surface of the Presenteseracae debris-covered glacier, as measured by manual digging at 10 locations, the debris thickness varies between a few cm in the upper part and at least (when ice was not reached) 60 cm in the lower part. In its upper part (~4075–3880 m asl), the debris-covered glacier exhibits a quite chaotic surface where there are some bare ice exposures owing to debris cover sliding, crevasses, or