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Recent evolution and degradation of the bent Jatunraju glacier (Cordillera Blanca, Peru)

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ABSTRACT

This article brings new insight into the recent evolution and degradation of the bent Jatunraju glacier in the northern part of the Cordillera Blanca, Peru. Analysis of topographical maps, aerial photos and satellite images covering a period of 66 years and a field survey performed in June 2013 and May 2014 helped to describe the geomorphological setting and ongoing processes. Recent evolution and degradation processes are also deduced from surface movements. Historical geodetic measurements (1967–1968; 1977–1984) and current LANDSAT images (2001–2013) were used to estimate surface velocities and changes in surface velocities over time. Our investigation showed that the most significant changes happened at an altitude of between 4300 and 4450 m asl. A significant decrease in surface velocities and increase in debris thickness indicate that this part of Jatunraju turned from a debris-covered glacier into an ice-cored rock glacier during the analyzed period. Particular parts of the article describe the cycle of formation and extinction of supraglacial lakes and the melting of buried (debris-covered) ice. A scenario of future evolution is outlined and discussed as well. We assume that ice degradation within the debris-covered glacier will continue and that the altitude of its presence will increase hand-in-hand with the changing environment.

1. Introduction

Rock glaciers and debris-covered glaciers are currently at the forefront of geomorphic and climatic research because of their potential for providing valuable information in helping to understand processes of mountainous landscape evolution. The significance of rock glaciers as sensitive indicators of climate change has often been described (e.g., Humlum, 1998; Kääb et al., 2007; Kellerer-Pirklbauer and Kaufmann, 2012) and also used for analysis of geomorphic evolution and paleogeographic conditions (Humlum, 2000; Ruiz and Trombotto, 2012). Rock glaciers and debris-covered glaciers have therefore been studied in various regions throughout the world including the North American Cordillera (Clark et al., 1994; Ackert, 1998; Burger et al., 1999), the South American Andes (Brenning and Trombotto, 2006), the Himalayas (Shroder et al., 2000; Benn et al., 2012), the European Alps (Berger et al., 2004; Diolaiuti et al., 2009), and Svalbard (Degendhardt, 2009).

The rock glaciers and debris-covered glaciers of the Cordillera Blanca (Peru) are currently not studied in as much detail as the above-mentioned regions, with one exception: the Jatunraju glacier, which is situated on the northern slopes of Mt. Huandoy (6395 m asl) in the Parón Valley in the northern part of the Cordillera Blanca (9°00′05″ S., 77°40′50″ W.; Figs. 1A, 2). Previous research in the Parón valley was mostly related to Lake Parón (Carey et al., 2012), which is dammed by the lowest part of the Jatunraju, and its hazardousness and its application of remedial works in the 1980s (e.g., Torres et al., 1964; Huaman, 1983). During these remedial works the water level of the lake was significantly lowered by a drainage tunnel, reducing the role of the Jatunraju as a lake dam. The water balance in the Parón watershed was also investigated (Suarez et al., 2008). The first work dedicated to the formation and evolution of the Jatunraju was presented by Lliboutry (1977, 1986) suggesting downslope movements of the whole glacier, not only its surface, and hypothesizing that a moraine breach may result in the bend shape of the Jatunraju. Some of these findings were recently revised by Iturrizaga (2013) who argued mainly for morphological constraints shaping the end of the Jatunraju glacier. Nevertheless, a clear explanation of its formation, description of its recent evolution and surface forming processes, as well as the geomorphological classification of this landform are still under debate.

Therefore, the aim of this paper is to contribute to these unsolved problems by performing the following tasks: (i) interpretation of the recent evolution of the Jatunraju glacier; (ii) description of its current state of development based on detailed geomorphic mapping; (iii) estimation / measurement of the surface velocities and interpretation

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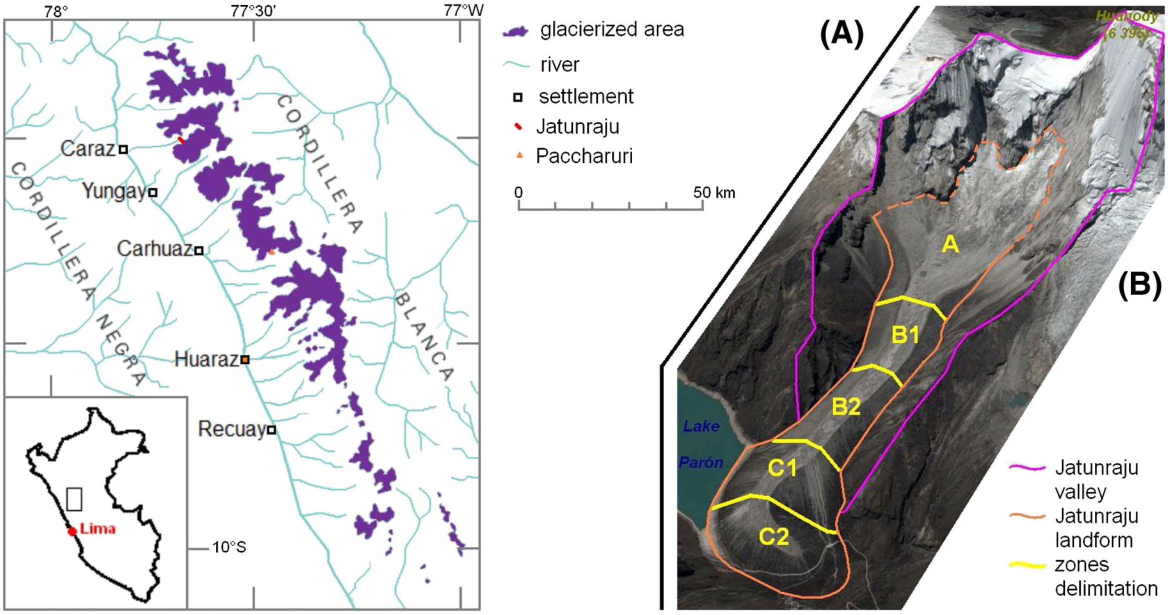

Fig. 1. Jatunraju location and zonation. Part (A) shows the location of the Jatunraju in the Cordillera Blanca (base map modified from a USGS map). Part (B) shows a panoramic Google Earth Digital Globe 2014 view of the Jatunraju glacier set in the Jatunraju valley situated on the northwestern side of the Huandoy massif (6395 m asl).

of their changes over time in different parts of Jatunraju; (iv) evaluation of the total movement of the Jatunraju body based on remotely-sensed images; and (v) geomorphic classification of different parts of the Jatunraju glacier.

Fig. 2. Huandoy massif (6395 m asl) and bent Jatunraju glacier as viewed from the opposite valley in May 2014.

2. Data, methods and terminology

2.1. Data and methods used

Remotely sensed images with submetric resolution covering a period of 66 years (1948–2014) were used for the geomorphic description of the Jatunraju, its surface evolution, and movement dynamics. These contain three sets of historical aerial photographs (1948, 1962, and 1970) from the archive of Autoridad Nacional del Agua (ANA, Huaráz, Peru) and later captured high resolution satellite images available on Google Earth Digital Globe 2014 (U.S. Geological Survey 2003 and CNES / Astrium 2014 images). Standard topographical maps 1:25,000 of the Peruvian cadastral office (COFOPRI, 1972) and bathymetrical measurements of Lake Parón of Unidad de glaciología y recursos hídricos (Ames, 1984; UGRH, 2007) were used for reconstructing the approximate floors of the Parón and Jatunraju valleys (thalwegs) before the Jatunraju formed.

LANDSAT 7 ETM + and LANDSAT 8 OLI with dates 30 June 2001 and 9 July 2013 were processed to describe the surface velocity of the debris-covered glacier. For this purpose, only the panchromatic bands (15-m pixel size) of the images were used with the LANDSAT 8 OLI as a base to which the LANDSAT 7 ETM + was rectified. Surface movement of the debris was determined through correlation of both images using the *Cosi-Corr* method (Leprince et al., 2007) by applying a 32 × 32 pixel window (Ayoub et al., 2009) with pixel size three times larger (45 m) than the original (15 m). The obtained pixel displacement values were used to calculate their velocity vectors. Residual errors in the surface movement measurements were estimated using the band weighting signal to noise ratio (SNR) method giving a maximum error of ± 14 m. Geodetic measurement of surface velocities of 43 boulders (Lliboutry, 1977) for the period 1967–1968 (237 days in total) and of 27 boulders (Ames, 1984) for the period 1977–1984 (2594 days in total) were used for evaluating changes in mean annual surface velocities. The position data were in both cases measured with an accuracy of 10^{-3} m.

Detailed geomorphological mapping, laser inclinometer/distancemeter-based topographical measurements (with submeter accuracy of measurements) and field reconnaissance were performed in June 2013 and May 2014. Detailed field data including historical geodetic surface movement measurements allow us to perform more reliable and in-depth interpretation of less detailed remotely sensed images and surface movements derived from satellite data.

2.2. Terminology

Terminology related to rock glaciers, debris-covered glaciers, and related glacial and periglacial landforms and processes is disunited. Different points of view based on morphology, topographic position, genetics, and dynamics allow different definition and landform interpretation for different purposes (Whalley et al., 1986; Hamilton and Whalley, 1995; Clark et al., 1998; Berthling, 2011). We define the landforms mainly based on morphology and features observable in a field using the approach of Summerfield (1991), who defined *rock glaciers* as tongue-shaped masses of angular boulders resembling in form a small glacier, which usually descend from cirques or cliff faces. Active rock glaciers contain ice at depth, either filling voids (ice-cemented subtype) or forming a core (ice-cored subtype). Some cases of the ice-cored variety are derived from debris-covered glaciers (e.g., Whalley and Palmer, 1998). *Debris-covered glaciers* are defined as glaciers acquiring supraglacial debris through material falling onto the ice surface from the rock walls or ice-free areas. The distinction between ice-cored rock glacier and debris-covered glacier is, therefore, something quite arbitrary without a reliable detection technique and mapping hidden ice. Based on Summerfield (1991), we differentiate between ice-cored rock glacier and debris-covered glacier on the basis of estimated surface debris thickness and movement activity represented by velocities of surface movements.

3. Study area

The Cordillera Blanca of Peru (Fig. 1A) is the most heavily glacierized tropical mountain range in the world (e.g., Ames and Francou, 1995). Repeated Quaternary glaciation and subsequent deglaciation has led to the evolution of a high mountain glacial landscape with all its typical landforms (Vilímek, 2002), including rock and debris-covered glaciers (Vilímek et al., in review). In most of the valleys of the Cordillera Blanca, well-visible terminal and lateral moraines demonstrate the extent of the glaciers during the last significant glacier advance, the Little Ice Age (LIA), culminating here in two periods (1590–1720 and 1780–1880; Thompson et al., 2000; Solomina et al., 2007). These glacial landforms are mostly extended to an altitude of between 4200 and 4700 m asl. Good examples can be found in the northern part of the Cordillera Blanca on the northwestern (Kinzl glacier) and southwestern (Schneider glacier) sides of the Huascarán massif or on the northeastern side of the Huandoy massif. The current glacier extent is estimated to be around 600 km^2 (Georges, 2004).

The local geological setting of the Cordillera Blanca was described by Wilson et al. (1995). Rockwalls have formed in the coarse-grained intrusive rocks (granodiorites and tonalites) of the Cordillera Blanca batholith. The southwestern slopes of the Cordillera Blanca batholith (facing the Santa River valley) are typical fault slopes with well-developed facets and other signs of young neotectonic uplift (e.g., Vilímek, 1998). Parallel to the regional fault situated at the foothill of the Cordillera Blanca, other faults stretch inside the massif, forming weakened zones, which contribute to the production of loose material transported later by gravitational processes, glaciers, and rivers.

The Jatunraju glacier (formerly spelled *Hatunraju*; Lliboutry, 1977) is located in a Pleistocene cirque (Lliboutry, 1986) on the southwestern side of the Huandoy massif (6395 m asl) in the northern part of the Cordillera Blanca in the Santa River catchment area (Figs. 1, 2). The upper part of the cirque is occupied by glacier 506a with an area of 271,000 m^2, and the volume of the whole Jatunraju landform is estimated to be around 92 · 10^6 m^3 (Lliboutry, 1986). The bent-shaped terminus of Jatunraju dams the superior Parón valley and retains Lake Parón — one of the largest lakes in the Cordillera Blanca (UGRH, 2007). Lichenometric measurements of Solomina et al. (2007) estimated the right lateral moraine of the Jatunraju to be 300–340 years old (formed 1660–1700) suggesting that the current Jatunraju was formed during the LIA. On the other hand, delta sediments from the eastern part (subbasin) of Lake Parón were estimated to be ~ 10,000–13,000 ^{14}C YBP (Seltzer and Rodbell, 2005). Clearly this part of the lake already existed at the end of the Pleistocene. This lake was dammed by the last glacial maximum moraine, which is identifiable on the current lake bottom, dividing the lake into two subbasins (east and west; Seltzer and Rodbell, 2005).

For the purpose of description clarity and due to the different morphological characteristics and properties, we have divided the Jatunraju glacier into five altitudinal zones (A, B1, B2, C1, C2; see Table 1; Fig. 1B). These zones were delimited retrospectively on the basis of differences in surface movements (see Section 4.3.2) and geomorphic settings (see Section 4.2). Zone A is situated directly below the steep rock walls of the Huandoy massif in the cirque and zone C2 covers the lowest, curved part of the Jatunraju (see Fig. 1B).

4. Results

4.1. The Jatunraju formation

The Jatunraju glacier transported a significant amount of material during glacier advance in the LIA and has created a well-pronounced moraine compared to other glaciers in the same catchment. The source of the loose material is the cirque headwall. Transversal profiles (Figs. 3A, 4) show extraordinary material deficit in the Jatunraju valley in comparison with profiles constructed through the Parón Valley below and above the Jatunraju. Lliboutry (1986) quantified the average amount of debris influx to be 5080 m^3/y (24,800 m^3/y including ice). The regular narrow shape of the Jatunraju is the result of material transport (pushing out) through the narrow gate of Jatunraju cirque (<400 m in the narrowest part).

The longitudinal profile of the Parón valley (Figs. 3B, 4) shows that the mean valley gradient beneath the lower part of the Jatunraju is probably no greater than 3°, assuming a gradual decreasing trend of the valley floor. Considering the fact that the Parón valley was rather narrow during the formation of the Jatunraju (~500–600 m; see Figs. 1, 3A), the frontal part of the glacier simply bends perpendicularly down the Parón valley in a path predisposed by previous glaciations.

4.2. Geomorphic description, current state and evolution

The maximal longitudinal length of the Jatunraju from the lowest point of the moraine abutment to the distal rock wall of the cirque is 3790 m, whereas its altitude ranges from 4100 to 5400 m asl (1300 m vertical difference). These figures provide a general surface inclination of 20°, in fact the surface inclination fluctuates from about 45° in the upper part of the cirque glacier (A on Fig. 1 and Table 1) to 9° in the segment directly below the upper part (B1 on Fig. 1 and Table 1), while the rest of the surface keeps a constant 16° surface inclination (Table 1). The wide vertical range enables segmentation and representation of different geomorphological processes resulting in the formation of different forms. Detailed geomorphic mapping (Fig. 5) showed

Table 1
Basic characteristics of the different parts of the Jatunraju.

Part	Zone	Surface altitude [m asl]	Surface area (without moraines) [m^2]	Mean surface inclination [°]
The upper part (A)	A	4750–5400	271,000	45 (upper part) 15 (lower part)
The middle part (B)	B1	4600–4750	152,000	9
	B2	4450–4600	73,000	16
The lower part (C)	C1	4300–4450	60,000	16
	C2	4200–4300	58,000	16

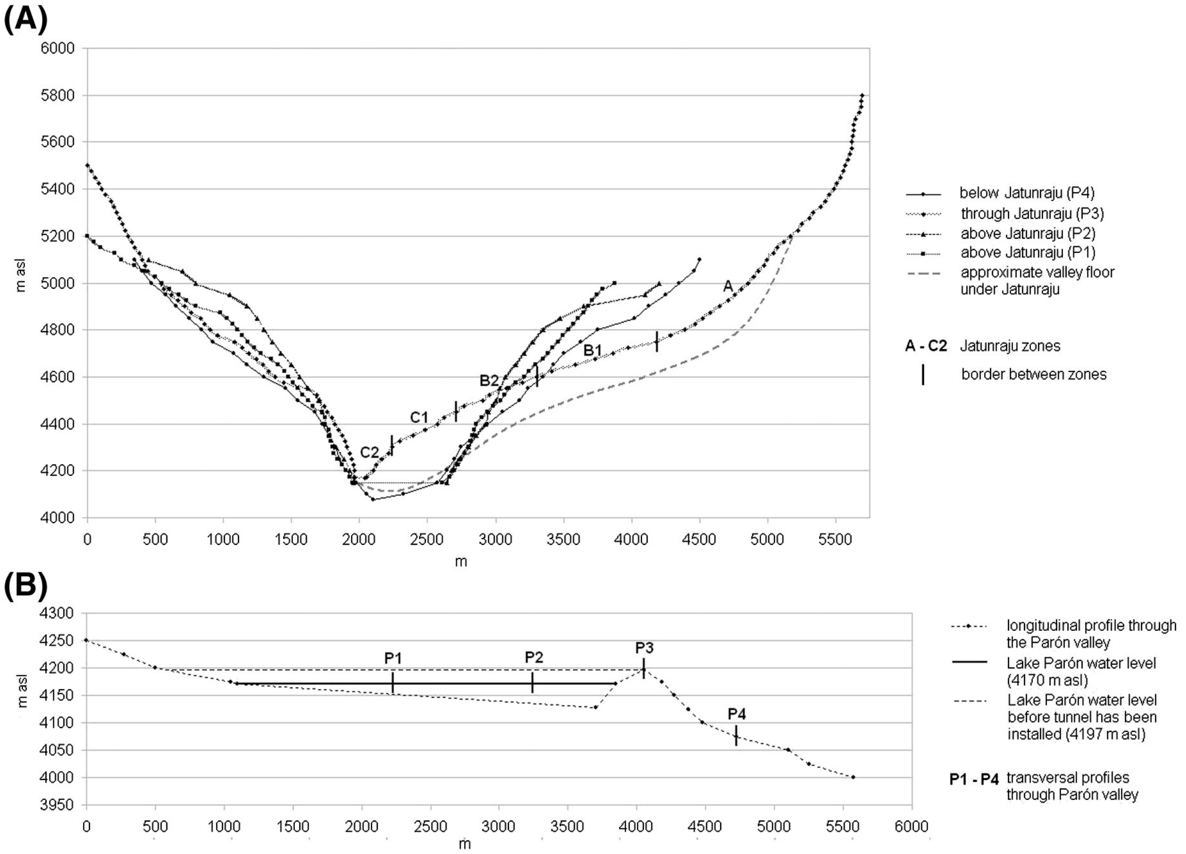

Fig. 3. Part (A) shows transverse profiles through the Parón valley, including a profile through the Jatunraju. Part (B) shows a broken longitudinal profile through the Parón valley. Topographical data: COFOPRI (1972).

different geomorphic forms within the different parts of the Jatunraju valley and its close surrounding. For a detailed interpretation, the five zones defined in Section 3 (Fig. 1B) are grouped into three parts in this section (upper part A, middle part B, lower part C; Table 1) as described below.

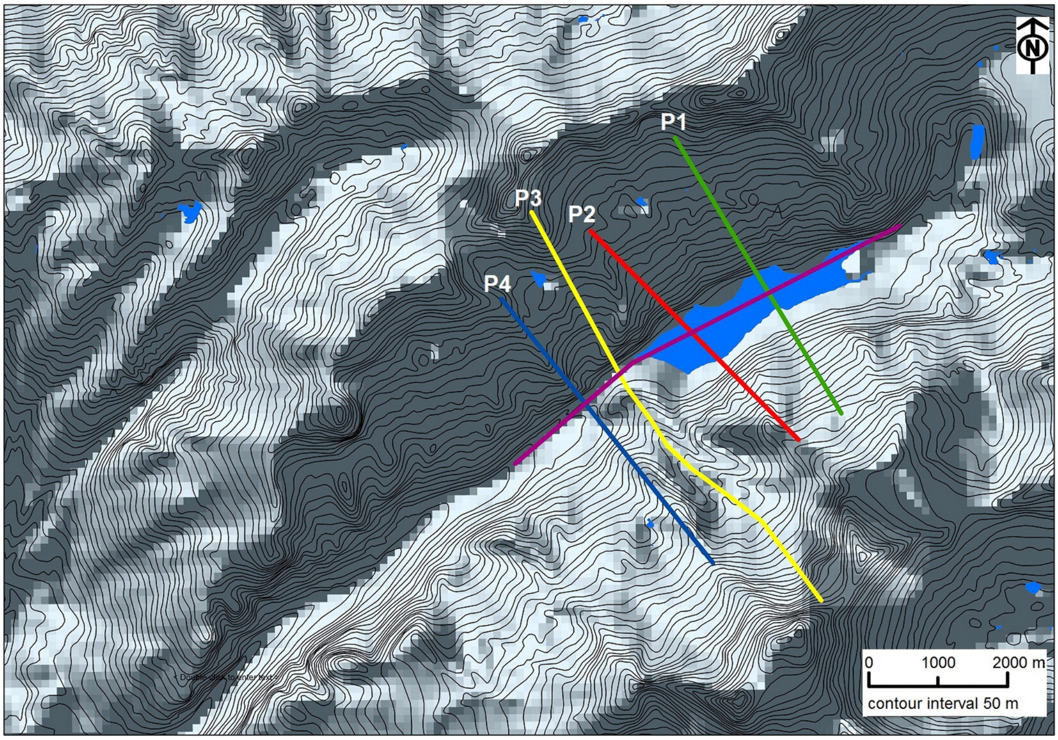

Fig. 4. Location of longitudinal and transversal profiles in the Parón valley constructed from topographical maps.

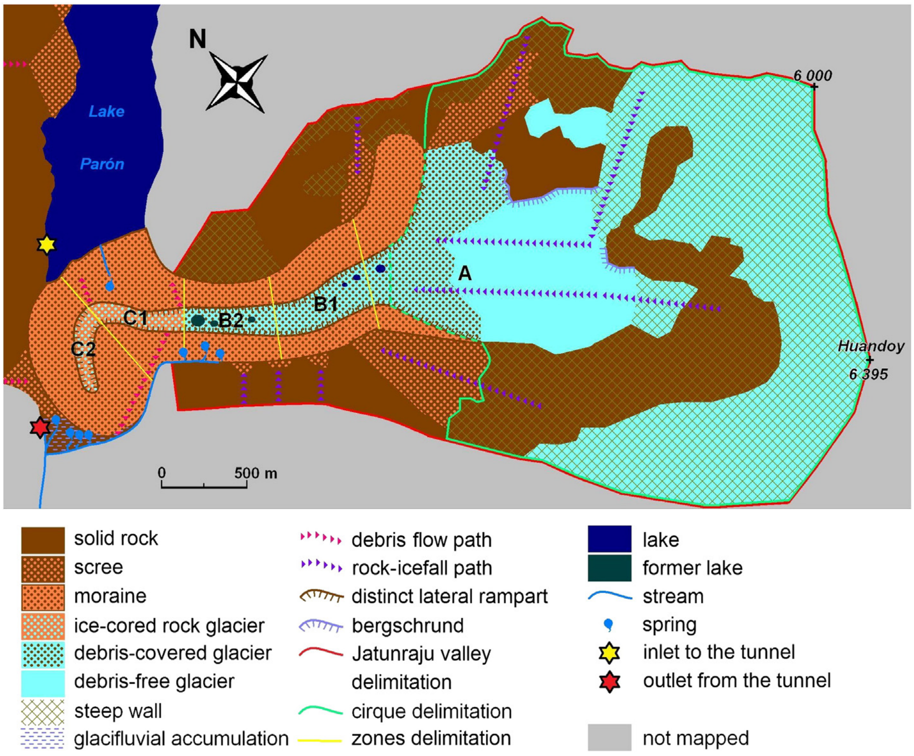

Fig. 5. Geomorphic map of the Jatunraju glacier, valley, and close surroundings based on the field survey performed in June 2013 and May 2014 and a Google Earth Digital Globe image (August 2013).

4.2.1. The upper part

A cirque glacier extending to an altitude of between 4750 and 5400 m asl, with a mean surface inclination varying between 15° and 45°, is located in the upper part of the Jatunraju (zone A, Table 1). The upper part of the Jatunraju is influenced by material influx resulting from fast slope movements (rockfalls and icefalls)

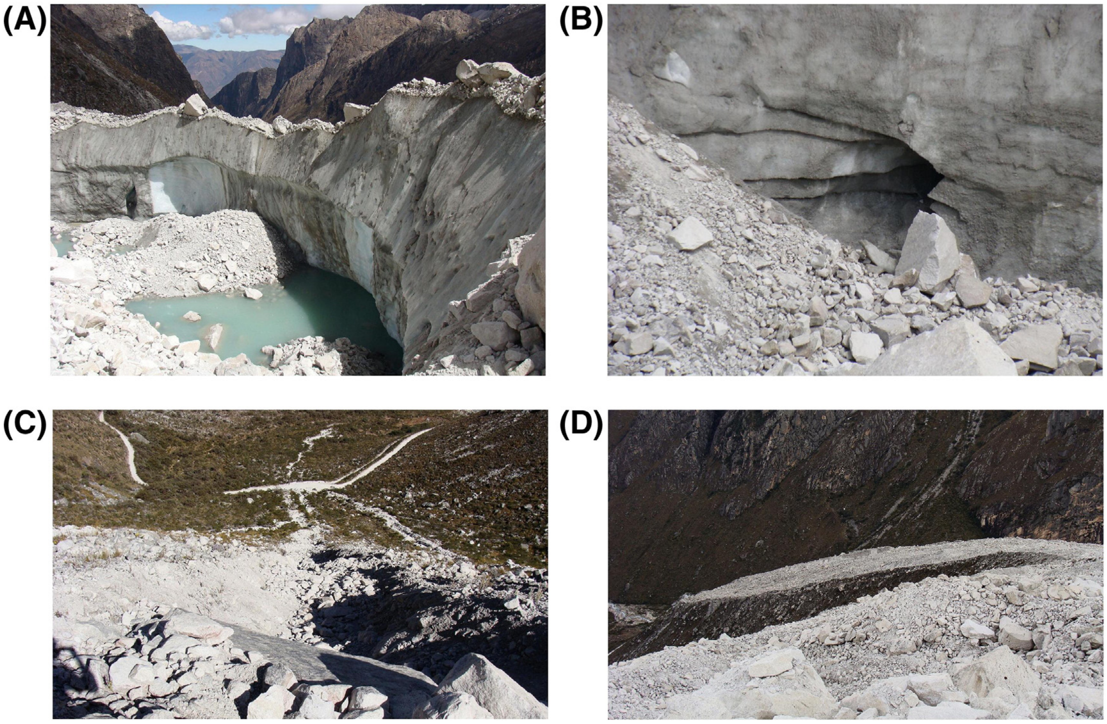

Fig. 6. An example of a relict supraglacial lake in the middle part of the Jatunraju glacier. Part (A) shows a clearly visible horizontal line indicating the former position of the lake level before water release. The shown depression is around 15 m deep, 70 m wide, and the debris cover thickness on the top of the ice headwalls is around 1 m. Part (B) shows the entrance to a tunnel through the glacier body, which drained the lake. Part (C) shows a gully formed 200 m below the lake on the left distal face of the Jatunraju moraine, probably as a result of sudden water release from the supraglacial lake situated above; the shown gully is 3 m wide, 2 m deep, and 500 m long. Part (D) shows the *hummocky* surface in the middle part of the Jatunraju and its lowest bent-shaped part.

from the Huandoy massif (see Section 4.3.3). Because of the steep mean surface inclination in the upper part of the cirque, fallen material is transported farther down, therefore the central and upper parts of zone A are debris-free, while the lower parts are debris-covered (see also Figs. 2, 5). The debris-covered lowest part of zone A at an elevation of around 4750 m asl forms the border with zone B and also the border between the cirque glacier and the debris-covered glacier tongue.

4.2.2. The middle part

The most significant changes (evolution) are currently taking place in the middle part of the Jatunraju. Almost the entire surface of the middle part of the Jatunraju (the most active part; see 4.3.2) is covered by debris, which is generally several meters thick. Almost pure ice with a minimal amount of debris is buried beneath the debris cover (Fig. 6A). The middle part is not characterized by constant surface inclination unlike the lower part (Table 1). The debris accumulation from rockfalls from the Huandoy massif is transported through this zone by movement of the debris-covered glacier tongue as well as gravitational surface movements (see Section 4.3).

From multitemporal aerial and satellite images as well as from field investigation, we can see that many supraglacial lakes with volumes of up to 50,000 m^3 have formed and subsequently become extinct on the debris-covered glacier body. The cycle of supragacial lake formation, evolution, and extinction is described in four basic steps in Fig. 7. Multiple repetition of this cycle in different parts of the debris-covered glacier has led to the formation and evolution of its typical *hummocky* surface (Fig. 6D) and buried ice degradation. Supraglacial lake extinction is also frequently connected with a sudden discharge (release) of retained water, which is closely tied with erosion and transport processes such as debris-flow movement on the left lateral moraine (Fig. 6C; see Section 4.3.3). Several new debris flow paths appeared between 1948 and 2013 (Fig. 8). We assume that all of the gullies formed on the distal faces of the Jatunraju moraine were created in such a way, following the overflow of lateral ramparts by escaped water.

4.2.3. The lower part

The lower part of the Jatunraju is characterized by a more or less constant surface inclination of 16°; its surface is much more regular than in the middle part (i.e., less hummocks). After the major disappearance (melting) of buried ice (debris-covered ice), the debris-covered glacier turned into a rock glacier (ice-cored rock glacier; e.g., Monnier, 2007). Melting of ice also leads to subsidence of the central part of the transversal profiles and formation of up to 10-m-high ramparts on both sides of the lateral moraines in the lower part of the Jatunraju (zones C1 and C2). In 1967, these ramparts were recorded to be 4 m high and suggested subsidence of the surface of 2 m in 20 to 40 years (0.05 to 0.10 m/y; Lliboutry, 1977). Subsidence of 6 m in the next 45 years (1967–2013) suggests a mean rate of up to 0.13 m/y. In fact, the mean rate of subsidence is greater, but parallel filling by transported debris occurs. Based on piezometric perforation, Huaman (1983) showed the debris thickness at an elevation of 4300 m asl as being 1 m and found 63 m of ice beneath it. During our field survey in 2013, the determined debris thickness was significantly higher in this part of the Jatunraju, which is evidence of melting buried ice.

4.3. Jatunraju movements

Measurements and interpretation of Jatunraju movements are vital for understanding the currently ongoing processes as well as for providing a protracted evolution context. Jatunraju movements were investigated from different points of view and scales: (i) entire body movements of the whole landform (see 4.3.1); (ii) movements of debris on the active surface (4.3.2); and (iii) fast slope movements (4.3.3).

4.3.1. Entire body movement of the Jatunraju since 1948

A comparison of historical aerial photos from the archive of Autoridad National del Agua (Huaráz, Peru) with current satellite images did not show any significant movement of the entire Jatunraju body at that scale (see Fig. 8). We did not identify any evidence of recent deformations related to the movement of the entire Jatunraju body on its bulky lateral moraines during the field reconnaissance in 2013 and 2014. An aerial photo from 1970 capturing the Jatunraju after the catastrophic earthquake (M = 7.9; USGS, 2014) showed no visible deformations or movements of the entire Jatunraju body. Therefore, analogically to the LIA moraines of the Cordillera Blanca, we assume that the entire Jatunraju body is currently a static landform. The only documented movements are surface movements of debris and the debris-covered glacier (see Section 4.3.2), small-scale slope movements

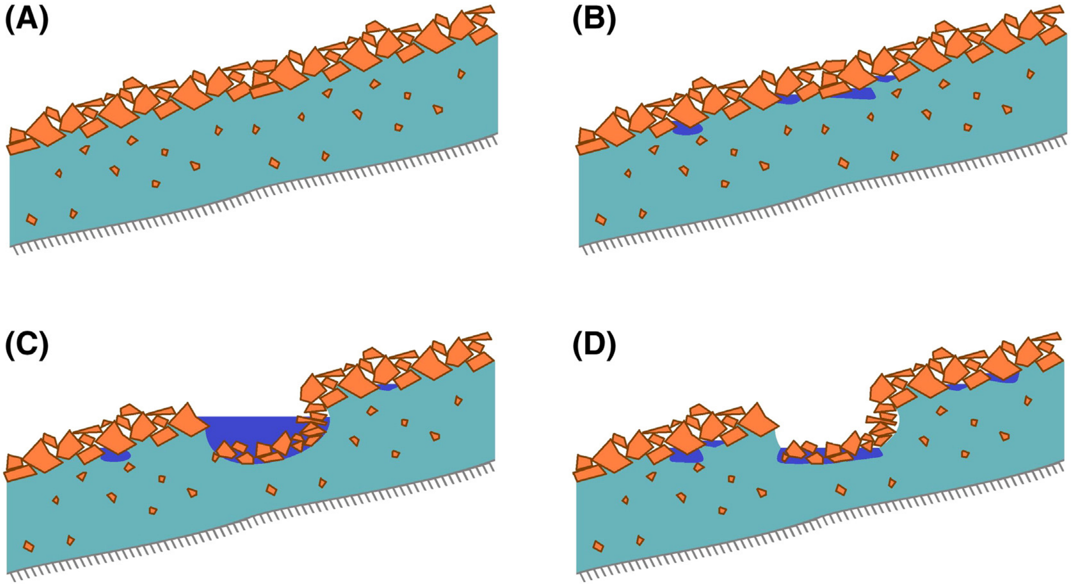

Fig. 7. Schematic sketch of the formation and evolution of a supraglacial lake on a debris-covered glacier body. (A) Initial state of the debris-covered glacier; (B) formation and evolution of small water pockets beneath the debris surface; (C) formation of the supraglacial lake by merging of small water pockets, debris cover immersion into the lake, and lake growing and deepening; (D) release of water from the supraglacial lake (e.g., through a glacial tunnel). Please note that the axes are out of scale.

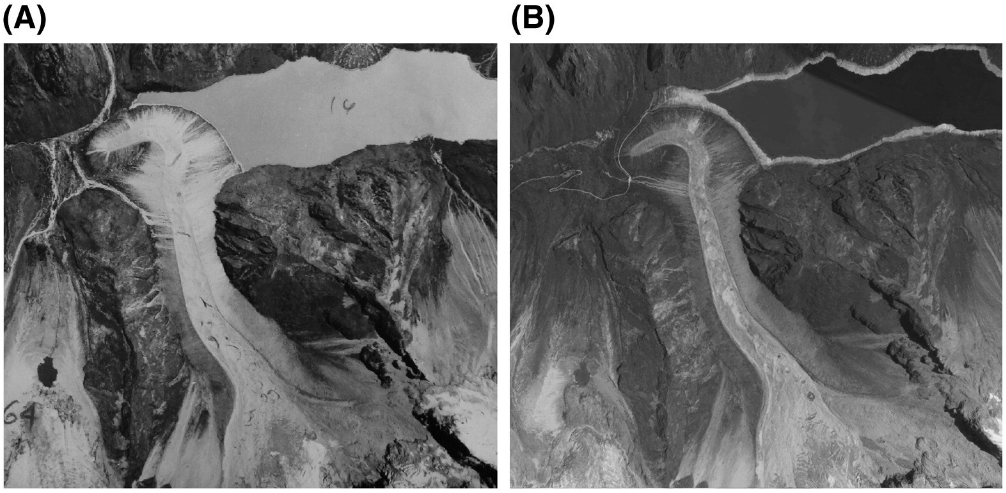

Fig. 8. Comparison of aerial views of the Jatunraju glacier in 1948 (Part A) and 2014 (Part B). The retreat of the shoreline as a result of lake level lowering in 1985 is clearly visible in part (B). Photos: part (A) Archive of Autoridad Nacional del Agua (ANA, Huaráz); part (B) CNES/Astrium image (20 August 2013) available from Google Earth Digital Globe 2014.

on distal moraine faces and icefalls/rockfalls from rockwall and glaciers situated above the Jatunraju cirque (see Section 4.3.3).

4.3.2. Surface movements

Based on the geodetic measurements made by Lliboutry (1977) between 1967 and 1968 and measurements made by Ames (1984) between 1977 and 1984 (see 2.1), we investigated the mean and maximal yearly velocities of large boulders situated on the active surface of the Jatunraju at an altitude of between 4215 and 4565 m asl (zones B2–C2). Unfortunately, no measurements were performed above (in zones A and B1). Both measurement campaigns showed that the mean velocity increases with increasing altitude (Table 2). A significant abrupt increase of surface velocities is present at the border between zones C1 and C2 at an altitude of around 4310 m asl in the case of Ames's (1984) data set and at an altitude of 4340 m asl in the case of Lliboutry's (1977) data set. The mean velocity in zone C2 was calculated as being 0.86 m/y (Ames's (1984) data set) and 1.40 m/y (Lliboutry's (1977) data set), while in zone C1 it was 4.82 m/y (Ames's (1984) data set) and 5.30 m/y respectively (Lliboutry's (1977) data set). In zone B2 it was 8.34 m/y (Lliboutry's (1977) data set; see Table 2). The maximal measured individual velocities reached about 10 m/y in zones B2 and C1.

Analysis of surface velocities based on LANDSAT images also showed clear differences between the defined zones. The surface displacements were most significant in the upper part of zone B2, where the mean annual velocity was estimated as being 4.4 m/y, with a maximal annual velocity of 11.2 m/y (Table 2). Zone B1 has a lower mean annual velocity (1.8 m/y) but contains a similar extreme detected maximal annual velocity of 10.8 m/y. The bend-shaped end of the glacier (zone C2) and the glacier cirque (zone A) shows only very limited surface mobility.

By comparing the surface velocities derived from satellite images (2001–2013) with surface velocities measured in the field between 1967 and 1984, we can observe an abrupt decrease of surface velocities beneath an altitude of around 4450 m asl (the border between zones C1 and B2). Zone C1 experienced a significant decrease (4.82 and 5.30 m/y during 1967–1968 and 1977–1984, respectively, to 1.0 m/y in 2001–2013), while zone C2 manifested the lowest mean annual surface velocities during all the analyzed periods. A significant decrease in mean surface velocity in zone C1 indicates depressed activity in this zone. We assume that the depressed activity is connected with internal changes caused by melting of ice (increase in the altitude of the border zone between the debris-covered glacier and the ice-cored rock glacier). Zone C1 is thus assumed to have turned from a debris-covered glacier in the 1970s to an ice-cored rock glacier.

The only evidence of large-scale surface deformations of the Jatunraju body is in the external part of the left band of the Jatunraju terminal (zone C1 on Fig. 3). The single lateral rampart branches out into three, which suggests gravitational movement in an outward north-east-north direction in the bend. No significant movement was detected here using the satellite data (2001–2013).

4.3.3. Slope movements

Different types of slope movements occur at the studied site. This mainly includes the following: (i) rockfalls and icefalls and (ii) debris flows. Rockfalls and icefalls originating on steep cirque walls surrounding the cirque glacier are an extremely important source of material. Rockfalls provide material, which partly fills the material deficit resulting from ice melting in the lower part of the Jatunraju. The main mechanism of debris flow is a sudden release of water retained in supraglacial or englacial lakes, which may reach volumes of up

Table 2
Surface velocities between 1967 and 1984, based on geodetic measurements and between 2001 and 2013 based on LANDSAT images (modified and calculated from Lliboutry (1977), Ames (1984) and LANDSAT images).[a]

Zone	Surface velocities between 1967 and 1968 (Lliboutry, 1977)		Surface velocities between 1977 and 1984 (Ames, 1984)		Surface velocities calculated from LANDSAT images (2001–2013)	
	Maximal annual velocity [m/y]	Mean annual velocity [m/y]	Maximal annual velocity [m/y]	Mean annual velocity [m/y]	Maximal annual velocity [m/y]	Mean annual velocity [m/y]
A	–	–	–	–	2.0	0.7
B1	–	–	–	–	10.8	1.8
B2	**10.26**	**8.34** (21)	–	–	**11.2**	**4.4**
C1	9.44	4.82 (18)	**9.97**	**5.30** (12)	2.1	1.0
C2	1.96	1.40 (4)	4.75	0.86 (15)	0.8	0.7

[a] No data available; (number of measured points).

to ~ 50,000 m^3 (see 4.2.2). The transport zone of debris flow (dry gullies on the distal face of left lateral moraine) is clearly visible in the field (Figs. 2; 6C) as well as on remotely sensed images (Fig. 8). The last significant debris flow occurred in 2008. As a consequence, the road to Lake Parón was blocked at an altitude of 4160 m asl and needed to be repaired.

5. Discussion

5.1. Jatunraju classification

A definitive classification of the Jatunraju is quite problematic because the individual forms defined in the literature are not unified (see Section 2.2) and different points of view allow for different interpretations. However, general consensus is that the Jatunraju is not a uniform landform but consists of several distinct parts. Lliboutry (1977) defined the Jatunraju as a 'covered glacier embedded within a rock glacier'. Based on our investigation, we assume that parts of the Jatunraju are separated vertically, based on the presence (absence) of buried ice, thickness of the debris cover of the ice, and its mobility (see also Section 2.2). These parameters are changing in time and allow us to observe the evolution of the classification of different parts of the Jatunraju. In other words, geomorphic classification of the Jatunraju is not constant over time according to the classification that was used and which represents the observed geomorphological changes well.

We have defined the upper part of the Jatunraju cirque glacier, while the middle part is characterized as a debris-covered glacier tongue. These findings are in accordance with those presented by Lliboutry (1977) and Iturrizaga (2013). Classification of the lowest part is more problematic. Iturrizaga (2013) defined the lower part as a *pedestal moraine*. According to the typology presented by Clark et al. (1998), we define the lower part of the Jatunraju (zones C1 and C2 on Fig. 1) as a *glacigenic rock glacier* or, according to Summerfield (1991), as an *ice-cored rock glacier* derived from a debris-covered glacier. The location of the exact limit between these two landforms is difficult to identify, but based on our field geomorphological mapping and a comparison of surface velocities between two periods (1967–1984 and 2001–2013), we place it at an altitude of around 4450 m asl (the border between zones C1 and B2).

The available data about surface velocities suggest that ice degradation occurred during the analyzed period but no relevant local climate data for describing it in more detail are available. Considering the available literature, we argue that the ice degradation was related to the changes of the 0 °C isotherm of the average annual temperature (Ruiz and Trombotto, 2012) and probably also to extreme temperatures and patterns of spatiotemporal distribution of precipitation in the Cordillera Blanca (Mark and Seltzer, 2005). The ice degradation is probably also closely connected with increasing ELA resulting from changing patterns in temperatures and precipitation (Kaser and Georges, 1997). The ELA was shown to increase from 4820 m asl in 2001 to 5078 m asl in 2013 (Loarte et al., in review). As a consequence, glacier tongues (even debris-covered glacier tongues) are frequently retreating and degrading, which also applies to the Cordillera Blanca (Mark and Seltzer, 2005). As a result, in combination with strong material (debris) influx from the glacier cirque, the lowest part of a debris-covered glacier turns into an ice-cored rock glacier.

5.2. Hypothesis of the bent-shaped formation

The bent shape of the Jatunraju rock/debris-covered glacier tongue was first explained by Lliboutry (1977) and later revised by Iturrizaga (2013). Lliboutry (1977) favors a singular extreme event, while Iturrizaga (2013) considered gradual processes caused by the Parón valley slope gradient and lateral debris displacement. We agree with the explanation presented by Iturrizaga (2013), suggesting a 3° inclination of the original surface of Parón valley and interplay with the original morphology of the valley floor having an important role in the formation of the terminal part. Bulky lateral moraines with a constant slope inclination of 30° on both sides of the Jatunraju indicate that no singular extreme event, such as a proglacial lake outburst or Parón glacier influence, as posed by Lliboutry (1977), is responsible for the bent shape of the Jatunraju.

A similar bent-shaped glacial landform is seen in the Ruripaccha valley, which is the right-side tributary of the Honda valley (9°17′24″ S., 77°27′47″ W.) in the Central Cordillera Blanca beneath Lake Paccharuri (Figs. 1, 9). From the geomorphic point of view, the bent shape of Lake Paccharuri seemingly is a result of downslope movement of the glacier terminus during a period of glacier advance on the junction of the tributary and the main valley in a predetermined path of the Pleistocene.

5.3. Detected movements of the Jatunraju

We present surface velocities derived using two techniques and acquired over three different time periods without temporal overlaps, performed by three different research teams. This leads to significant questions about the comparability of the results. Thus, in the interpretation we consider the average values and relative differences between the time periods and different zones rather than focusing on the absolute velocity values. We are also aware that the first monitoring period, which lasted less than one year (1967–1968), is the least representative, i.e., it is possibly affected by anomalous movements occurring during the short monitoring period. On the other hand, the two other monitoring periods (1977–1984, 2001–2013) provide much more representative results summarized for monitoring periods of 7 and 12 years, respectively. We did not use the advantage of more frequent and more localized velocity detection through geodetic measurements (Ames, 1984) because the results are available only for two zones and the objective of the study does not demand it.

We consider the interpretation of satellite images to be very useful, as the results summarize the resulting movement during longer time periods and for a broader area showing a general movement trend. Knowledge of mean annual surface velocities (MASV) for different parts of the Jatunraju allows a comparison with the determined relationship between the MASV and mean annual air temperatures (MAAT) published by Kääb et al. (2007), which reflects the observation of many authors that rock glaciers with temperatures close to thawing point move faster than cold rock glaciers (e.g., Lambiel and Delaloye, 2004). When applied to the surface velocities determined for 2001–2013 (Table 2), we obtain the highest MAAT for zone B2 (0 °C), which is decreasing with increasing altitude suggesting MAAT for B1 of −1 °C and for zone A from −2 °C to −3 °C. The suggested MAAT are only indicative and long-term averages, which do not need to correlate well with the actual or short-term temperature conditions at the studied site, which are unfortunately unknown.

The acquired mean annual velocities for 2001–2013 suggest that the Jatunraju moves at very high (zone B2) or high (zones B1, C1) velocities, as defined for rock glaciers in Lambiel et al. (2008). The GPS monitoring of rock glaciers in Switzerland (Lambiel and Delaloye, 2004) only revealed movements of up to 1.35 m after a three-year monitoring period, while comparable surface movements were detected on debris covered glaciers in the Himalayas (Shroder et al., 2000). Much lower velocities in the range of 10^{-2} m/y were detected on rock glaciers on Svalbard (Kääb et al., 2002) and in the French Alps (Whalley and Palmer, 1998). Whalley and Palmer (1998) attributed the different velocities to different stages of rock glacier evolution. Clearly, rock glacier movement velocities are very variable depending not only on environmental conditions (e.g., temperatures, slope dip, content of ice in debris) but also on technical aspects of data acquisition. The most important one is probably the length of time during which the glacier was monitored, which varies between days in the case of the study by Shroder et al. (2000), three years (Lambiel and Delaloye, 2004), and 10 years (Lambiel et al., 2008). In addition, the used methods, e.g., geodetic

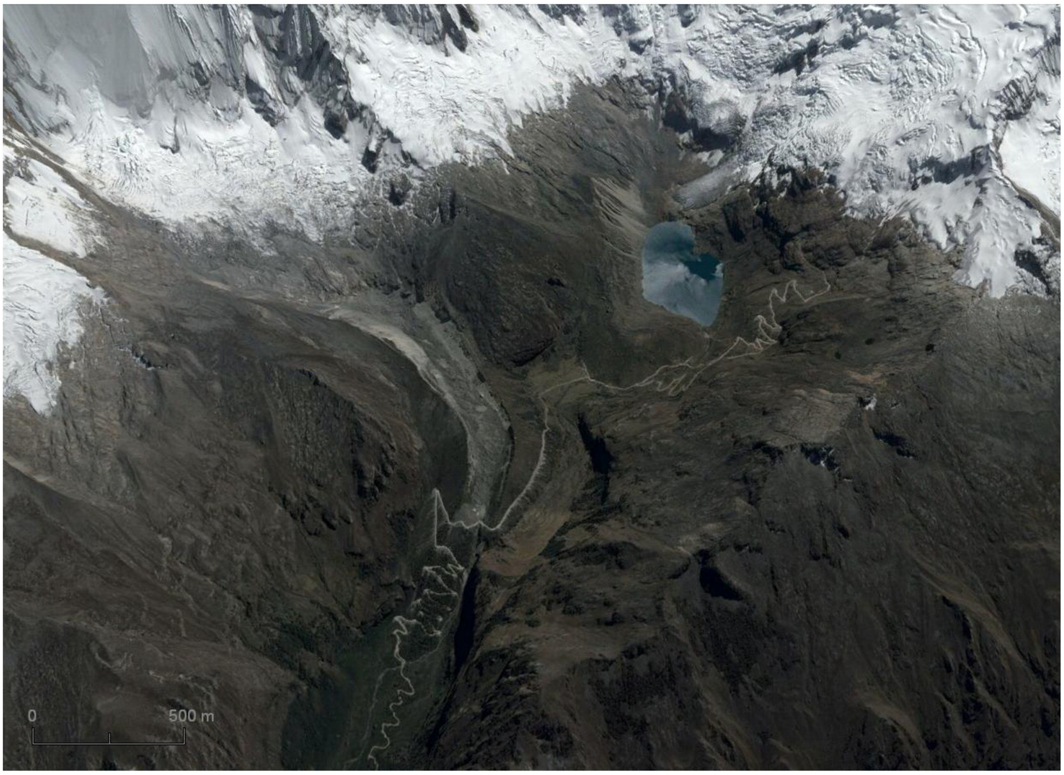

Fig. 9. Panoramic view of the bent-shaped glacial landform and Lake Paccharuri in the Ruripaccha valley (central Cordillera Blanca) as seen on the CNES/Astrium image (20 August 2013) available from Google Earth Digital Globe 2014. Valley is oriented in the NE–SW direction.

(Shroder et al., 2000), GPS measurements (Lambiel and Delaloye, 2004), InSAR or satellite image analysis (Leprince et al., 2007; Lambiel et al., 2008) and aerial photo interpretation (Kääb et al., 2002) affect absolute values of the acquired movements and spatial resolution. Some methods provide point measurement data (e.g., GPS), while others detect movement over larger terrain units (e.g., 45 m in the presented analysis of LANDSAT images). Therefore, a direct comparison of the movement monitoring results is often not possible.

The detected surface movements can be explained mainly as a result of subsurface glacier flow and ice degradation with a certain delay before the changes are accommodated on the surface. This is caused by the chaotic and unconsolidated nature of the glacier debris containing mainly boulders of different sizes. Possible evidence of this was acquired during the field work when it was possible to hear moving rocks close to the observer with no movements detected on the surface. Based on the movement monitoring and historical surface landform development, we assume that the determined movement pattern represents only a temporal state and can be subjected to significant alternation, especially in the upper parts of the Jatunraju, probably as a result of continuous climate change.

Specific superficial entities related to climate change, which also significantly affect surface movements, are supraglacial lakes. They are currently most abundant in zone B2 and probably caused the most significant mean annual velocity detected there during the period 2001–2013. The discharge mechanism of the lakes described in this article requires specific conditions: rather steep downslope inclination of the glacier surface, rather low moraine ramparts, and preferential underground waterways leading the water toward the outside moraine slope. Such conditions are probably not very widespread within the Cordillera Blanca as we are not aware of any debris-covered glacier with evidence of similar processes (supraglacial lakes on its surface with downslope located debris flow paths on the outside moraine slope). One reason for this is that the majority of debris-covered glaciers are situated in concave valleys resulting either in less steep surfaces or surfaces slightly upward inclined toward the periphery of the forms.

5.4. Jatunraju evolution scenario

One of the key questions of Lliboutry's (1977) article is “Must we fear any fast evolution in the future?” We assume that the gradual ice degradation will continue hand in hand with climate changing within the Cordillera Blanca as well as the related changes in mean annual and seasonal temperatures and spatiotemporal patterns of precipitation influencing ELA (Mark and Seltzer, 2005). For a near future evolution, we therefore expect a successive increase in the altitude of the border zone between the debris-covered glacier tongue and the ice-cored rock glacier. Similar processes probably occurred unnoticed between 1984 and 2001. In accordance with Huaman (1983), we found no evidence of buried ice within the moraine ridges, thus we assume that the near future evolution of the Jatunraju should not have a significant influence on the hazardousness of Lake Parón, under the condition that the level of the lake remains at the current elevation or lower, which ensures dam stability and can be maintained by reasonable operation of the tunnel built in 1985 (Carey et al., 2012). Therefore, the only way a flood may occur is after large-scale slope movement into the lake, producing a displacement wave large enough to overtop the lake dam with a freeboard of 40 m (e.g., dam overtopping of lake Safuna Alta with 80 m of freeboard in 2003; Hubbard et al., 2005). We found no evidence that such an event may originate from the Jatunraju at present.

6. Conclusions and future research

Our investigation showed that the Jatunraju is an example of a combination of a cirque glacier in the upper part, continuing into a debris-covered glacier tongue in the middle part, and probably ice-cored rock glacier in the lowest part, which formed during the Little

Ice Age as a result of glacier advance. Blocking of the main valley subsequently caused damming and impounding of Lake Parón — one of the biggest lakes in the Cordillera Blanca. Ice cores in the rock glacier part and the debris-covered glacier tongue are melting and degradating because of the conditions forcing increased ELA. In addition, the cycle of supraglacial lake formation and extinction contributes to the ice melting. Surface velocities of debris were described as well. Thus mean annual surface velocities in the lower part of the Jatunraju have significantly decreased (from 4.82 m/y during the period of 1967–1968, 5.30 m/y during the period of 1977–1984, to 1.0 m/y during the period of 2001–2013). This suggests that the altitude of the border zone between the debris-covered glacier tongue defined by higher velocities and the ice-cored rock glacier increased during the analyzed period (1967–2013) from < 4300 m asl in 1970 to 4450 m asl in 2013. The terminus of the debris-covered glacier is retreating to a higher altitude, while melted ice is partly being replaced by debris moving down from the cirque. Nevertheless, none of the above-mentioned processes influence the overall stability of the entire Jatunraju body, which has been stationary for at least the last 66 years (since the first aerial photographs taken in 1948).

For future research, we recommend especially:

- investigation of the internal structure and its evolution over time in different parts of the Jatunraju using the appropriate geophysical methods and GPS surface movement monitoring and its comparison with similar landforms (e.g., Paccharuri);
- morphometric analysis of Jatunraju cirque and comparison with other cirques of the Cordillera Blanca, quantifiying the amount of transported material;
- paleogeomorphological reconstruction of the evolution of Parón valley since the end of the LIA/Last Glacial Maximum; and
- multihazard assessment of the risks posed by glaciers and glacial lakes (with an emphasis on newly forming lakes) in the entire Parón watershed and assessment of their eventual impact on Lake Parón.

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