

Associate Editor Decision

Thank you for a much-improved revised manuscript. I attach a version in which I have annotated some punctuation suggestions which I would like you to include if you decide for a resubmission. As you will see from the commissioned referee reports there remain questions of your data reliability and methodology reproducibility which you will want to address before we can consider your manuscript for final publication. I hope that you will be able to address these two concerns and forward us a revised version for final appraisal for inclusion in Earth Surface Dynamics.

***Answer:** We have completely reprocessed the data using another program and used new pre-processing of images (contrast enhancement and snow masking) along with more stringent filtering criteria in order to address the two abovementioned concerns (see below and new Methodology Section). The paper has been modified accordingly, with important changes to the figures and tables, and corresponding changes to the text where needed to accommodate the updated results; the core of the interpretations and main insights drawn in the Discussion section remain quite unchanged. Most modifications to the interpretations concern the updated results on the surface displacements obtained from the new feature tracking analysis. We have furthermore taken into account the punctuation and language suggestions provided by the Associate Editor for this new version. We have included as uploaded files a revised version of the manuscript (V3) where the main changes are highlighted using the MS Word change track function, and a clean copy of this latter file.*

Referee #1 (Prof. Dr. Andreas Kääh)

General comment

The paper looks much improved. However, at this stage I looked in detail only at the displacement vectors as they were a key critic from my side. I am still quite sure that there is a major problem with the displacement measurements.

I copied the orthophotos of the different years and different rock glaciers from the pdf and overlaid and flickered them. In the lower parts of the rock glaciers there clearly is coherent movement that could be measured. In the upper parts, though, I doubt that most of the displacement vectors shown in the paper are true, especially not for the longer time periods investigated. Many of the vectors are on places which either have snow in one of the images, or where heavy thermokarst processes seem to alter the surface. Under such circumstances, I cannot imagine how image correlation should be able to provide displacements, even if only low-res versions of the air photos are available to me for my assessment.

***Answer:** We finally totally acknowledge that in the previous versions of our MS, issues occurred relating with the processing of images with CIAS. The whole analysis was re done completely, using more careful pre-processing of the images and more stringent filtering criteria. This included masking out snow-covered surfaces, image contrast enhancement, adapting the template window according to the image quality and the spatial scale of surface morphology expected to be preserved over time, and application of a 3-criteria filtering procedure to the output vectors matched by the NCC algorithm. As detailed in the updated Methodology section, we have decided to re-process entirely the images using the MATLAB toolbox ImGRAFT, with which the second author had extensive experience. The updated analysis resulted in much less matches as well as the removal of blunders and/or too chaotic patterns, which were correctly detected by A. Kääh (especially those related to snow cover...). The new results are nonetheless interesting and instructive, with spatially coherent displacement vector patterns, indicative of slow creep, being most consistently found over rock glacier areas, whereas debris-covered areas were rather characterized by either a lack of movement detection and/or chaotic, poorly organized flow patterns evocative of thermokarst degradation processes. The rest of the paper has been modified according to these new results.*

Referee #2

General comment on the revised version

The manuscript has been substantially improved since the first version. All the questions have been satisfactorily answered. The manuscript is now much better structured, the discussion much more consistent and the significance of the study clearer.

I have just a problem with the streamlines. It is not clear how they were drawn, and so their mapping appears to be highly subjective. There are probably hundreds of ways of drawing the streamlines. As they obviously come from the displacement vectors, the same analyse could somehow be done from the displacement vectors. Thus, how the streamlines were drawn must be much better explained, because the method must be reproducible by others. Otherwise you may also consider removing the streamlines.

Answer: *Following the modifications related to the methodological changes (see responses to Referee #1), we have decided to remove the streamline delineation from this study. The updated velocity fields did not allow depicting the streamlines for each landform and periods, as in some cases only limited movement was detected on the surface*

Other comments:

P1, l28. Prefer « evolved » to « transformed »

Answer: *OK.*

P3, l23. Remove « That being said, »

Answer: *OK.*

Fig. 3. The limit between the Western and Eastern units are still missing.

Answer: *We have added a dotted line on the figure in order to separate both units.*

P6, l26. Replace « well-defined steep frontal talus slopes » by « a well-defined steep front », because a talus slope is an accumulation of debris at the foot of a rock wall. This is not the case here. Same remark for p7, l29.

Answer: *OK.*

Legend Fig. 7. The front of which landform? Debris-covered glacier I guess, so please give precision. What is the black line?

Answer: *The front of the studied landform. Considering that the latter has evolved over the studied period from a single debris-covered glacier to a currently forming rock glacier, we prefer not give to any precision.*

P12, l7. « ...where they now approximately represent three quarters... ». How can you give this estimation since the western and eastern units are not mapped?

Answer: *We have dropped such approximate precision in the new version of the manuscript.*

P12, l13-15. Again, we want to see a mapping of the thermokarst areas.

Answer: *Thermokarst areas are mapped on Fig. 9–14 when present and detectable.*

P14, l3-5. Why thermokarst would be controlled by the glacier size? Maybe there is no thermokarst because of the steep slope?

Answer: *Glacier size increase the area and volume of materials (debris and even more ice), morphological pattern diversity, and, subsequently the probability of encountering thermokarst. Nevertheless, indeed, the slope may play here a role in the absence of thermokarst. We modified the sentence accordingly.*

1 Pluri-decadal (1955–2014) evolution of glacier–rock glacier 2 transitional landforms in the central Andes of Chile 3 (30–33°S)

4
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10 11 **Abstract**

12 Three glacier–rock glacier transitional landforms in the central Andes of Chile are investigated
13 over the last decades in order to highlight and question the significance of their landscape and
14 flow dynamics. Historical (1955–2000) aerial photos and contemporary (>2000) Geoeye
15 satellite images were used together with common processing operations including imagery
16 orthorectification, digital elevation model generation, and image feature tracking. At each site,
17 the rock glacier morphology area, thermokarst area, elevation changes, and horizontal surface
18 displacements were mapped. The evolution of the landforms over the study period is
19 remarkable, with rapid landscape changes, particularly an expansion of rock glacier
20 morphology areas. Elevation changes were heterogeneous, especially in debris-covered glacier
21 areas with large heaving or lowering up to more than $\pm 1 \text{ m yr}^{-1}$. The use of image feature
22 tracking highlighted spatially coherent flow vector patterns over rock glacier areas and, at two
23 of the three sites, their expansion over the studied period; debris-covered glacier areas are
24 characterized by a lack of movement detection and/or chaotic displacement patterns reflecting
25 thermokarst degradation; mean landform displacement speeds ranged between 0.50 and 1.10 m
26 yr⁻¹ and exhibited a decreasing trend over the studied period. One important highlight of this
27 study is that, especially in persisting cold conditions, rock glaciers can develop upward at the
28 expense of debris-covered glaciers. Two of the studied landforms initially (prior to the study
29 period) developed from an alternation between glacial advances and rock glacier development

1 phases. The other landform is a small debris-covered glacier having evolved into a rock glacier
2 over the last half-century. Based on these results it is proposed that morphological and
3 dynamical interactions between glaciers and permafrost and their resulting hybrid landscapes
4 may enhance the resilience of the mountain cryosphere against climate change.

6 **Key words:**

7 Rock glacier; Debris-covered glacier; Cryosphere landscape evolution; Flow dynamics;
8 Remote Sensing

10 **1 Introduction**

11 Glacier–rock glacier interactions related to Holocene glacier fluctuations (e.g., Haeberli, 2005)
12 and the current evolution of small debris-covered glaciers having survived to the post-Little Ice
13 Age (LIA) warming (e.g., Bosson and Lambiel, 2016) are important issues in high mountain
14 studies. They may provide key insights into the mechanisms of rock glacier development (Dusik
15 et al., 2015) and of cryosphere stability and resilience against climate changes; the latter topic
16 is of societal importance in arid–semiarid mountain areas, where the potential permanence of
17 underground solid water resources subsequent to deglaciation may constitute a non-negligible
18 water resource (e.g., Rangecroft et al., 2013).

19 The most striking geomorphological expression of glacier–rock glacier interactions are large
20 glacier–rock glacier transitional landforms which are assemblages of debris-covered glaciers in
21 their upper part and rock glaciers in their lower part (e.g., Kääb et al., 1997; Krainer and
22 Mostler, 2000; Ribolini, 2007; Monnier et al., 2014; Janke et al., 2015). Here, it is important to
23 recall and highlight the differences between both types of landforms (Nakawo et al., 2000; Kääb
24 and Weber, 2004; Haeberli et al., 2006; Degenhardt, 2009; Benn and Evans, 2010; Berthling,
25 2011; Cogley et al., 2011;). Rock glaciers are perennially-frozen homo- or heterogeneous
26 ice–rock mixtures covered with a continuous and several metres thick ice-free debris layer that
27 thaws every summer (known as the permafrost ‘active layer’); rock glaciers movement is
28 governed by gravity-driven permafrost creep. Debris-covered glaciers are glaciers covered with
29 a thin (no more than several decimetres thick) and generally discontinuous debris layer; debris-
30 covered glaciers movement is governed by gravity-driven ice creep and sometimes basal slip
31 in response to a mass balance gradient; debris-covered glaciers do not require permafrost

1 conditions. Rock glaciers and debris-covered glaciers exhibit distinct morphologies that are of
2 critical importance in the surface energy balance and subsurface heat transfer. On their surface,
3 rock glaciers exhibit “the whole spectrum of forms created by cohesive flows” (Barsch, 1992,
4 p. 176) of “lava-stream-like (...) viscous material” (Haeberli, 1985, p. 92). These features vary
5 for each case and study area; according to our field surveys in the Andes, they can be grouped
6 in three main types: small-scale (<1 m high) ripples or undulations resulting from deformations
7 in the active debris layer moving together with the underlying perennially-frozen core; medium-
8 scale (1–5 m high) ridge-and-furrow assemblages resulting from the compression of the whole
9 ice–debris mixture; and large scale (5–20 m thick and >100 m long) superimposed flow lobes
10 upon which the first two feature types may naturally appear. Hereafter, we will simply refer to
11 these features as ‘cohesive flow-evocative features’. Contrarily, debris-covered glaciers are
12 characterized by a chaotic distribution of features evocating surface instability such as
13 hummocks, collapses, crevasses, meandering furrows, and thermokarst depressions and
14 pounds. As a consequence, on rock glaciers the large- and fine-scale surface topography is
15 rather smooth and convex, whereas on debris-covered glaciers it is rather rough and concave.
16 Another morphological difference is the presence of ice visible from the surface: whereas ice
17 is generally invisible from the surface of rock glaciers, it is frequently exposed on debris-
18 covered glaciers due to the discontinuity of the debris cover or the occurrence of the
19 aforementioned morphological features. Finally, and correlatively, over pluri-annual to pluri-
20 decadal periods the morphology of well-developed rock glaciers is quite stable (beside cases of
21 climate warming-related destabilizations, the geometry of surface features evolves but their
22 overall pattern remains the same) while debris-covered glacier morphology is characterized by
23 instability (surface features rapidly appear and disappear).

24 According to the literature at least three types of glacier–rock glacier interactions can be
25 distinguished:

- 26 (i) The readvance(s) and superimposition/embedding of glaciers or debris-covered
27 glaciers onto/into rock glaciers, with related geomorphological and thermal
28 consequences (Lugon et al., 2004; Haeberli, 2005; Kääb and Kneisel, 2006; Ribolini
29 et al., 2007, 2010; Bodin et al., 2010; Monnier et al., 2011, 2014; Dusik et al., 2015).
30 This is the sensu stricto significance of ‘glacier–rock glacier relationships’
31 (Haeberli, 2005) as defined by what has been called the ‘permafrost school’ in
32 reference to the long-term ‘rock glacier controversy’ (see Berthling, 2011).

1 (ii) The continuous derivation of a rock glacier from a debris-covered glacier by
2 evolution of the surface morphology (see above) together with the conservation and
3 creep of a massive and continuous core of glacier ice (e.g., Potter, 1972; Johnson,
4 1980; Whalley and Martin, 1992; Potter et al., 1998; Humlum, 2000). This process
5 was not initially called a ‘glacier–rock glacier relationship’; this view is indeed held
6 by what has been called the ‘continuum school’ in opposition to the permafrost
7 school (Berthling, 2011). Nevertheless, such phenomenon does belong, literarily, to
8 the domain of glacier–rock glacier interactions.

9 (iii) The transformation of a debris-covered glacier into a rock glacier not only by the
10 evolution of the surface morphology but also by the evolution of the inner structure,
11 i.e., the transformation of the debris-covered continuous ice body into a perennially
12 frozen ice–rock mixture by addition from the surface of debris and periglacial ice
13 and fragmenting of the initial glacier ice core. This has been described as an
14 alternative to the dichotomous debate between the permafrost school and continuum
15 school (Monnier and Kinnard, 2015); such phenomenon has been described as
16 achievable over human life or historical time scale (Schroder et al., 2000; Monnier
17 and Kinnard, 2015; Seppi et al., 2015).

18 In the present study, we aim to provide insights into the aforementioned issue using the variety
19 of glacier–rock glacier transitional landforms encountered in the semiarid Andes of Chile and
20 Argentina. These landforms have shown a particularly rapid evolution over the last decades
21 which allow studying glacier–rock glacier interactions on an historical time scale. Three
22 landforms with distinct morphologies have been chosen in the central Andes of Chile in an
23 attempt to diagnose their geomorphological significance, especially in terms of glacier–rock
24 glacier interactions and cryosphere persistence in the current climatic context. To this purpose,
25 this study makes use of aerial and satellite imagery and remote sensing techniques in order to
26 document the morphological and dynamical evolution of the studied landforms over a pluri-
27 decadal time span.

28 **2 Study sites**

29 We studied three glacier–rock glacier transitional landforms in the central Andes of Chile,
30 respectively named Navarro, Presenteseracae, and Las Tetas (Fig. 1). Navarro and
31 Presenteseracae are located in the Navarro Valley, in the upper Aconcagua River catchment

1 (33° S). Las Tetas is located in the Colorado Valley, in the upper Elqui River catchment (30°
2 S).

3 **2.1 Upper Navarro Valley**

4 The upper Navarro Valley belongs to the Juncal River catchment and Juncal Natural Park,
5 which are part of the upper Aconcagua River catchment, in the Valparaíso Region of Chile
6 (32°53' S, 70°02' W; Fig. 1). In the Juncal River catchment (~1400–6110 m asl), glaciers cover
7 14% of the area (Bown et al., 2008; Ragettli et al., 2012) while active rock glaciers cover almost
8 8% (Monnier and Kinnard, 2015). The climate is a mediterranean mountain climate. Brenning
9 (2005) and Azócar and Brenning (2010) located the 0 °C isotherm of mean annual air
10 temperature (MAAT) close to 3700 m asl and reported precipitations above 3000 m asl as
11 ranging between 700 and 800 mm yr⁻¹. An automatic weather station located at 2800 m asl at
12 the foot of the Juncal glacier, 10 km SW from Navarro Valley, recorded a MAAT of 6.3 °C
13 during the hydrological year 2013–2014. The upper Navarro Valley crosses, from west to east,
14 the Albánico Formation (Upper Cretaceous; andesites, volcanic breccias), the San José
15 Formation (Lower Cretaceous; limestones), and the Lagunilla Formation (Upper Jurassic;
16 sandstones, lutites, gypsum). The glacial footprint is conspicuous through the Navarro Valley:
17 the valley is U-shaped, with corries in the upper parts and latero-frontal moraines in the lower
18 parts (Figs. 2 and 3).

19 **2.1.1 Navarro**

20 Navarro fills the major part of the upper Navarro Valley floor between ~3950 and 3450 m asl
21 (Fig. 3). The landform was described by Janke et al. (2015, p. 117) as a system composed of
22 several classes of debris-covered glaciers and rock glaciers according to their presumed ice
23 content. It is indeed a huge (>2 km long and up to >1 km wide) and complex assemblage with
24 debris-covered glacier morphology in its upper parts and rock glacier morphology in its lower
25 parts. The main presumed flow direction of the landform points towards N170°. At least ten
26 conspicuous and sometimes >15 m high morainic crests are visible at the surface of the
27 landform, some of them being included in the rock glacier morphological unit. At one location
28 (red circle in Fig. 3), the superposition of two series of morainic crests onto a rock glacier lobe
29 suggests that the landform developed from a succession of glacier advances and rock glacier
30 development phases.

1 Navarro is divided between an eastern and a western unit; the two being separated by a central
2 series of aligned morainic crests (Fig. 3). The eastern unit, which is located in the more
3 shadowed north-eastern part of Navarro Valley, is ~1.2 km long, and about two-thirds of its
4 area exhibits a rock glacier morphology. The terminal part exhibits three adjacent terminal
5 lobes. The western unit is ~2.4 km long and more complex. Sets of embedded morainic crests
6 in the upper part delimit the retreat of a former glacier. The median part (~1 km long) is peculiar,
7 with the boundary between the debris-covered and rock glacier morphology extending far
8 downslope and following the contour of an elongated central depression (10–15 m lower in
9 altitude than the lateral margins) (Figs. 3 and 4). This central depression is characterized by
10 numerous large (up to 50 m of diameter) thermokarst depressions with bare ice exposures,
11 generally on their south-facing walls. The lower part of the western unit exhibits a rock glacier
12 morphology and three superimposed fronts close to the terminus, the slope of the lowest front
13 being gentler than that of the two upper fronts, which are almost at the same location.

14 Monnier and Kinnard (2015) provided an empirical model of permafrost probability based on
15 logistical regression for the upper Aconcagua River catchment. According to this model,
16 Navarro may be in a permafrost state. The permafrost probability is close to 1 in the upper parts,
17 nevertheless there is a marked decreasing gradient in permafrost probability from 0.9 to 0.7
18 between the central part and the terminus of the western unit (Fig. 3).

19 2.1.2 Presenteseracae

20 Presenteseracae is a small (~600 m long and 300 m wide) debris-covered glacier located
21 between ~4080 and 3800 m asl, in a narrow, SW-facing cirque, ~300 m above and only 500 m
22 east of Navarro (Fig. 3). The main presumed flow direction points towards N225°. This
23 landform has been thoroughly analysed by Monnier and Kinnard (2015). The debris-covered
24 glacier exhibits rock glacier features in its lower part (Figs. 3, 4, and 7). The transverse and
25 curved ridges (<1.5 m high) and well-defined steep front (~10 m high) have appeared during
26 the last 15 years. The permafrost model of Monnier and Kinnard (2015) gave a permafrost
27 probability of 1 for the whole Presenteseracae landform. The authors also correlated the
28 development of the cohesive flow-evocative rock glacier morphology with the low estimated
29 sub-debris ice ablation rates, and demonstrated that the sediment store on Presenteseracae and
30 the potential formation times are in agreement with common rock wall retreat rates. They
31 concluded that Presenteseracae is a debris-covered glacier currently evolving into a rock
32 glacier. In the upper part of the landform, the debris cover is very thin (a few cm) and bare ice

1 exposures are frequent. The debris cover thickens to more than 60 cm in the lower part, where
2 the rock glacier morphology develops below a steeper sloping segment. Push moraine ridges
3 (Benn and Evans, 2010) occur at the surface above 3780 m asl (Fig. 3). The lower part which
4 displays a rock glacier morphology is clearly composed of two adjacent lobes, dividing away
5 from a morainic crest overridden by the landform (Fig. 4). Depressed meandering furrows
6 where buried ice is exposed are also present (Fig. 3). During hot summer days, the water flowing
7 in the northernmost furrow sinks down a hole just before the front.

8 **2.2 Las Tetas**

9 Las Tetas is located in the Colorado Valley, which is the uppermost part of the Elqui River
10 valley, in the Norte Chico Region of Chile (30°10' S, 69°55' W; Fig. 1). Elevations in the
11 Colorado valley range between ~3100 m asl and 6255 m asl. The landform is located on the
12 south-facing side of Cerro Las Tetas (5296 m asl), less than one km south of Glacier Tapado
13 (e.g., Ginot et al., 2006; Pourrier et al., 2014). The climate of the area is a semiarid mountain
14 climate. At the La Laguna artificial dam (~3100 m asl, 10 km west of the study site), the mean
15 annual precipitation was 167 mm during the 1970–2009 period, and the MAAT was 8 °C during
16 the 1974–2011 period. The 0 °C-isotherm is located near 4000 m asl (Brenning, 2005; Ginot et
17 al., 2006). Materials composing the rock basement belong to the Pastos Blancos Formation
18 (Upper Palaeozoic; andesitic to rhyolitic volcanic rocks). A set of embedded latero-frontal
19 moraines is encountered ~700 m downslope from the front of Las Tetas, between ~4170 and
20 4060 m asl.

21 Las Tetas is a ~1 km long landform located between 4675 and 4365 m asl (Fig. 5). The main
22 presumed flow direction points towards N140°. The boundary between debris-covered and rock
23 glacier morphology is clear, in the form of a large and deep furrow, and divides the landform
24 in two approximately equal units. The upper unit is characterized by a chaotic and hummocky
25 morphology, and vast (up to more than 50 m of diameter) and deep (up to 20 m) thermokarst
26 depressions exposing bare ice generally along their south-facing walls. The lower part of the
27 landform exhibits tension cracks superimposed onto the ridge-and-furrow pattern. The front of
28 Las Tetas is prominent; including the talus slope at the bottom, which may bury sediments or
29 outcrops downward, it is almost 100 m high (Figs. 4 and 5). According to the logistic
30 regression-based empirical permafrost model proposed by Azócar (2013) for the area, the 0.75
31 probability level crosses the landform in its central part (Fig. 5). Permafrost favourability index

1 (PFI) values proposed by Azócar et al. (2016a and b) are >0.7 in the upper part and between
2 0.6 and 0.7 in the lower part.

3 **3 Material and methods**

4 **3.1 Satellite image and aerial photo processing**

5 We acquired historical (prior to 2000) aerial photos and contemporary (after 2000) satellite
6 images for the three study sites. Stereo pairs of aerial photos were inspected, selected, and
7 scanned at the Geographic and Military Institute (IGM) of Chile. Scanning was configured in
8 order to yield a ground resolution of 1 m. At Las Tetas, photos from 1978 and 2000 were
9 selected; at Navarro and Presenteseracae, photos from 1955 and 2000 were selected. A stereo
10 pair of Geoeye satellite images was also acquired for each site. The Geoeye imagery was
11 acquired on 23 March 2012 and 14 February 2014 at Las Tetas and Navarro Valley,
12 respectively, as panchromatic image stereo pairs (0.5 m of resolution) along with four bands in
13 the near-infrared, red, green, and blue spectra (2 m of resolution).

14 Orthoimages, orthophotos, and altimetric information were generated from the data. The first
15 step involved building a digital elevation model (DEM) from the stereo pair of Geoeye satellite
16 images. The Geoeye images were triangulated using a Rational Polynomial Camera (RPC)
17 model supplied by the data provider. The exterior orientation was constrained using one or two
18 (according to the site) ground control points (GCPs) acquired with a differential GPS system in
19 the field in 2014 over bedrock outcrops visible on the images. Sets of three-dimensional (3D)
20 points were extracted automatically using standard procedures of digital photogrammetry
21 (Kääb, 2005) and edited manually to remove blunders. A 2×2 m DEM was generated using
22 triangular irregular network interpolation of the 3D points. The same processing scheme was
23 followed for the aerial photo stereo pairs using control points visible both on the Geoeye image
24 and the aerial photo stereo pairs. The vertical bias of the aerial photo DEMs was calculated by
25 comparison with the Geoeye DEMs over flat and stable areas outside the landform studied and
26 was removed from the subsequent calculations (see below). The automatic and manual
27 extraction of 3D points from aerial photo stereo pairs proved to be challenging in steep areas
28 with unfavourable viewing geometry. The process failed for the 1955 stereo pair of Navarro
29 Valley, with only a very sparse set of 3D points extracted and including possible blunders,
30 ruling out the possibility to generate a reliable and complete DEM and to estimate the vertical
31 bias.

1 The Geoeye images were pansharpned and orthorectified using the Geoeye DEM. The aerial
2 photos were then orthorectified using the corresponding DEMs, except when no reliable DEM
3 could be obtained (as for 1955 at Navarro); in that case, the Geoeye DEM was used. The
4 orthorectification was constrained by the internal camera information, tie points, and GCPs
5 extracted during the process. The accuracy of the orthorectification was estimated using the
6 GCPs. The root mean square error (RMSE) corresponding to the sets of GCPs at the different
7 times is displayed in Table 1. The ground resolution of the orthophotos was then resampled at
8 0.5 m in order to equal that of the Geoeye products.

9 The altimetric information was used to calculate the elevation changes of the landforms
10 between the different dates, after removal of the vertical bias. The total elevation change was
11 further converted in annual rates of elevation change. As outlined by Lambiel and Delaloye
12 (2004), elevation changes at the surface of rock glaciers may be explained by several and
13 possibly concomitant factors: (i) downslope movement of the landform and advection of local
14 topographic features, (ii) extensive or compressive flow, and (iii) melting or aggradation of
15 internal ice. Therefore, it is difficult to unambiguously interpret elevation changes. Studying
16 the Muragl rock glacier (Swiss Alps), Kääb and Vollmer (2000) highlighted how mass
17 advection caused subtle elevation changes (between -0.20 and $+0.20$ m yr⁻¹), while surface
18 lowering of up to -0.50 m yr⁻¹ was considered as indicative of massive losses of ice.
19 Accordingly, taking into account the range of values measured and the uncertainty (or detection
20 threshold) on the measurements (see Table 2), we used an absolute value of 0.50 m yr⁻¹ to
21 generally discriminate between ‘moderate’ and ‘large’ vertical changes. The former were
22 considered to relate primarily to the downslope expansion of the landform (including long
23 profile adaptation and advection of topographic features) and, thus, to extensive flow; in the
24 case of the latter, additional ice melting or material bulging by compression were considered
25 necessary in the interpretation.

26 **3.2 Image interpretation**

27 The geomorphology of each landform was carefully interpreted from the orthoimages and
28 orthophotos. First, we located and mapped the boundary between debris-covered and rock
29 glacier morphology, according to the detailed criteria of differentiation presented in the
30 Introduction. The thermokarst area was also monitored over time by mapping the thermokarst
31 depressions at the surface of the landforms as polygonal shapes, and their total area was

1 calculated. Salient and recently appeared features such as cohesive flow-evocative ridges on
2 Presenteseracae and cracks on Las Tetas were also mapped.

3 **3.3 Image feature tracking**

4 We used image feature tracking in order to measure horizontal displacements at the surface of
5 the landforms. Computer-programmed image feature tracking is a sub-pixel precision
6 photogrammetric technique that has been widely used for studying the kinematics of glaciers,
7 rock glaciers, and other mass movements. We followed the principles and guidelines provided
8 by Kääb and Vollmer (2000), Kääb (2005), Wangenstein et al. (2006), Debella-Gilo and Kääb
9 (2011), and Heid and Kääb (2012). We used ImGRAFT, which is an open source image feature
10 tracking toolbox for MATLAB (Messerli and Grinsted, 2015) using two orthoimages (from
11 spaceborne, airborne, or terrestrial sensors) of the same area and resolution but at different
12 times. All the orthoimages were pre-processed in order to enhance their contrast. Two template
13 matching methods were tested: normalized cross-correlation (NCC) and orientation correlation
14 (OC). The NCC method was found to yield more consistent results at the different sites and was
15 thus used for this study. NCC gives an estimate of the similarity of image intensity values
16 between matching entities in the orthoimage at time 1 (I_1) and their corresponding entities in
17 the orthoimage at time 2 (I_2). In I_1 , a ‘search template’ is defined around each pixel located
18 manually or automatically inside a regular grid; the algorithm extracts this search template from
19 I_1 and searches for it in I_2 within the area of a predefined search window (see, e.g., Fig. 2 in
20 Debella-Gilo and Kääb, 2011, p. 132); the algorithm then computes the NCC coefficient
21 between the search template in I_1 and that in I_2 and moves the search template until the entire
22 search window is covered. The location that yields the highest correlation coefficient within the
23 search window is considered as the likely best match for the original location in I_1 . The size of
24 the search template and search window were first defined based on image quality and the time
25 period considered; larger template and search windows were used for long periods, as only
26 larger scale morphological features were expected to be preserved over periods of several
27 decades. The final choice of template and search window size was then set after several
28 iterations of the algorithm (see Table 3). The NCC algorithm was performed over the whole
29 area of the landforms using a 10 m-spacing grid. Snow-covered areas were delineated on each
30 image and excluded from the analysis, leaving an additional buffer of 10 m around the snow
31 masks.

1 Results from feature tracking generally need to be filtered, especially when dealing with old
2 orthophotos (Wangensteen et al., 2006). In this study, the following filtering procedure was
3 followed: (1) We excluded displacements smaller than the orthorectification error (RMSE,
4 Table 1). (2) We excluded displacements exhibiting a signal-to-noise ratio (SNR) < 2 (as
5 recommended by Messerli and Grinsted, 2015); SNR is the ratio between the maximum NCC
6 coefficient and the average of the NCC coefficient's absolute values in the search window, and
7 can be used as an indicator of the 'noise' in the results. (3) A directional filter was applied in
8 order to eliminate vectors diverging excessively from one another, based on Heid and Kääh
9 (2012). For that purpose, the mean displacements in the X (\overline{du}) and Y (\overline{dv}) directions were
10 calculated in a 5 × 5 m running window centred on each displacement vector. The displacement
11 vector was excluded if its du and dv component exceeded \overline{du} and \overline{dv} , respectively, by more
12 than 4 × the RMSE presented in Table 1. This last filtering step allowed to exclude chaotic
13 vectors with potential blunders not removed by the first two filtering criteria, and to highlight
14 areas with spatially coherent movement. Finally, the total displacements were converted to
15 annual displacement rates and mapped.

16 Whereas all vectors obtained after filtering were mapped (see Results and related figures), the
17 final displacement statistics were calculated after removing upslope-pointing vectors (vectors
18 deviating from more than $\pm 45^\circ$ from the landform longitudinal axis) (Table 4). These may
19 include some remaining blunders, but may also results from thermokarst degradation on debris-
20 covered ice, as discussed later. As displacements statistics aimed at quantifying mean
21 downslope movement rates, these vectors were hence excluded from the calculation.
22 Furthermore, for each landform, the mean annual displacement rate was re-calculated only over
23 areas where movements was detected both during the historical (1955–2000 for Navarro valley
24 and 1978–2000 for Las Tetas) and recent (after 2000) periods, in order to remove the spatial
25 sampling bias (see Table 4). For this purpose, all the points present in a 20-m radius of each
26 other's from one period to another were retained to estimate a mean displacement rate over a
27 common area.

28 **4 Results and interpretations**

29 **4.1 General performance of and insights provided by the methods**

30 The methods used in this study first allowed to obtain series of images depicting at first sight
31 conspicuous landscape evolutions: Figs. 6, 7, and 8 show the orthophotos and orthoimages

1 obtained at each site together with the delineated boundary between debris-covered and rock
2 glacier morphology areas and the front slope base at each time. These figures highlight how the
3 landforms' landscape has changed over both historical (before 2000) and contemporary (after
4 2000) periods. Thermokarst areas could be easily mapped and calculated, except in 2000 at Las
5 Tetas.

6 Reliable DEMs and related maps of elevation changes were obtained for the 2000–2014 period
7 at Navarro (Fig. 10) and Presenteseracae (Fig. 12), and for both the 1978–2000 and 2000–2012
8 periods at Las Tetas (Fig. 13 and 14, respectively). However, and as mentioned in the Method
9 section, no reliable and complete DEM could be obtained for the Navarro valley in 1955, which
10 explained the lack of elevation change measurements at Navarro and Presenteseracae.

11 The efficiency of the image feature tracking method varied according to the sites and periods
12 but, on the whole, provided valuable information (Figs. 9–14 and Table 4). Filtering led to keep
13 between 12 and 38% of the measured horizontal displacements according to the site and period
14 (Table 4). The order of magnitude of the mean horizontal displacements is 0.50–1 m yr⁻¹.
15 Horizontal displacements were consistently detected in rock glacier areas, and much less in
16 debris-covered glacier areas; Figs. 9–14 highlight spatially coherent flow vector patterns in the
17 former while the latter are characterized by either a lack of movement detection and/or spatially
18 chaotic patterns. This is consistent with the fact that the surface morphology of rock glaciers is
19 more stable and preserved for longer times than the one of debris-covered glaciers, which is
20 rather unstable and disrupt rapidly. Upslope-pointing vectors were kept in the figures in order
21 to show that they frequently occur in sectors with thermokarst morphology where mass wasting
22 processes are likely to occur. Finally, one will note that the most graphically striking results are
23 obtained over the largest landform, i.e., Navarro (Figs. 9 and 10).

24 The interpretation of the main geomorphological evolution, elevation changes, and horizontal
25 displacement patterns is summarized for each individual landform in Tables 5a, 5b, and 5c,
26 respectively, and the results discussed jointly in the following section.

27 **5 Discussion**

28 The three cases studied have distinct significance in terms of glacier–rock glacier relationships
29 and cryosphere persistence under ongoing climate change. Our results lead us to consider the
30 following issues: (i) initial development of the landforms; (ii) differences between debris-
31 covered and rock glacier areas; and (iii) current and future evolution of the landforms.

5.1 Initial landform development

Navarro and Las Tetas are composite landforms with a debris-covered glacier in their upper part and a rock glacier in their lower part. Considering the clear spatial organisations of surface features and the strong morphological boundaries, in particular the way the debris-covered glacier embeds into the rock glacier in the Navarro's western unit (Fig. 3) and the abrupt transition at Las Tetas (Fig. 5), these landforms most probably result from the (re)advance(s) of glaciers onto, or in the back of pre-existing rock glaciers. Many other examples of such development of glacier–rock glacier assemblages were studied and reported in the literature (Lugon et al., 2004; Haeberli, 2005; Kääb and Kneisel, 2006; Ribolini et al., 2007, 2010; Bodin et al., 2010; Monnier et al., 2011, 2014; Dusik et al., 2015). In the central part of the Navarro's western unit, the elevated lateral margins exhibit cohesive flow-evocative ridges, which probably resulted from the lateral compression exerted by the glacier during its advance ('composite ridges' of the glaciological terminology; Benn and Evans, 2010, p. 492). Also, the boundary between the debris-covered and rock glacier morphologies in 1955 (Fig. 6) gives a minimum indication of the lowest advance of the debris-covered glaciers onto the rock glaciers. However, the origin and age of the rock glaciers located in the lower part of the landforms are almost impossible to assess. Nonetheless, considering the context, they may have developed following several glacier advances and moraine deposition phases, suggesting the idea of a cycle in the landform development (see Study site and the red circle in Fig. 3). Such development has led the rock glacier being cut off from the main rock debris sources (i.e., the rock walls up-valley), resulting in the rock glacier being dependent on the ability of the debris-covered glacier to provide material (debris and ice) required for the sustainment of the rock glacier.

Presenteseracae is a completely distinct case. As studied by Monnier and Kinnard (2015) and the present work, in 1955 Presenteseracae was a debris-covered glacier and is now a debris-covered glacier transforming into a rock glacier. The initial development phase, or in this case the 'glacier–rock glacier transformation', has been occurring over the last decades. In less than 20 years, the surface debris cover spread over almost all of the northern part; a front appeared at the terminus, and cohesive-flow evocative ridges appeared in the lower part, perpendicularly to flow vectors (Figs. 7, 11, and 12). The latter ridges may be related to emergent, debris-rich shear planes (Monnier and Kinnard, 2015) bended by the landform movement. Displacement speeds were high ($> 1 \text{ m yr}^{-1}$ on average) between 1955 and 2000, in agreement with the fast

1 landscape evolution, before slowing down after 2000, which may reflect an acceleration of the
2 transition towards a rock glacier. In the current state of our knowledge, what may have occurred
3 in the internal structure in response to these drastic surface changes is uncertain: the continuous
4 glacier core may however evolve into patches of buried ice progressively mixed with ice-mixed
5 debris accumulated onto the surface.

6 **5.2 Differences between debris-covered and rock glacier areas.**

7 Our study basically relied on the landscape differentiation between debris-covered and rock
8 glacier areas. The criteria enounced and discussed in the Introduction section have been used
9 to distinguish and partition the surface morphology of the landforms studied. Our subsequent
10 results show that, at Navarro and Las Tetas, debris-covered and rock glacier areas are
11 characterized by contrasting patterns of horizontal displacements and elevation changes. Flow
12 patterns in rock glacier areas are conspicuous, spatially coherent, and express the cohesive
13 extensive flow of the landform in the direction of the main longitudinal axis. Flow patterns in
14 debris-covered glacier areas are either not detectable or when detected, they are generally more
15 chaotic. This low movement detection rate and chaotic organization of displacement patterns
16 in debris-covered glacier areas can be explained by the inherently less cohesive mass flow and
17 the unstable surface morphology resulting from the ablation of ice under a shallow debris layer.
18 Elevation changes in debris-covered glacier areas have larger amplitudes and are spatially
19 heterogeneous; in rock glacier areas elevation changes are rather moderate and thus expressive
20 of cohesive extensive flow. These different flow dynamics appear perfectly coherent with the
21 definition of, and distinction made between debris-covered and rock glaciers in the Introduction
22 section.

23 **5.3 Current evolution and its significance**

24 **5.3.1 Landscape evolution**

25 All the landforms studied are characterized by a rapid landscape evolution over the last few
26 decades. Changes occurred over the entire surface (Presenteseracae), in the contact/transition
27 area between debris-covered and rock glaciers and in the debris-covered glacier area (Navarro),
28 or even in both areas though more subtly in the rock glacier area (Las Tetas). This continuum
29 in surface evolution perhaps best illustrates the process of glacial–periglacial transition. To our
30 knowledge, an important result of our study not previously reported is the observed upward

1 progression of the rock glacier areas which proceeds at the expense of the debris-covered
2 glaciers on such composite landforms. At Presenteseracae, over a time span of a few decades,
3 the rock glacier morphology has grown from being inexistent, to covering approximately half
4 the landform surface. At Navarro, rock glacier areas have subtly (in the western unit) or
5 considerably (in the eastern unit) expanded, until, in the latter case, covering most parts of the
6 essentially debris-covered glacier morphology present initially. As a first order consideration,
7 topoclimatic conditions seem to play a key role in this differentiated evolution: Presenteseracae
8 and the eastern unit of Navarro are located in more shadowed and thus colder sites (see Figs. 3
9 and 5).

10 5.3.2 Dynamical evolution

11 The dynamical evolution correlates with the landscape evolution, to varying degrees according
12 to the site. As stated in the Introduction, when areas with debris-covered glacier morphology
13 evolve into areas with rock glacier morphology, changes occur in the surface energy balance
14 and subsurface heat transfers, which is likely to result in changes in flow dynamics depending
15 upon the topography and the topoclimatic context. The displacement speed of the three studied
16 landforms has decreased over the study period, at least over the overlapping areas where
17 movement was detected in the different periods (Tables 4, 5a, 5b, and 5c). Whereas in other
18 areas of the world many studies have reported rock glaciers to be accelerating under the current
19 climate warming trend (e.g., Roer et al., 2005 and 2008; Delaloye et al., 2010; Kellerer-
20 Pirklbauer and Kaufmann, 2012), the decreased velocity highlighted in this analysis suggests
21 an increasing stabilisation of the landforms as they evolved from debris-covered glacier bodies
22 to rock glaciers. As the transition from debris-covered to rock glacier seems to be proceeding
23 mainly from the terminus upward, the increasingly debris-rich, lower rock glaciers may exert
24 and increasing buttressing force on the remaining debris-covered glacier upslope, causing a
25 general deceleration of the landform.

26 At Las Tetas however, increasing displacement speeds downslope and the apparition of tension
27 cracks in the lower rock glacier area during the recent (2000--2012) period point towards a
28 possible acceleration or even destabilization of the landform terminus (Figs. 3, 8, and 14). Such
29 evolution may be related to the observed decrease in modelled permafrost probability along the
30 landform area (Fig. 5) and the climate evolution in this region: Rabatel et al. (2011) reported a
31 warming trend of 0.19 °C decade⁻¹ for the 1958–2007 period in the Pascua-Lama area, 80 km
32 north of Las Tetas, and Monnier et al. (2014) also reported a trend of 0.17 °C decade⁻¹ for the

1 [1974–2011 period in the Río Colorado area. Such evolution is reminiscent of reports of](#)
2 [acceleration and destabilization phenomena over rock glaciers in response to air and permafrost](#)
3 [temperature increases \(e.g., Roer et al., 2005, 2008; Delaloye et al., 2010; Kellerer-Pirklbauer](#)
4 [and Kaufmann, 2012\).](#)

5 5.3.3 Final diagnostics and future evolution of the landforms

6 According to the results and interpretations [presented](#) for the Navarro's eastern part and
7 Presenteseracae, rock glaciers can develop at the expense of debris-covered glaciers, by an
8 upward progression of their morphology and correlative widespread development of cohesive
9 mass flow. These are true cases of debris-covered glaciers evolving in rock glaciers (see
10 Introduction: type [iii]). At Presenteseracae, however, the flow does not appear as strikingly
11 cohesive as [for](#) the Navarro's western unit, possibly due to the smaller size of the landform as
12 well as a steeper slope that may [constitute a limiting dynamical parameter \(Monnier and](#)
13 [Kinnard, 2015\)](#). As these two landforms are located in favourable topoclimatic conditions, they
14 should thus pursue their evolution towards rock glaciers. Despite the important insights
15 [presented](#) by our study, it must be stressed out that the evolution of the internal structure in
16 response to morphological and dynamical [changes](#) at the surface remains unknown; it would
17 require decades of borehole and geophysical survey monitoring to properly assess this.
18 However, the transition may proceed by fragmentation of the glacier ice core and its mixing
19 with debris and other types of ice (interstitial, intrusive) entrained from the surface. This is an
20 alternative to the common and controverted model of the glacier ice-cored rock glacier where
21 the evolution of the landform is controlled by the expansion and creep of a massive and
22 continuous core of glacier ice (e.g., Potter, 1972; Whalley and Martin, 1992; Potter et al., 1998).

23 The Navarro's western unit and Las Tetas are more commonly known cases of assemblages
24 that have formed and evolved in reaction to the superimposition/embedding of glaciers onto or
25 in the back of rock glaciers and their subsequent dynamical interactions (see Introduction: type
26 [i]). In both cases, the progression of the rock glacier at the expense of the debris-covered
27 glacier is rather limited (Navarro's western unit) or null (Las Tetas). It is [here](#) difficult to assert
28 whether the debris-covered glaciers are 'pushing away' the rock glaciers or if the latter are
29 'pulling' the former; both processes probably occur [\(see also Section 5.3.2.\)](#). The dynamical
30 links between both units certainly constitutes a complex issue deserving more attention.
31 Furthermore, as these whole landforms continue to advance, the rock glaciers could plausibly
32 become entirely isolated from their main debris source in the upper cirques while the

1 increasingly warming conditions could cause the debris-covered glacier to become stagnant or
2 disappear. Also, as the rock glaciers penetrate in areas with less favourable topoclimatic
3 conditions, their future sustainment can be questioned.

4 **6 Conclusion**

5 We have used remote sensing techniques including imagery orthorectification, DEM
6 comparisons, and image feature tracking, in order to depict and measure the geomorphological
7 evolution, elevation changes, and horizontal displacements of three glacier–rock glacier
8 transitional landforms in the central Andes of Chile over a human life-time scale. Our study
9 highlights how, as climate changes and mountain landscapes and their related dynamics shift,
10 the glacial and periglacial realms can strongly interact. The pluri-decadal landscape evolution
11 at the three studied sites is noticeable: rock glacier morphology areas expanded, as well as the
12 movement detection area in image feature tracking; thermokarst reduced; elevation changes
13 tended to become more homogenous; the mean horizontal displacement decreased and spatially
14 coherent flow patterns enhanced. These overall results point toward the geomorphological and
15 dynamical expansion of rock glaciers. However, the modalities and significance vary between
16 sites. Navarro and Las Tetas are composite landforms resulting from the alternation between
17 glacier (re)advance and rock glacier development phases; they currently exhibit an upward
18 progression of the rock glacier morphology with associated cohesive mass flow and surface
19 stabilization, or ice loss-related downwasting and surface destabilization features.
20 Presenteseracae is a special case of small debris-covered glacier that has evolved into a rock
21 glacier during the last decades, with the rock glacier morphology having mostly developed ~15
22 years ago. Topoclimatic conditions appear to have been determinants in the landforms’
23 evolution and, by extrapolation, could thus be expected to exert an important control on the
24 development and conservation of underground ice in high mountain catchments. From the latter
25 point of view, our study stresses how spatial and dynamical interactions between glaciers and
26 permafrost create composite landforms that may be more perennial than transitory: depending
27 on the frequency of glacial–periglacial cycles, they participate in sustaining a hybrid
28 cryospheric landscape that is potentially more resilient against climate change. This conclusion
29 is of societal importance considering the location of the studied landforms in semiarid areas and
30 the warming and drying climate predicted for the coming decades (Bradley et al., 2006;
31 Fuenzalida et al., 2006).

1 We have furthermore provided new insights into the glacier–rock glacier transformation
2 problem. Most of the common and previous glacier–rock glacier evolution models depicted a
3 ‘continuum’ process based on the preservation of an extensive core of buried glacier ice. On
4 the contrary, our findings rather suggest that the transformation of a debris-covered glacier into
5 a rock glacier may proceed from the upward progression of the rock glacier morphology at the
6 expense of the debris-covered glacier, in association with an expanding cohesive mass flow
7 regime and a probable fragmentation of the debris-covered glacier into an ice–rock mixture
8 with distinct flow lobes. The highlighted importance of topoclimatic conditions and
9 corresponding morphologic evolutions also supports the inclusion of the permafrost criterion
10 within the rock glacier definition.

11

12 **Acknowledgements**

13 This study is part of the Project Fondecyt Regular No. 1130566 entitled: “Glacier-rock glacier
14 transitions in shifting mountain landscapes: peculiar highlights from the central Andes of
15 Chile.” Fondecyt is the National Fund for Research and Technology in Chile. The authors want
16 to thank Arzhan Surazakov who performed the image processing, and Valentin Brunat, who
17 was involved in the software handling and related data management in the framework of a
18 Master Thesis supported by the abovementioned project. The authors also thank Andreas Kääb
19 and one anonymous referee for their important help in improving this manuscript, as well as
20 the Associate Editor for final edition and language corrections.

21

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27 Geography*, 16, 127–186, 1992.
- 28

1 **Table 1.**

2 Errors generated during the aerial photo processing. The ground root mean square error (RMSE) relates
 3 to sets of ground control points (GCPs) extracted from the Geoeye orthoimage and used for the
 4 orthorectification of the aerial photos.

5

Site	Date	Horizontal ground RMSE (m)		Number of GCPs
		<i>x</i>	<i>y</i>	
Las Tetas	1978	1.13	1.16	10
	2000	0.33	0.54	8
Navarro valley	1955	1.82	1.32	13
	2000	0.76	1.49	9

6

7

8 **Table 2.**

9 Uncertainty related to the measurement of annual elevation changes. Reported uncertainties correspond
 10 to one and two-standard deviation (σ) probability of vertical errors for the generated DEMs. In Navarro
 11 valley, no reliable DEM could be generated from the 1955 aerial photos, which explains the absence of
 12 data in the table for the 1955–2000 interval.

13

Site	Period	Vertical uncertainty (m yr ⁻¹)	
		1 σ (66%)	2 σ (95%)
Las Tetas	1978–2000	0.04	0.09
	2000–2012	0.22	0.43
Navarro valley	1955–2000	—	—
	2000–2014	0.05	0.10

14

1 **Table 3.**

2 Sizes of search template and search window used for the image feature tracking.

3

Site	Period	Search template size (pixels)	Search window size (pixels)
Las Tetas	1978–2000	100	250
	2000–2012	150	250
Navarro	1955–2000	300	550
	2000–2014	50	100
Presenteseracae	1955–2000	150	400
	2000–2014	80	180

4

5

6 **Table 4.**

7 Summary statistics of horizontal displacements detected on the landform surfaces (see text for further
 8 details). The mean displacement (\bar{d} , m yr⁻¹) and standard deviation (σ , m yr⁻¹) are presented for the
 9 entire (snow-free) areas where movement was detected, and then only for the overlapping areas where
 10 movement was detected during both periods compared. The later aimed at removing the spatial sampling
 11 bias when comparing movement statistics over time. n refers to the numbers of vectors retained and f to
 12 the corresponding fraction (%) of snow-free areas where movement was detected.

13

Site and period	Whole areas				Overlapping areas only		
	\bar{d}	σ	n	f	\bar{d}	σ	n
Navarro							
1955–2000	0.52	0.30	832	33	0.54	0.34	372
2000–2014	0.52	0.20	970	38	0.51	0.18	310
Presenteseracae							
1955–2000	1.04	0.46	219	15	1.10	0.41	73
2000–2014	0.96	0.47	162	12	0.82	0.40	63
Las Tetas							
1978–2000	0.88	0.35	79	15	0.69	0.21	18
2000–2012	0.86	0.45	163	31	0.65	0.37	30

14

1 **Table 5a.**

2 Summary of corresponding geomorphological evolution, elevation changes, horizontal displacements, and associated interpretations at Navarro for historical
 3 (1955–2000) and contemporary (2000–2014) periods.

4

Geomorphological evolution	Elevation changes	Horizontal displacements	Interpretation
Rock glacier morphology areas have expanded spatially between 1955 and 2014, both upward (eastern unit) or inward from the margin (western unit).	Elevation changes have been more pronounced and heterogeneous in debris-covered glacier morphology areas than in rock glacier morphology areas. In rock glacier areas, their moderate rates express the extensive flow of the landform (Fig. 10).	The area where movement was detected slightly increased (33 to 38%), during 1955–2000 and 2000–2014. The mean displacement speed decreased over snow-free, overlapping areas (Table 4).	The progression of the rock glacier morphology correlates with a decrease in thermokarst areas, an expansion of coherent flow patterns, and a general deceleration of the landform movement. This reflects the expansion of slow, coherent downslope creep with minimal surface disturbance (typical of rock glacier) as the main geomorphic process. In the central depression of the western unit, general downslope movement occurred along with ice losses-related downwasting.
The upward progression of the rock glacier morphology areas has been particularly strong in the eastern unit, especially between 1955 and 2000.	Elevation changes have been moderate in the eastern unit (Fig. 10).	Figs. 9 and 10 highlights conspicuously spatially coherent patterns of flow vectors in the eastern unit, especially between 1955 and 2000.	
In the western unit, the progression has been more limit and occurred inward from the margins, toward the central depression (Figs. 6, 9, and 10).	Very large surface lowering (until more than 1 m yr ⁻¹) and moderate surface heaving alternate in the central depression (Fig. 10).	Many displacement spatially coherent vector patterns head towards the central depression (Figs. 9 and 10).	
Between 1955 and 2000, thermokarst area expanded from 11,950 to 16,520 m ² , before shrinking by a factor of two in less than 15 years (8,560 m ² in 2014).	The most pronounced surface lowering occurs at thermokarst locations (Fig. 10).	At thermokarst locations, displacement vectors are grouped in poorly organized, chaotic patterns, frequently pointing upward (Figs. 9 and 10).	

5

1 **Table 5b.**

2 Summary of corresponding geomorphological evolution, elevation changes, horizontal displacements, and associated interpretations at Presenteseracae for
 3 historical (1955–2000) and contemporary (2000–2014) periods.

4

Geomorphological evolution	Elevation changes	Horizontal displacements	Interpretation
<p>The geomorphological evolution at the surface has been very fast, with the apparition of a rock glacier morphology in the lower half of the landform since 2000, in agreement with the description and analysis given by Monnier and Kinnard (2015) (Figs. 7, 11, and 12).</p>	<p>Elevation changes have been spatially very heterogeneous for such a small-size landform between 2000 and 2014. Nevertheless, the major part of the surface exhibits moderate elevation changes, which is seen as the expression of the extensive flow of the landform (Figs. 12).</p>	<p>The area where movement was detected slightly decreased (15 to 12%) during 1955–2000 and 2000–2014, while the mean displacement speed decreased over snow-free, overlapping areas (Table 4). Horizontal flow vectors patterns are spatially more coherent in the lower than in the upper half of the landform (Figs. 11 and 12).</p>	<p>The geomorphological development, the distribution of flow vector patterns, and the deceleration of the landform movement point towards a transition towards rock glacier (Monnier and Kinnard, 2015); however, the decrease of the area where movement was detected does not correlate such interpretation. The absence of thermokarst at the surface of the landform for both periods studied may be explained by the small landform size, the cold conditions casted by the cirque topography (permafrost probability defined by the model in Fig. 3 is 1), the cirque floor slope, and/or even by the glacier–rock glacier transition phenomenon.</p>
<p>New morphological surface features, in the form of cohesive, flow-evocative downward (SE) convexly-bended ridges, appeared in the lower-northern part of the landform (Figs. 3 and 7).</p>	<p>Elevation changes between 2000 and 2014 were generally moderate in the lower-northern part of the landform. Large surface heaving nevertheless occurred at the front of the landform. (Figs. 12).</p>	<p>Horizontal displacement vectors in the lower part head towards SE (Figs. 11 and 12).</p>	
<p>No thermokarst.</p>			

5

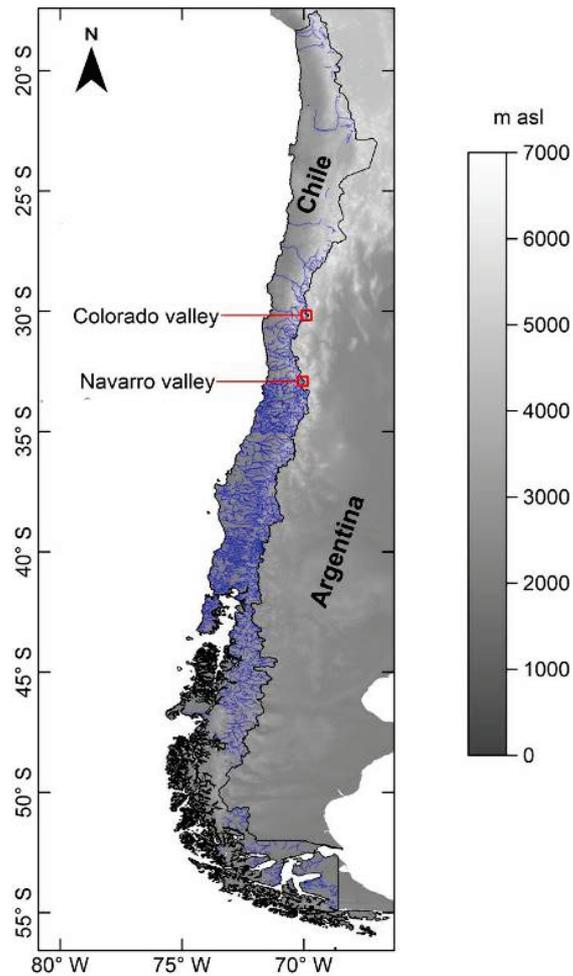
1 **Table 5c.**

2 Summary of corresponding geomorphological evolution, elevation changes, horizontal displacements, and associated interpretations at Las Tetas for historical
 3 (1978–2000) and contemporary (2000–2012) periods.

4

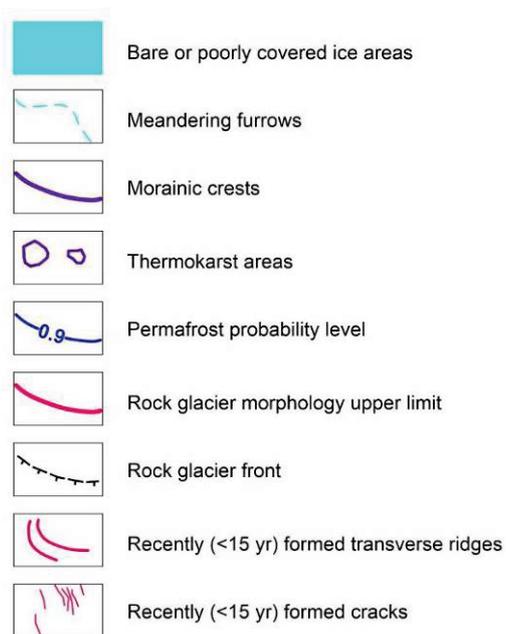
Geomorphological evolution	Elevation changes	Horizontal displacements	Interpretation
<p>The boundary between debris-covered and rock glacier morphology area has followed the overall displacement of the landform (Figs. 8, 13, and 14).</p>	<p>On the whole, elevation changes tended to decrease and be more spatially-homogeneous from 1978 and 2000 to 2000 and 2012, with moderate rates expressing the extensive flow of the landform, especially in the lower rock glacier part (Figs. 13 and 14).</p>	<p>The area where movement was detected has strongly increased (15 to 31%) between 1955–2000 and 2000–2014. The mean displacement speed decreased slightly (Table 4). However, between 2000 and 2012, the lower rock glacier part has displaced faster than the upper debris-covered glacier part (Fig. 14).</p>	<p>The decrease of thermokarst areas, the strong increase of movement detection areas, the apparition of coherent flow vectors patterns, and the deceleration of the whole landform support the idea that the rock glacier continues to develop. The higher displacement speed and the tension cracks in the lower rock glacier area nevertheless point towards an acceleration or even destabilization of the landform toward its terminus</p>
<p>Tension cracks appeared in the lower part of the landform during the last decades (Fig. 5 and 8).</p>		<p>Whereas the mean displacement speed decreased slightly (Table 4), the lower part may be currently accelerating (Fig. 14).</p>	
<p>Thermokarst is striking by its aspect (depressions occur in the centre of coalescent mounds, reminiscing of impact craters) and its rapid evolution (Fig. 8). Between 1978 and 2012, thermokarst areas decreased twofold, from 23,248 m² in 1978 to 11,099 m² in 2012.</p>	<p>Large surface lowering occurred at the locations of thermokarst mounds and ponds, especially between 2000 and 2012 (Figs. 13 and 14).</p>	<p>Between 1978 and 2000, chaotic displacement patterns, with vectors frequently pointing upward, correlate with the thermokarst locations (Fig. 13). Between 2000 and 2012, very few vectors associated with thermokarst-related mass wasting are detected (Fig. 14).</p>	

5



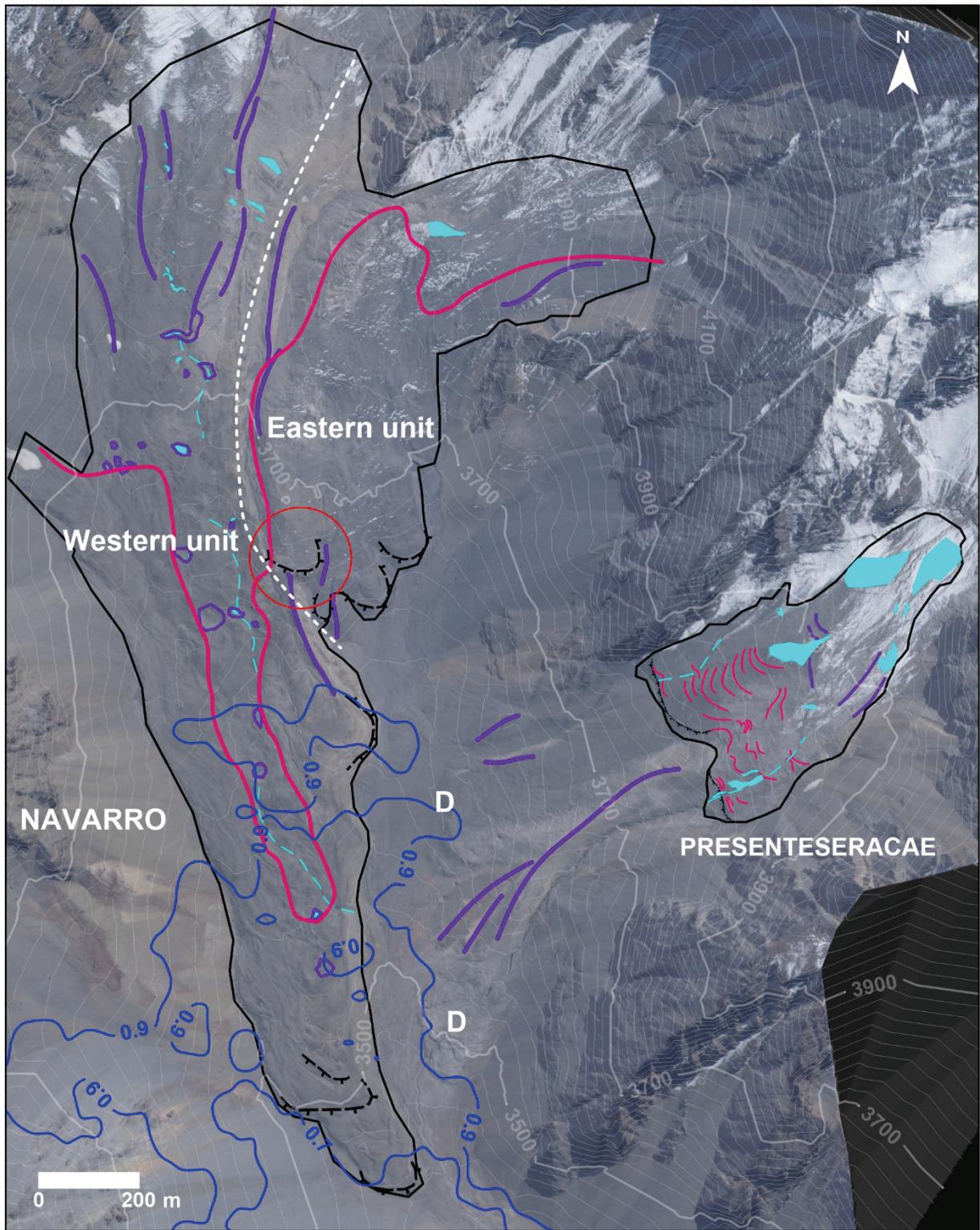
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Figure 1. Location of the study sites. Drainage network, which reflects the variations of climatic–hydrologic conditions along the Chilean territory, is shown in blue.



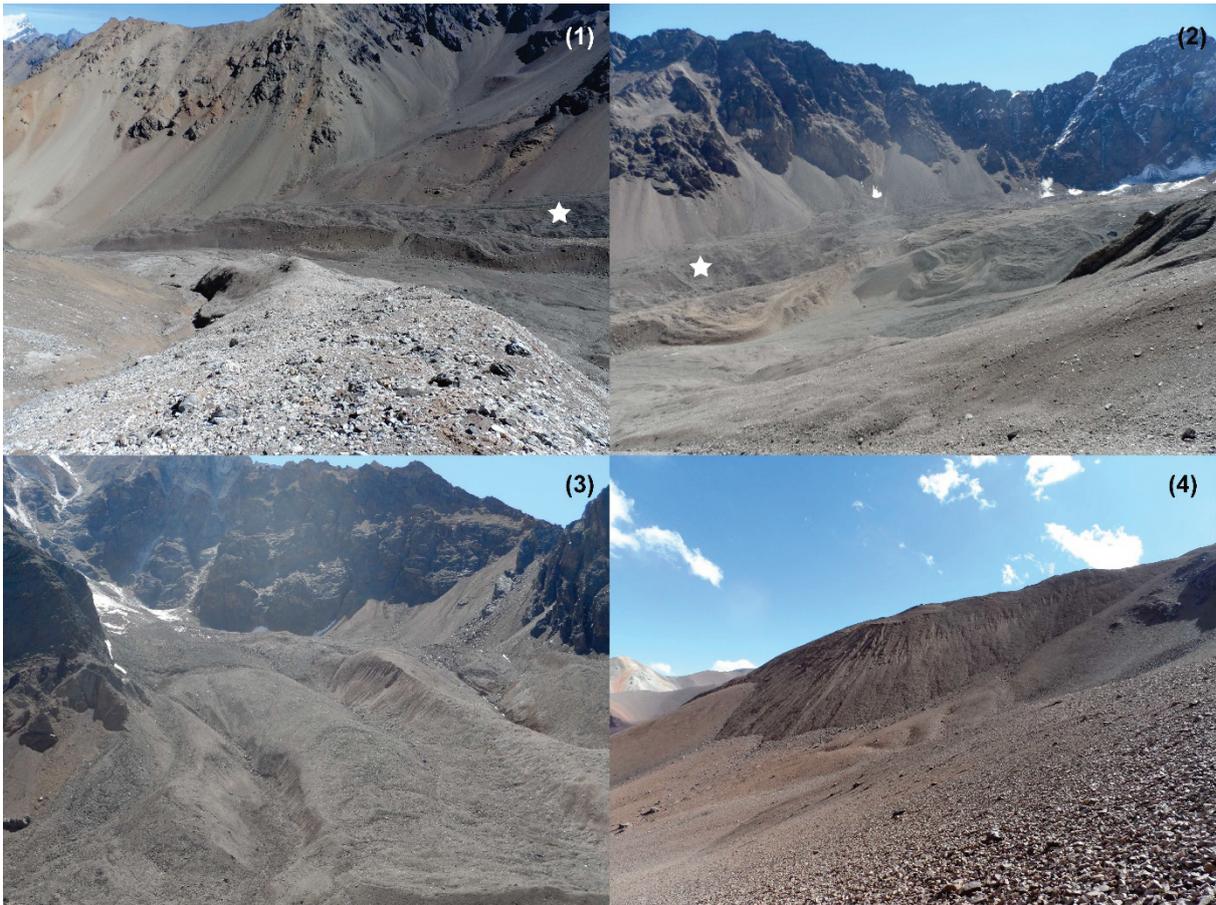
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Figure 2. Geomorphological legend shared for all subsequent figures.

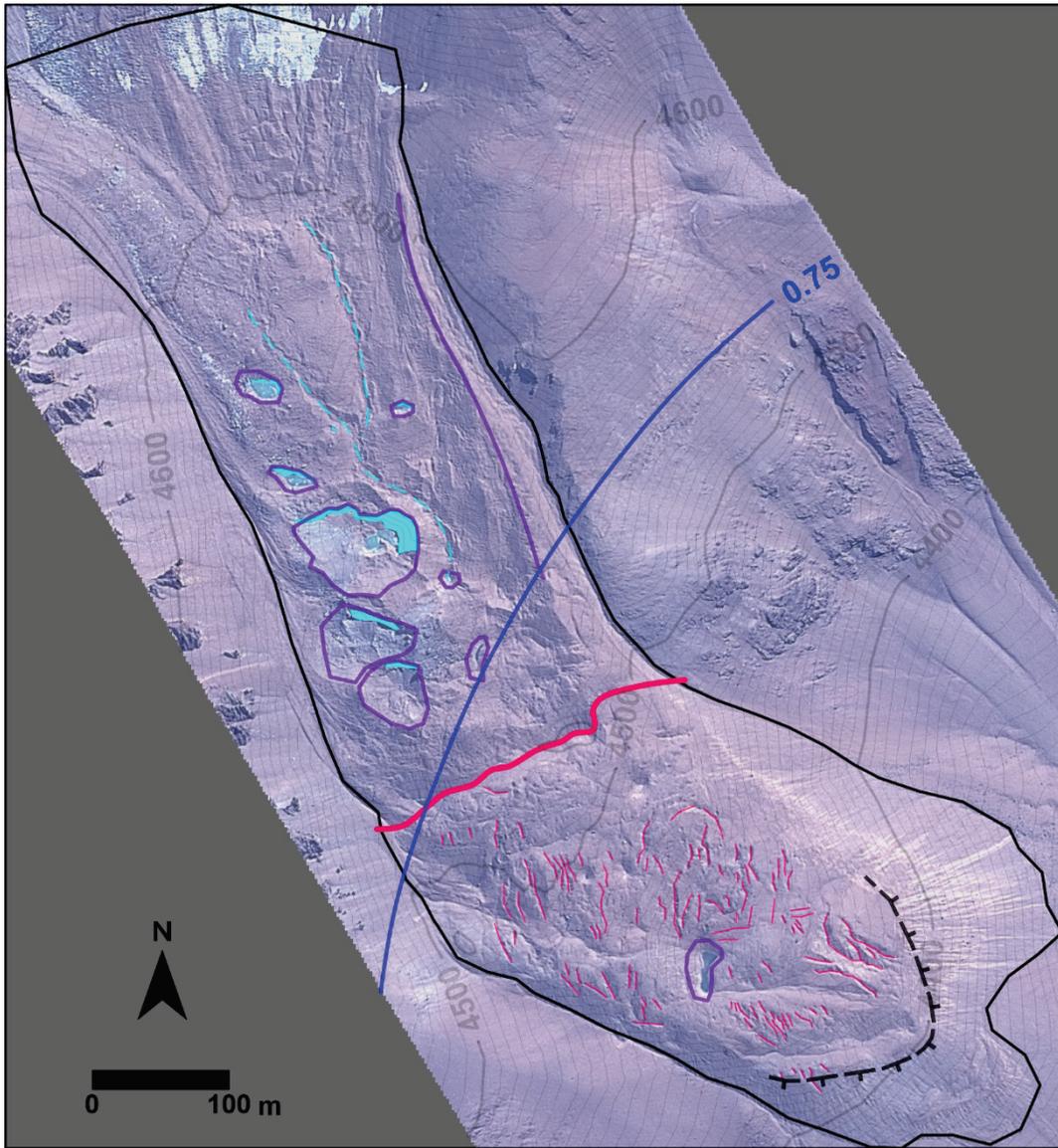


1

2 **Figure 3.** Map of the Navarro Valley. See Fig. 2 for legend. The background of the map is the 2014
 3 Geoeye image draped over the Geoeye DEM (see the Methods section). Elevation contours are derived
 4 from the Geoeye DEM and the contour interval is 20 m. The boundary between the Navarro’s western
 5 and eastern units is indicated with a dashed white line. The red circle indicates the location described in
 6 the text where morainic crests and rock glacier lobes are superimposed. Note also the decayed (D) rock
 7 glacier lobes in the area between Navarro and Presenteseracae.

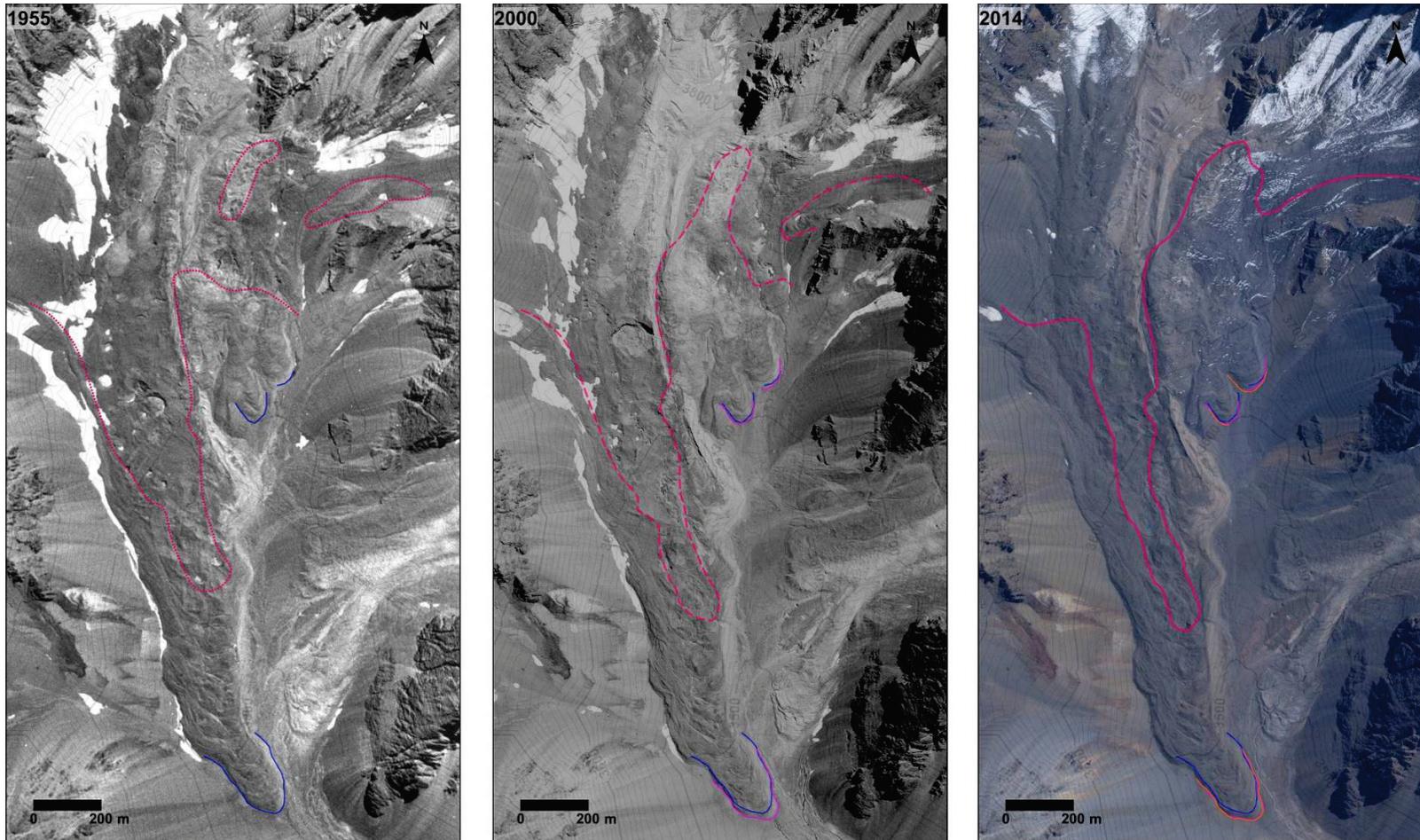


1
2 **Figure 4.** Photos of the lower (1) and upper part (2) of Navarro, seen from Presenteseracae;
3 Presenteseracae seen from Navarro (3), and the terminal part of Las Tetas (4) seen from its northeastern
4 surrounding area. The white stars on photos (1) and (2) indicates the main location of the central
5 depression and related thermokarst morphology on Navarro (see Fig. 3).



1

2 **Figure 5.** Map of the Las Tetas landform. See Fig. 2 for legend. The background of the map is the 2012
3 Geoeye image draped over the Geoeye DEM (see the Methods section).



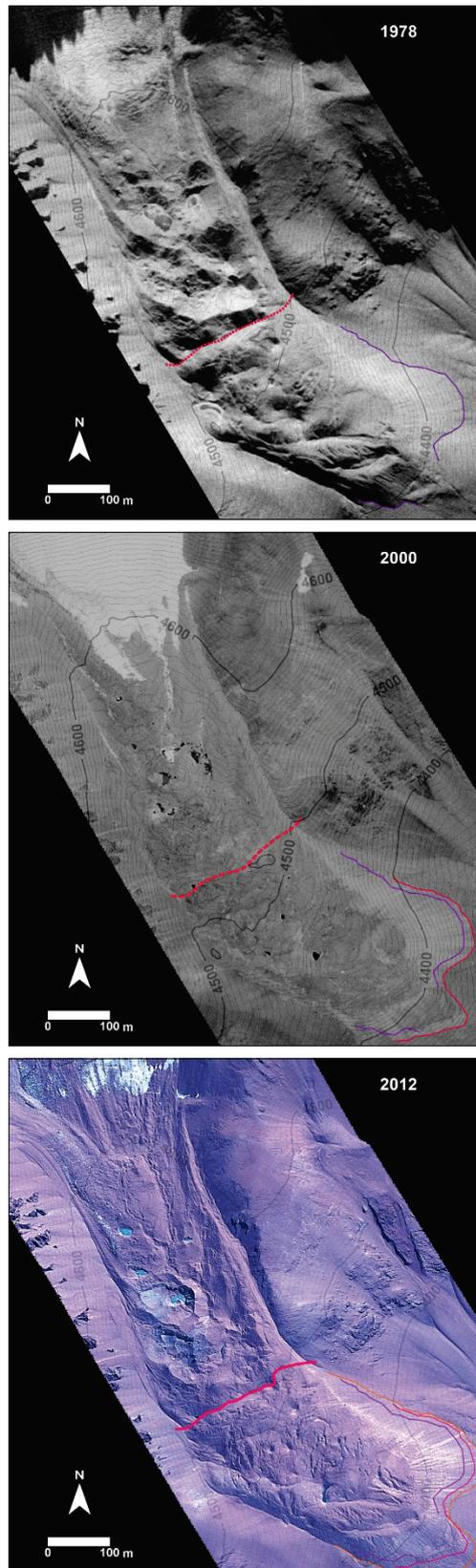
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2 **Figure 6.** Sequence of orthophotos obtained for Navarro. The base of the landform front that could be reliably identified is indicated in color (blue, magenta,
 3 and orange line in 1955, 2000, and 2014, respectively). At each date the boundary between debris-covered and rock glacier morphology is depicted with a red
 4 line (dotted in 1955, dashed in 2000, continuous in 2014).



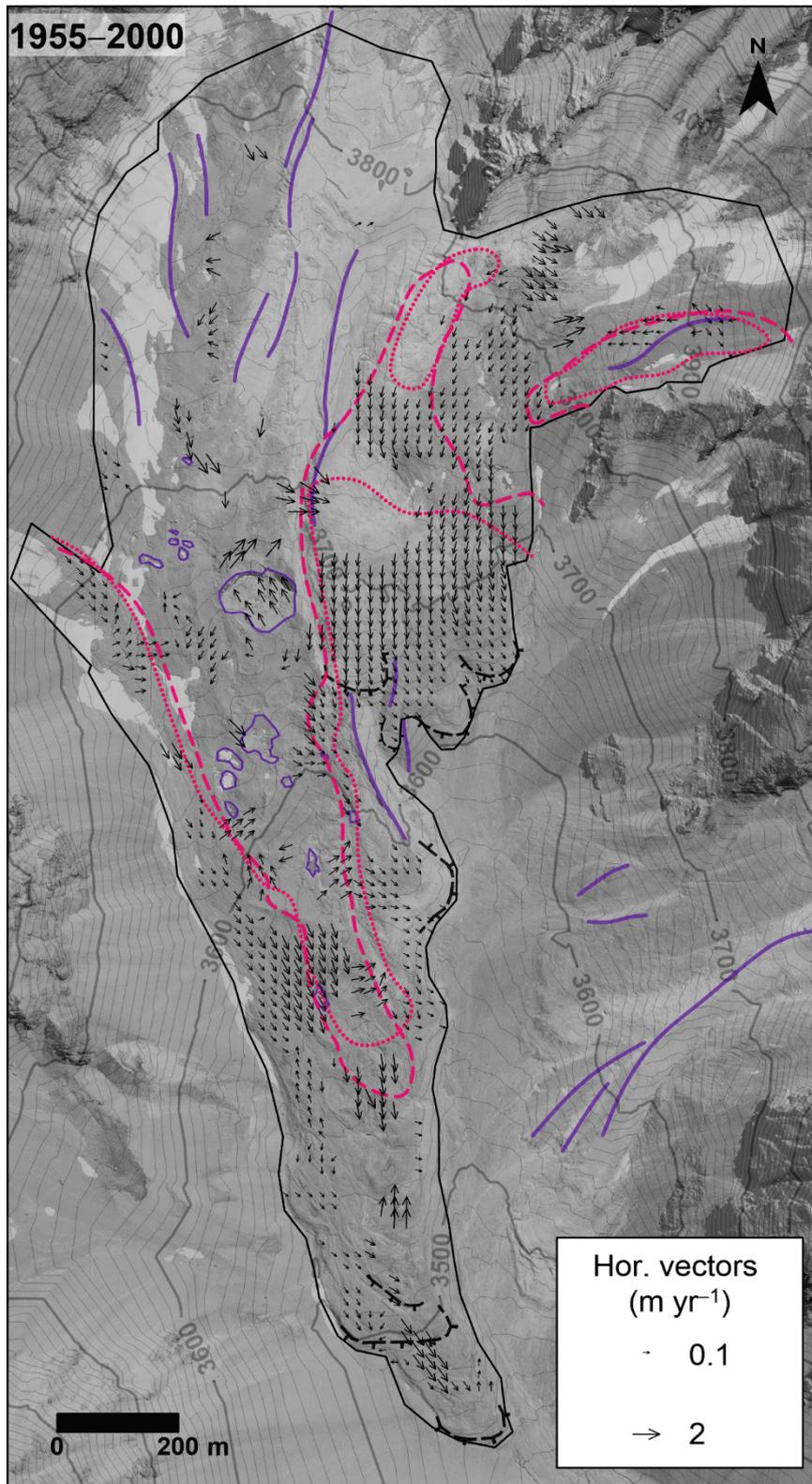
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2 **Figure 7.** Sequence of orthophotos obtained for Presenteseracae. The base of the landform front that
3 could be reliably identified is indicated in color (blue, magenta, and orange line in 1955, 2000, and 2014,
4 respectively). Note how the rock glacier morphology developed since 2000. In the southern part of the
5 landform, it is nevertheless less well defined and more unstable; it is conspicuously cut by a central
6 furrow and exhibits a few areas of bare ice over which debris slumps may occur. In the northern part of
7 the landform, the rock glacier morphology is more developed; there is neither remaining bare ice area
8 nor evidences of debris cover instability and sliding.



1

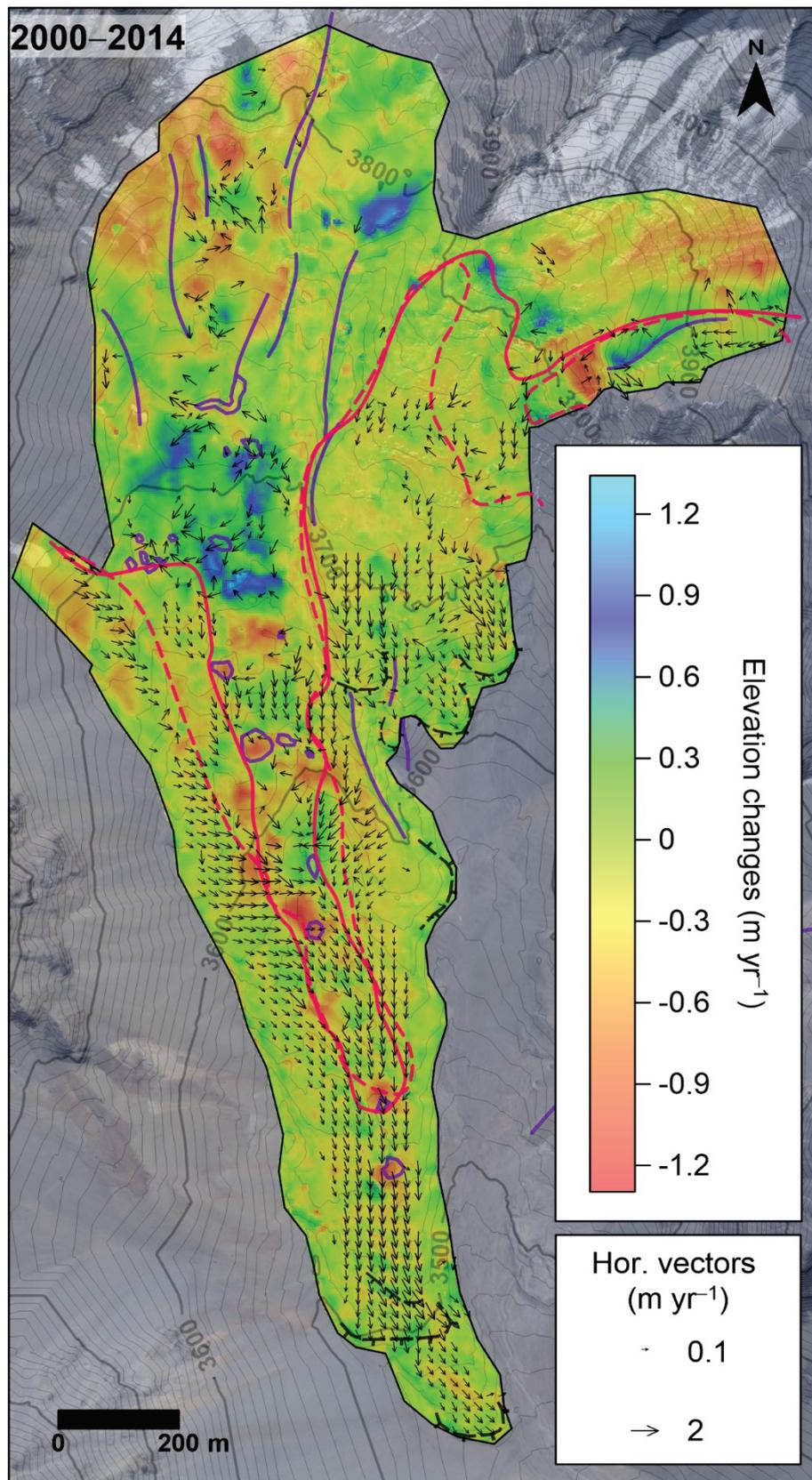
2 **Figure 8.** Sequence of orthophotos obtained for Las Tetas. The base of the landform front that could be
 3 reliably identified is indicated in color (blue, magenta, and orange line in 1978, 2000, and 2012,
 4 respectively). At each date the boundary between debris-covered and rock glacier morphology is
 5 depicted with a red line (dotted in 1978, dashed in 2000, and continuous in 2012).



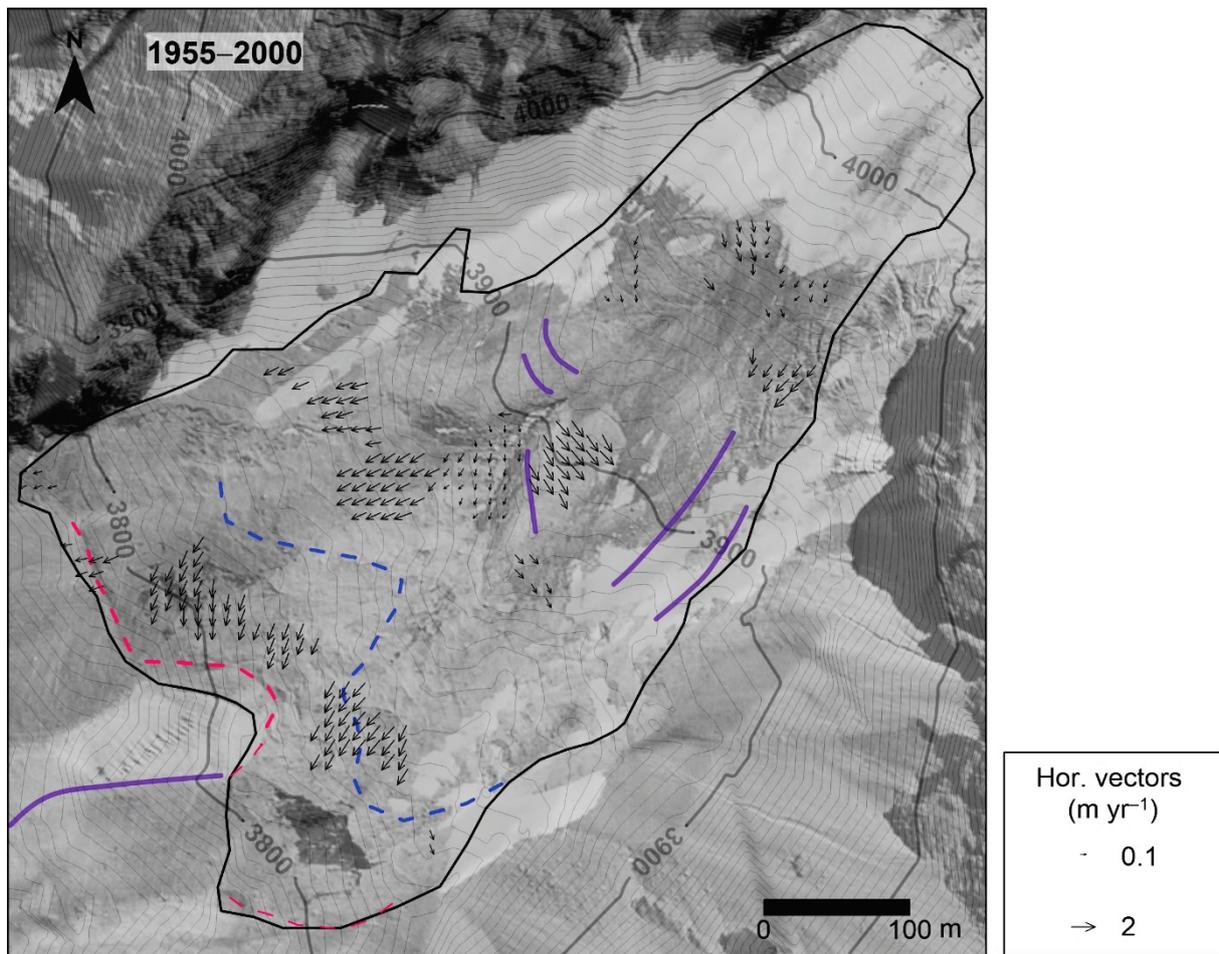
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2 **Figure 9.** Horizontal displacements at the surface of Navarro between 1955 and 2000. The boundary
 3 between debris-covered and rock glacier morphology is depicted with a dotted red line in 1955 and with
 4 a dashed red line in 2014. Note that moraine crests and thermokarst depressions in 2000 are indicated.
 5 The background of the map is the 2000 orthophoto.

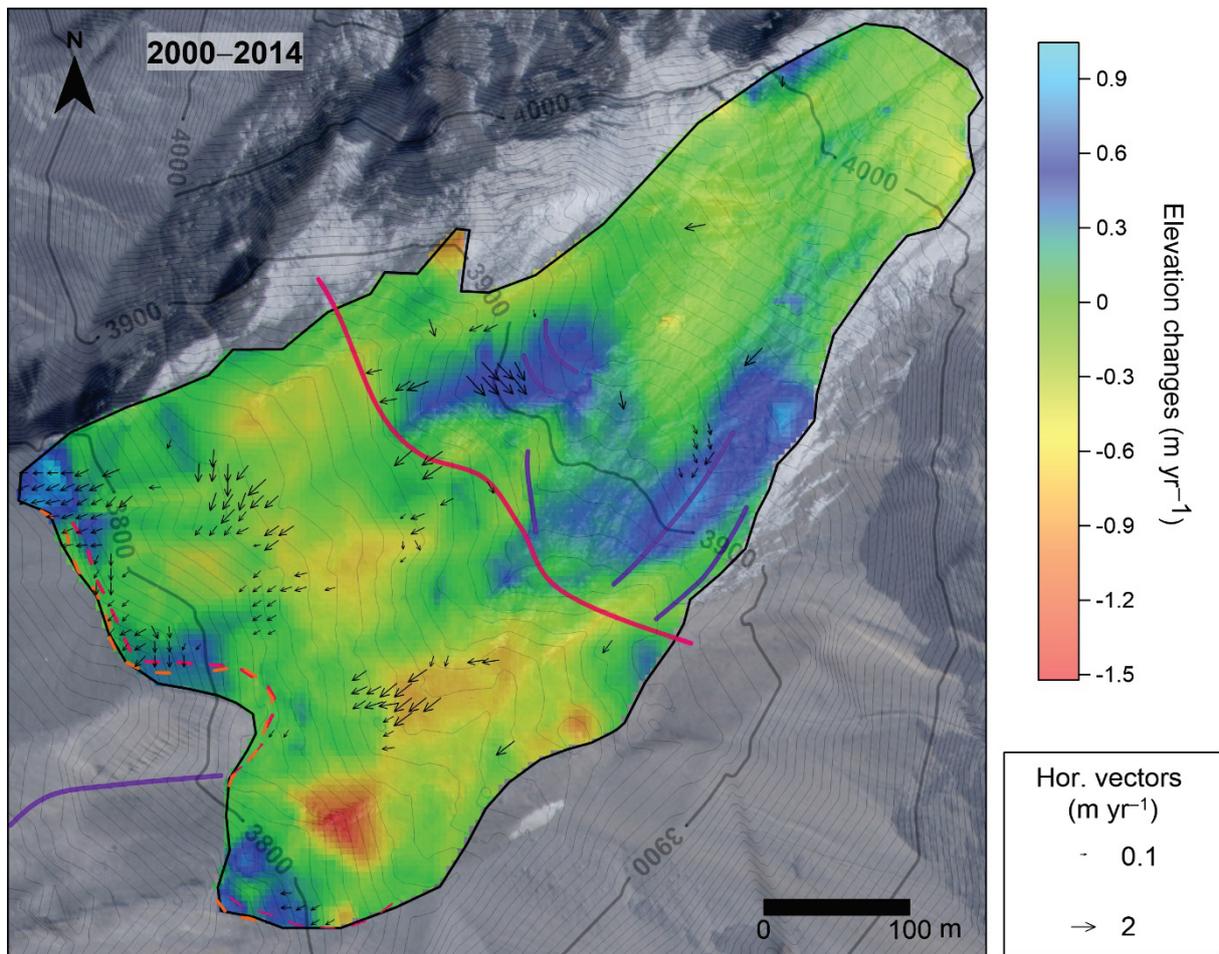
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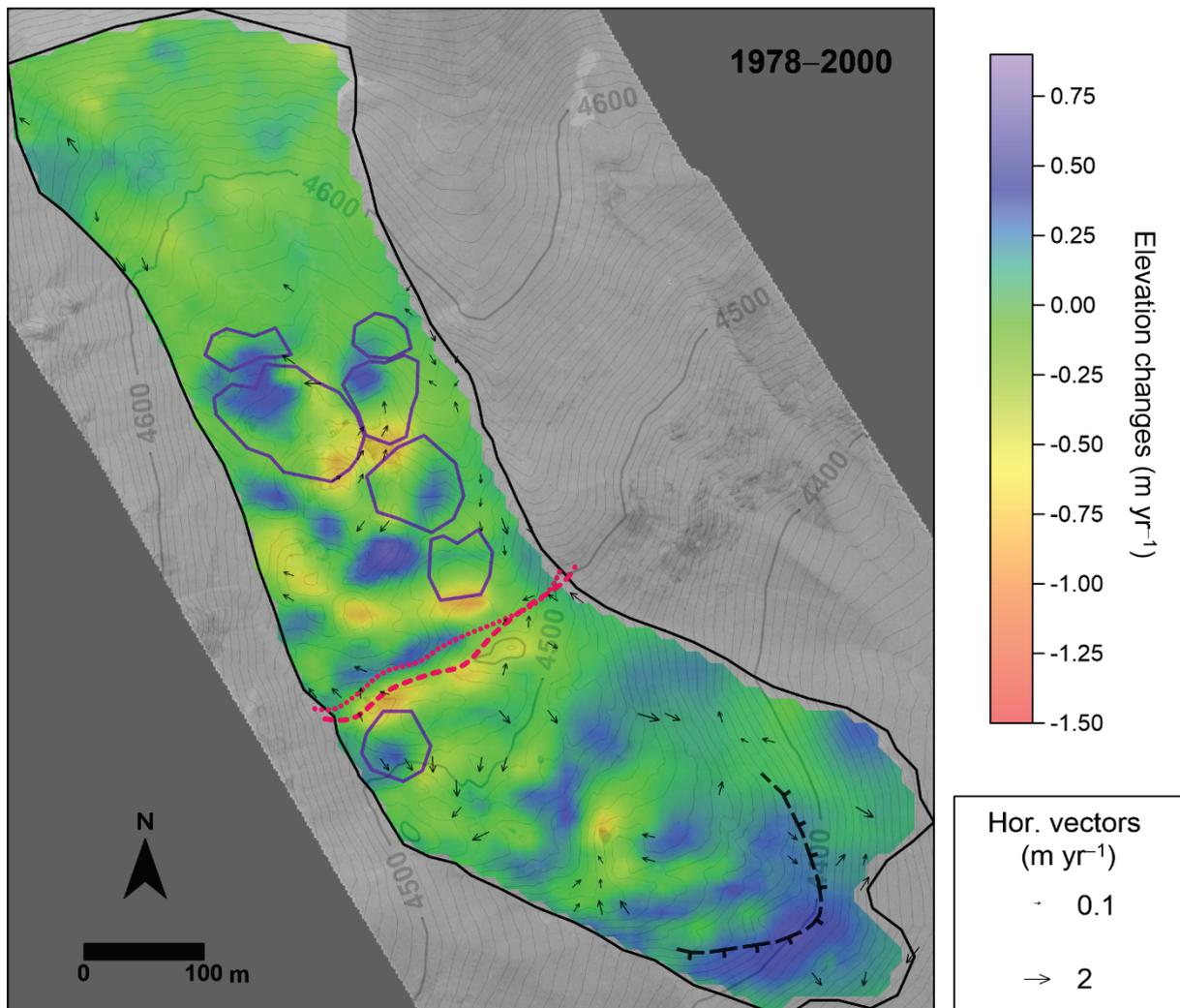
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 2 **Figure 10.** Horizontal displacements and elevation changes at the surface of Navarro between 2000 and
 3 2014. The boundary between debris-covered and rock glacier morphology is depicted with a dashed red
 4 line in 2000 and with a continuous red line in 2014. Note that moraine crests and thermokarst depressions
 5 in 2014 are indicated. The background of the map is the 2014 Geoeye image.



1
 2 **Figure 11.** Horizontal displacements at the surface of Presenteseracae between 1955 and 2000. The
 3 position of the base of the front at the two dates is indicated with dashed lines, as in Figure 7; push
 4 moraine ridges in the upper part are also indicated. The background of the map is the 2000 orthophoto.

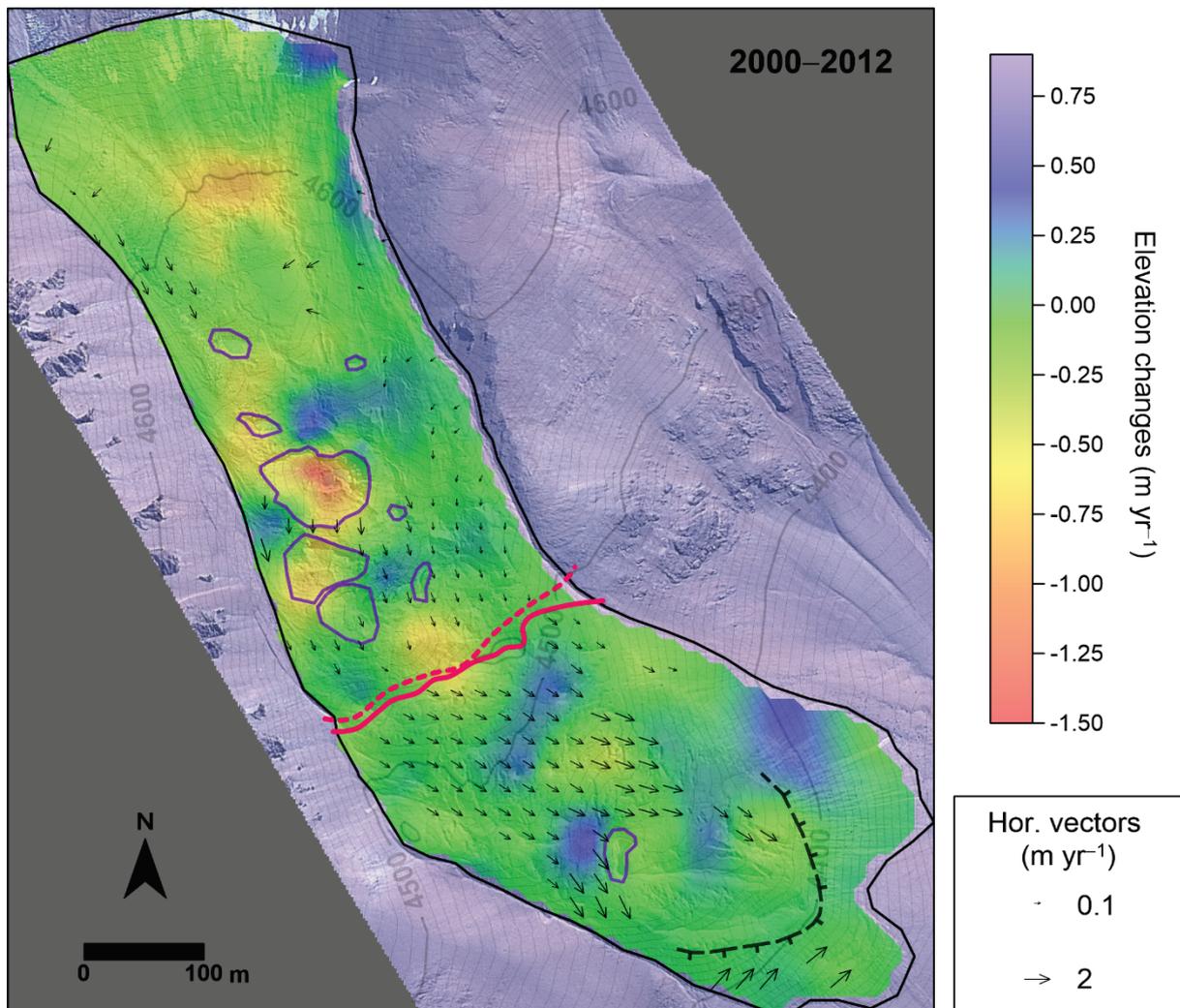


1
 2 **Figure 12.** Horizontal displacements and elevation changes at the surface of Presenteseracae between
 3 2000 and 2014. The position of the base of the front at the two dates is indicated with dashed lines, as
 4 in Figure 7; the boundary between rock glacier and debris-covered glacier features and push moraine
 5 ridges in the upper part are indicated. The background of the map is the 2014 Geocye image.



1

2 **Figure 13.** Horizontal displacements and elevation changes at the surface of Las Tetas between 1978
 3 and 2000. The boundary between debris-covered and rock glacier morphology is depicted with a dotted
 4 red line in 1978 and with a dashed red line in 2000. Thermokarst depressions in 1978 are indicated.
 5 Thermokarst areas could not be accurately and reliably delineated on the 2000 orthophoto and are hence
 6 not mapped. The background of the map is the 2000 orthophoto.



1

2 **Figure 14.** Horizontal displacements and altitudinal changes at the surface of Las Tetas between 2000

3 and 2012. The boundary between debris-covered and rock glacier morphology is depicted with a dashed

4 red line in 2000 and with a continuous red line in 2012. Note that thermokarst depressions in 2012 are

5 indicated. The background of the map is the 2012 Geoeye image.