Relative Paleoenvironmental Adjustments Following Deglaciation of the Byers Peninsula (Livingston Island, Antarctica)

Authors: Ruiz-Fernández, Jesús, and Oliva, Marc

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Jesús Ruiz-Fernández[1,*] and Marc Oliva[2]

[1]Department of Geography, University of Oviedo, Teniente Alfonso Martínez s/n, 33011, Oviedo, Spain
[2]Centre for Geographical Studies–Institute of Geography and Spatial Planning, University of Lisbon, Alameda da Universidade, 1600-214, Lisbon, Portugal
*Corresponding author's email: ruizjesus@uniovi.es

A B S T R A C T

In the present context of fast warming in the Antarctic Peninsula (AP), understanding past and recent environmental dynamics is crucial to better assess future environmental responses in this region. Very detailed geomorphological maps can help to interpret the interaction between glacial, periglacial, and paraglacial systems. The Holocene environmental sequence on Byers Peninsula, an ice-free area in the westernmost part of Livingston Island (Maritime Antarctica), is still poorly understood. This paper focuses on the geomorphology of the Cerro Negro, a volcanic plug located on the southeast fringe of this peninsula. The distribution of landforms and deposits generated by different geomorphological processes provides insights into the Holocene environmental dynamics on Byers Peninsula. During the fieldwork campaign in January 2014, an accurate geomorphological map of Cerro Negro and its surroundings was generated. Four geomorphological environments were identified: hill, north slope, southern escarpment, and marine terraces and present-day beach. Periglacial landforms are abundant, especially patterned ground features (blockstreams, sorted stone circles, stone stripes). All these cryoturbation landforms, except blockstreams, are active under present-day climate conditions. In addition to a sequence of Holocene marine terraces and slope deposits, such as talus cones and rockfalls, there is a glacial moraine adjoining the northern slope of the hill. From the morphostratigraphic correlation between the active and inactive landforms, we infer three main phases describing the paleoenvironmental evolution in this area: (1) maximum glacial expansion; (2) Holocene glacial retreat, lake formation, and intense periglacial dynamics; and (3) deglaciation of the Byers Peninsula and widespread periglacial processes. The Cerro Negro has been a nunatak for most of the Holocene; the lake located near the summit of this hill appeared when most of the Byers Peninsula was still covered by glacial ice. This study constitutes an example of how an accurate geomorphological characterization of a small area can complement other approaches to generate a better understanding of the paleoenvironmental evolution in the region.

INTRODUCTION

Antarctica, with 99.6% of its surface covered by ice, includes a few ice-free areas such as (1) nunataks standing out of the glacier ice, (2) dry valleys in the interior of the continent, which are climatically conditioned by topographic constraints, and (3) ice-free environments near the coast, where mean annual temperatures are close to 0 °C. In coastal environments at the northern tip of the Antarctic Peninsula (AP), the glacial retreat following the Last Glacial Maximum continued throughout the Holocene, exposing new ice-free surfaces (Ingólfsson et al., 2003; Seong et al., 2009; Simms et al., 2011;

Balco et al., 2013). This is the case for the Byers Peninsula, on Livingston Island, the second largest island of the South Shetland Islands (SSI) with 845 km². Cerro Negro, the study area of this research, is located here on the southeastern fringe of the Byers Peninsula.

The present distribution of geomorphological features provides key data to understand landscape changes in ice-free environments since the deglaciation of these areas. Understanding past environmental dynamics in the rapidly changing environments of the AP region—affected by one of the fastest rates of warming on Earth (Turner et al., 2005)—may help to anticipate the future environmental response in these regions.

The first papers focusing on the geomorphological mapping of Antarctica date from the early 1960s (e.g., Yoshida, 1961; Araya and Hervé, 1966). Significant developments occurred during the 1980s and early 1990s in response to improved Antarctic logistics, including the building of new research stations and the use of satellite imagery, Geographic Information Systems (GIS), and various techniques and editing programs for mapping (Baroni et al., 1997). The maps and geomorphological sketches produced during these decades were mostly focused on the ice-free areas and external fringes of the continent (Derbyshire and Peterson, 1978; Stuiver et al., 1981; Zhang and Peterson, 1984; Mayewski and Goldthwait, 1985; Brunk, 1989; Marchant et al., 1993; Baroni and Orombelli, 1994; Salvatore et al., 1997). Since then, the geomorphological features of the AP region and sub-Antarctic islands have been subjects of much research (López-Martínez et al., 1996, 2000, 2002, 2012; Birkenmajer, 1997; Serrano and López-Martínez, 2000; Guglielmin et al., 2008; Michel et al., 2014). The general spatial distribution of the landforms in the SSI, as well as their geomorphological dynamics, is therefore widely understood. However, in contrast to other polar and alpine environments where cold-climate geomorphological processes are widespread (e.g., Gómez Ortiz, 2006), in Antarctica there has been comparably little research focusing on very detailed geomorphological mapping of specific areas (e.g., Serrano and López-Martínez, 2000; Davies et al., 2013; Goyanes et al., 2014). High-resolution geomorphological studies can provide insights into interactions between glacial, periglacial, and par-

aglacial systems in the SSI during the Holocene, complementing our knowledge of the postglacial environmental change in this archipelago.

This paper focuses on the geomorphology of a small region in the SSI, the Byers Peninsula, which constitutes the environment with the largest biodiversity in Antarctica (Toro et al., 2013). López-Martínez et al. (1996) published a general geomorphological map with a scale of 1:25,000, complemented with some descriptive studies of the glacial and periglacial geomorphology of the peninsula (Martínez de Pisón et al., 1996; Serrano et al., 1996; López-Martínez et al., 2012). However, Ó Cofaigh et al. (2014) emphasized the lack of geochronological data on the glacial history of the Byers Peninsula. Current knowledge of the process of deglaciation lies only in some paleolimnological data from lacustrine sedimentary sequences collected on several lakes in Byers Peninsula, namely the Chester, Limnopolar, Escondido, Cerro Negro, and Domo lakes (Björck et al., 1996; Toro et al., 2013; Martínez-Cortizas et al., 2014; Oliva et al., 2016). Nevertheless, for a complete understanding of the sedimentary processes prevailing in these lakes and for an accurate sequencing of past environmental and climatic events, it is necessary to identify the sediment source areas and the geomorphological processes and landforms existing in lake basins. In this study, we present a detailed geomorphological study of an area surrounding one of these lakes (Cerro Negro), with the following specific objectives:

- Present a detailed geomorphological mapping of the Cerro Negro area and lake catchment.
- Use the Cerro Negro area as a small-scale example to infer a relative paleoenvironmental reconstruction for the long-term deglaciation of the Byers Peninsula based on geomorphological evidences.
- Integrate this knowledge within the Holocene paleoenvironmental evolution already existing for the Byers Peninsula and the SSI.

STUDY AREA

The Byers Peninsula is located on the westernmost fringe of Livingston Island between latitudes 62°34′35″S–62°40′35″S and longitudes 60°54′14″W–61°13′07″W (Fig. 1). With an area of
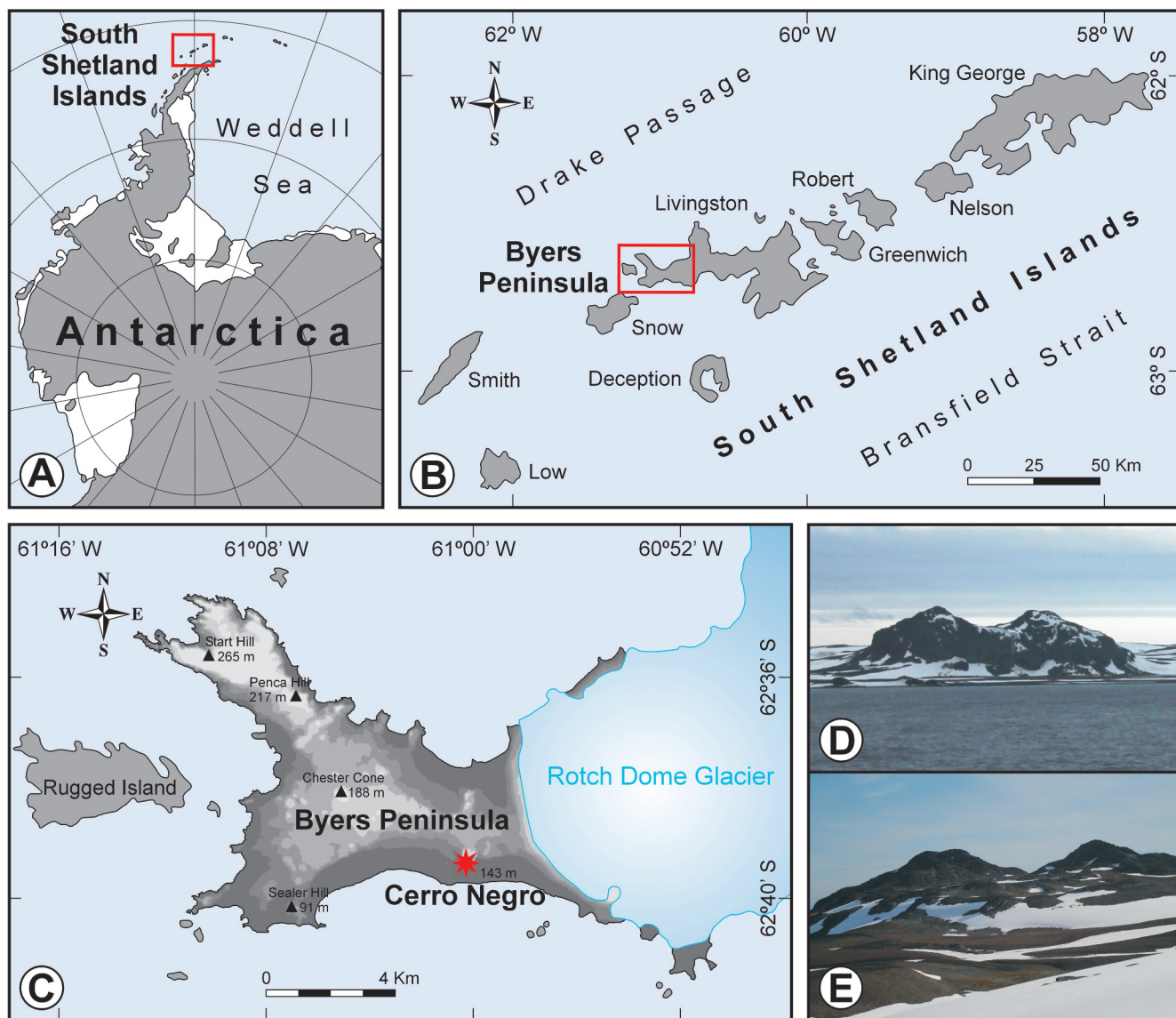
FIGURE 1. (A) Location of the South Shetland Islands (SSI) in Antarctica, (B) Byers Peninsula within the SSI, (C) Cerro Negro in the Byers Peninsula, (D) Southern slope of Cerro Negro, and (E) Northeastern side of Cerro Negro.

more than 60 km², this region constitutes the largest ice-free environment on the SSI.

The SSI has a polar maritime climate, with annual precipitation rates of between 500 and 800 mm (mostly concentrated in the summer season) in the form of both rain and snow (Bañón et al., 2013). Between 2002 and 2010, the mean annual air temperature was −2.8 °C (70 m a.s.l; Bañón et al., 2013), with low daily and annual temperature ranges. The relatively flat topography in the Byers Peninsula favors the occurrence of stronger winds than in other more topographically protected areas on the SSI.

The Byers Peninsula is composed of volcanic, volcaniclastic, and clastic sedimentary rocks (sandstones, mudstones, and conglomerates) of Jurassic and Cretaceous age. Sills, dikes, and other intrusive rocks are also of Cretaceous age (Hathway and Lomas, 1998). The relief is structured in a series of staggered platforms at different elevations. The upper platform constitutes the central plateau extending across the central part of the peninsula at altitudes between 70 and 100 m. A few isolated hills composed of resistant volcanic rocks stand above the plateau, such as Start Hill (265 m), Chester Cone (188 m), and Cerro Negro (143 m). The lowest are-

as of the peninsula surround the central plateau and correspond to Holocene marine terraces and the present–day beach (López–Martínez et al., 2012).

As with the rest of the SSI, Livingston Island is extensively glaciated with ~84% of its surface covered by polythermal glaciers (Navarro et al., 2013). Alpine glaciers flow down from the mountains, while the lower areas are covered by coalescing domes with their fronts falling gently to the sea (e.g., the Rotch Dome Glacier). The eastward retreat of this ice dome throughout the Holocene has generated the ice-free terrain on Byers Peninsula and has formed tens of lakes (Toro et al., 2013; Oliva et al., 2016). At present Rotch Dome Glacier is located 2 km from Cerro Negro hill.

The present-day geomorphological processes on Byers Peninsula are conditioned by the presence of permafrost and the annual evolution of the active layer, which reaches a depth of ~1.3 m (de Pablo et al., 2014). Periglacial processes are active even at low elevations, with widespread cryoturbation landforms such as sorted stone circles and stone stripes. This pattern is very similar to that observed in other environments on the SSI (López–Martínez et al., 2012). By contrast, in the ice-free areas of the eastern AP region, the interactions between the glacial, periglacial, and paraglacial landsystems are particularly intense, with more widespread periglacial slope features than on Byers Peninsula, such as rock glaciers, protalus ramparts, stone-banked solifluction lobes, and so on (Carrivick et al., 2012; Davies et al., 2013). A similar interaction between these landsystems occurred in the past on Cerro Negro, and a detailed study of its geomorphology can provide insights into past environmental and climatic processes following deglaciation.

Seasonal runoff from snow and glacier melting has a significant geomorphological impact on the landscape on Byers Peninsula by increasing the energy of the fluvial processes, which in turn may generate changes in the drainage network (Mink et al., 2014). The vegetation cover is scarce; lichens have colonized inactive or weakly active periglacial landforms and rocky outcrops, and moss carpets are abundant in poorly drained environments. On the highest marine terraces, the only two Antarctic vascular plants are present (*Deschampsia antarctica* and *Colobanthus quitensis*) (Vera, 2011).

The impact of human activities on Byers Peninsula has been largely restricted to the early sealers who sheltered on these shores between the late 18th and early 19th century (Zarankin and Senatore, 2005). Now, human activities are only related to scientific purposes. As a result of its geological, geomorphological, limnological, and ecological interest, the Byers Peninsula was declared a protected area in 1967 within the framework of the Antarctic Treaty and constitutes today the Antarctic Specially Protected Area No. 126.

Within the Byers Peninsula, this study focuses specifically on Cerro Negro and its surroundings. This hill is of basaltic rock composition and is located on the southeast margin of the peninsula, standing out from the neighboring platforms and the sea (Fig. 1).

MATERIALS AND METHODS

Detailed geomorphological mapping of the Cerro Negro area covering an area of 1.4 km^2 was carried out in the field at the end of January 2014, when the snow had already melted in much of the study area after a snowy year on the SSI. The geomorphological map was generated using the following sources: (1) a high–resolution satellite image WorldView–2 of 2013, and (2) the topographic map of the Byers Peninsula at a scale of 1:25,000, published in 1992 by the Spanish Army Geographical Centre in collaboration with the British Antarctic Survey and the Autonomous University of Madrid. The digital base map was created with ArcGIS 10 (combining both the satellite image with the topographic information), and edited using CorelDraw 14, following the RCP-77 geomorphological mapping system of the French Centre National de la Recherche Scientifique (CNRS). Geomorphological criteria were used to infer the paleoenvironmental sequence in the area.

GEOMORPHOLOGICAL DISTRIBUTION OF LANDFORMS, DEPOSITS, AND PROCESSES

The morphology of Cerro Negro resembles a half-moon. On this hill and the surrounding areas,
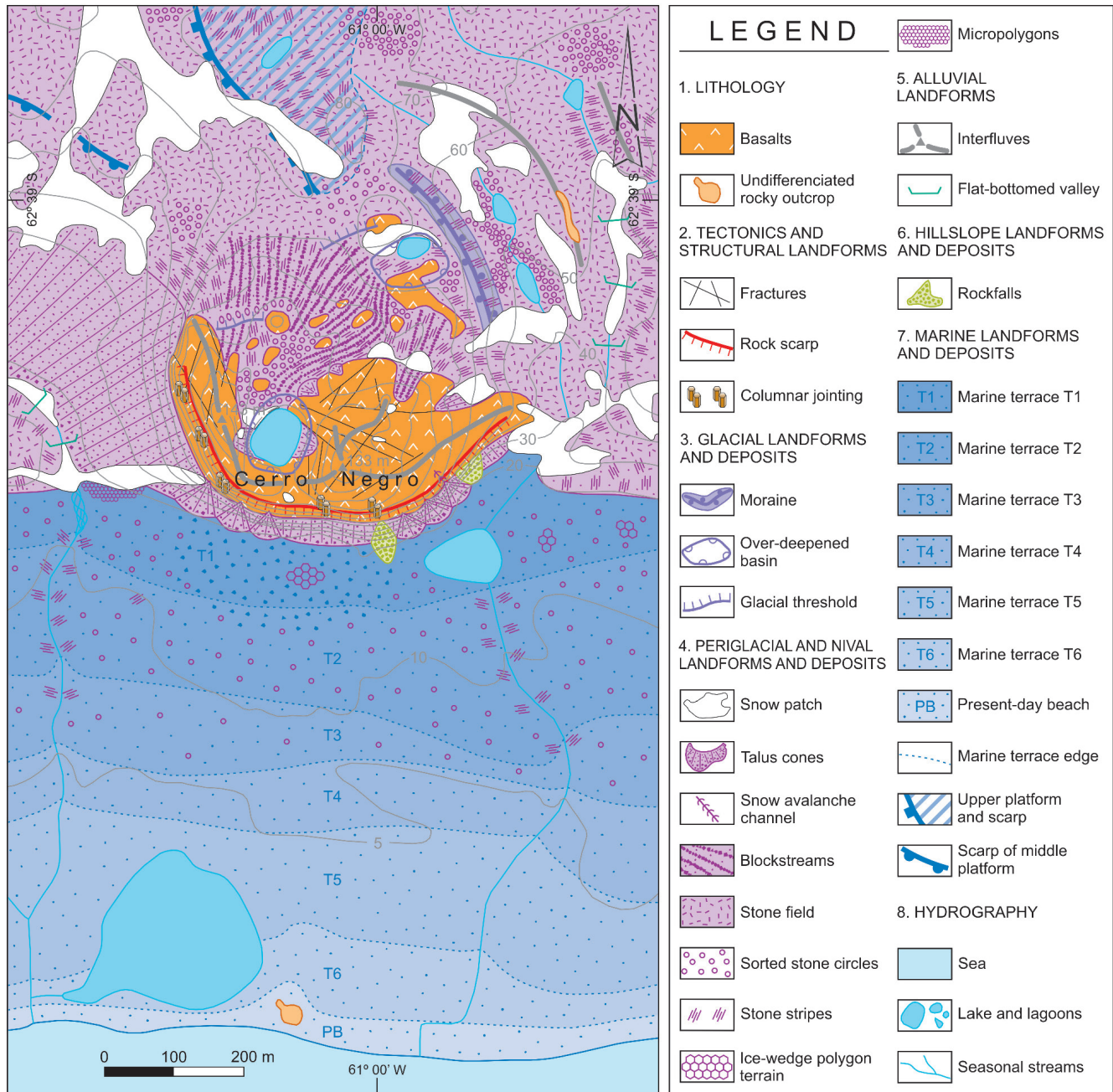
FIGURE 2. Geomorphological map of the study area.

we identified the following geomorphological environments (Fig. 2, Table 1).

Hill

The maximum elevation of the Cerro Negro is 143 m, the perimeter is 1.47 km, and its surface 0.14 km². This volcanic plug is composed of basalt showing columnar jointing (Fig. 3) and culmi-

nates in two peaks aligned E to W. Between these two peaks, the Cerro Negro Lake is situated at an altitude of 100 m inside an overdeepened basin. The lake is approximately circular, with a surface area of 3572 m² (Fig. 3). Its drainage basin is geographically limited to the basaltic outcrops surrounding the lake on the east, west, and partly on the southern margins. There are two talus cones on the eastern and western margins of the lake com-

TABLE 1

**Geomorphological landforms identified in the area.**

Areas	Landforms	Main characteristics, distribution, and dimensions
Hill	Volcanic plug	Highest lands composed of two main peaks exceeding 130 m and aligned E to W.
	Sorted circles	Landforms of centimeter size formed in areas with fine-grained sediments and gentle slopes (4–6°).
	Talus cones	Deposits of coarse sediments at the foot of the cliffs. The rock surfaces show a poor to moderate colonization by lichens.
	Over-deepened basin and Cerro Negro lake	Basin excavated by glacial ice placed between the two major peaks, relatively open to the south and north. Its dimensions are 115 m long and 100 wide. Inside the basin, a water body (69 m long, 55 m wide) is located at an elevation of 100 m and extends over a surface of 3572 m².
North slope	Blockstreams	Ridges of boulders and gravel formed in slope angles between 10 and 23°, with a length ranging between 45 and 230 m. The boulders are broadly covered by lichens.
	Sorted circles	Landforms of decimeter size (0.6–1 m) formed in areas with fine-grained sediments and gentle slopes (4–6°).
	Stone stripes	Landforms of centimeter size formed in areas with fine-grained sediments and gentle to moderate slopes (8–12°).
	Moraine	Partially dismantled moraine surrounding the northeastern slope of the Cerro Negro hill.
	Over-deepened basin with lake inside	Water body (29 m long, 22 m wide) located above the moraine, inside a basin excavated by glacial ice of 70 m long and 55 m wide.
	Stone fields	Deposits of coarse and fine sediments formed in dry environments. Presence of ventifacts.
Southern escarpment	Basalts outcrops with columnar jointing	Structural landforms very common in the southern escarpment.
	Talus cones	Deposits of coarse sediments at the foot of the cliffs. The rock surfaces show a poor to moderate colonization by lichens.
	Rockfalls	Large accumulations of angular and heterometric blocks fallen from the major scarp.
	Snow avalanche channels	The columnar jointing favors the existence of channels through which sediments are transferred downslope.
Marine terraces and present-day beach	Marine terraces	Sequence of six levels of marine terraces at elevations ranging between 2 and 15 m. They show an alternation of flat surfaces and gentle slopes in the ramps of the terraces.
	Ice-wedge polygonal terrain	Presence of visible cracks in the soil surface. They have been observed only in poorly drained areas from the highest marine terraces.
	Sorted circles	Landforms of centimeter size formed in areas with fine-grained sediments and gentle slopes (4–6°).
	Micropolygons	Landforms of centimeter size (10 to15 cm) composed of small gravel (~1 cm).
	Lagoons and flooded areas	Abundance of lagoons and flooded environments in the flat areas of the terraces. Presence of a dense cover of vegetation cover, mainly mosses.
	Present-day beach	Environment with marine influence used intensely by the wildlife.

posed of large, angular, heterometric boulders, with small areas with poorly developed cryogenic soils. The northern shore of the lake is a flat area of fine sediments, where decimetric sorted stone circles are widespread (Fig. 3).

Therefore, the sources of sediment that can be mobilized into the lake are restricted and are limited mostly to fine particles transported by seasonal snow–melt and eolian sediments. Small semipermanent snow patches are distributed along the northern shoreline of
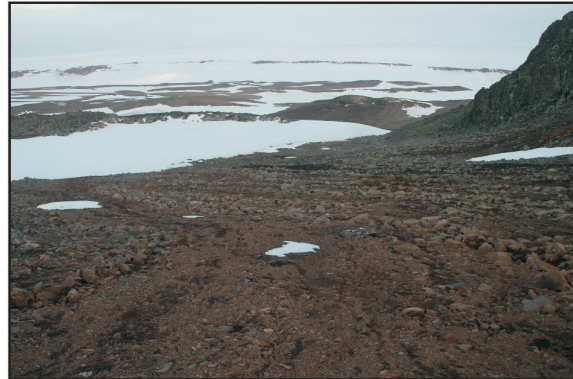
Basalts outcrops with columnar jointing
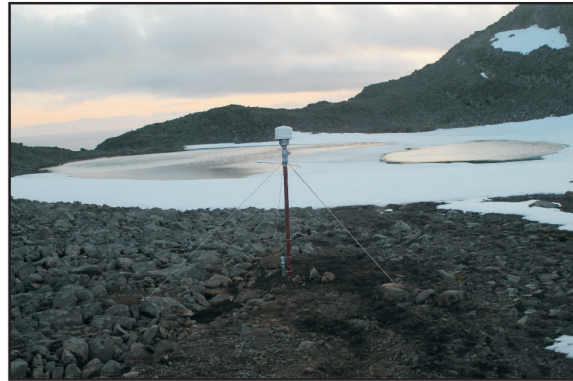
Cerro Negro Lake

Sorted stone circles

Blockstreams

Stone stripes

Moraine

Talus cones and snow avalanche channels

Micropolygons

FIGURE 3. Main geological and geomorphological features observed in the area of Cerro Negro.

the lake. The rest of the high lands are mostly bedrock exposures, with scree deposits. The basaltic outcrops of the hill show abundant fractures with prevailing directions SW-NE and NW-SE (Fig. 2).

North Slope

The northern slope of Cerro Negro descends gently toward the central plateau (70–85 m elevation; Fig. 2), with a slope angle ranging from 5° to 32°. Periglacial slope landforms are widespread on this hillside. Blockstreams defined as ridges of boulders and gravels separated by fine particles were observed all across the slope (Fig. 3). Most of the boulders are colonized by lichens, which suggests current geomorphic stability. By contrast, on the fine-grained sediments existing between the blockstreams, several stone stripes are developing under present-day climatic conditions.

The length of the blockstreams range from 45 m in the western area of the slope to 230 m of the blockstreams descending northeastward from the margin of the Cerro Negro Lake toward another small lake located in another overdeepened basin (Fig. 2). The slope angles of the blockstreams vary between 10° and 23°. In some cases the blockstreams merge, adapting to the hillside topography. In the western area of the northern slope, there is a small rocky escarpment (glacial threshold), next to which there is a flat surface with sorted stone circles of diameter (Ø) between ~0.6 and 1 m. Here, the slope increases down-valley; the long axis of the sorted stone circles therefore increases progressively, ultimately resulting in stone stripes (Fig. 3).

In the northeastern area of the Cerro Negro, in contact with the central plateau, there is an arcuate moraine at an altitude of 70 m partially dismantled by slope processes (Figs. 2 and 3). Finally, the stone fields—areas defined by scarce fines and the presence of dispersed boulders and flat-lying clasts (López-Martínez et al., 1996)—are abundant in the surroundings of the northern slope. Some of these boulders and shattered rock fragments exhibit traces of wind abrasion on the windward sides (ventifacts).

Southern Escarpment

The southern slope of Cerro Negro comprises a major scarp falling steeply 70 to 110 m down to the marine terraces distributed along the coastline. In addition to rockfalls (composed of blocks of varying size), at the foot of the scarp there are several very active talus cones. Some of them are fed by snow avalanche channels distributed through the fractures of the bedrock (Fig. 3). Rockfalls are very frequent, favored by the profuse network of joints in the columnar basalt. These joints act as planes of weakness within the rock.

Marine Terraces and Present–Day Beach

The slope deposits accumulated at the foot of the southern escarpment of the Cerro Negro hill connect with the six levels of marine terraces that are cut by streams flowing southward (Fig. 2). On the highest raised beaches, we identified several periglacial landforms associated with the presence of ground ice such as incipient ice-wedge polygonal terrain with visible evidence of recent frost cracking. On these terraces, there are also micropolygons (Ø ≈ 10–15 cm) composed of small gravels (Ø ≈ 1 cm) separated by a sandy matrix (Figs. 2 and 3) and sorted stone circles, some of them covered to a greater or lesser extent by mosses in poorly drained areas. Stone stripes are widespread on the highest marine terraces, even in gentle slopes of only 6°, though they are more developed in the ramps of the terraces where the slope is greater. Some ventifacts were also observed in dry areas of the highest marine terraces. In the flat surfaces of the lowest raised beaches, there is a permanent lagoon, as well as many seasonally flooded areas. Interestingly, on the highest marine terraces ~2 km eastward of the study area, there are several rounded boulders (Ø = 30–100 cm) exotic to the local bedrock, namely granites and granodiorites.

Discussion

The morphostratigraphic correlation between the inherited and the contemporary landforms distributed in the Cerro Negro and its surrounding area, as well as identification of the processes responsible for their formation, enable us to infer three major phases of paleoenvironmental evolution in this area (Fig. 4):

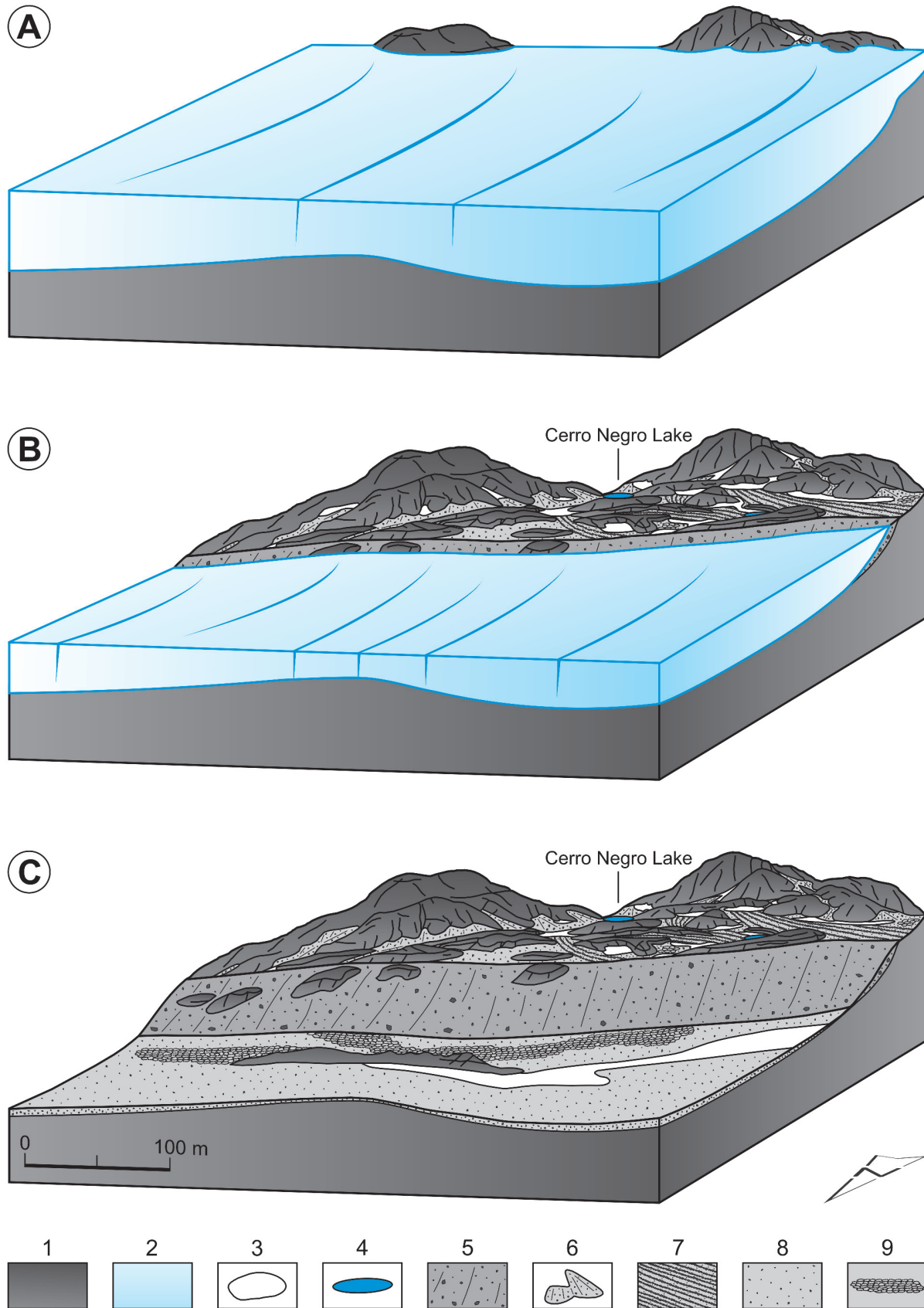**FIGURE 4.** Major phases of the paleoenvironmental evolution of the study area. (A) Maximum glacial expansion. (B) Holocene glacial retreat, lake formation, and intense periglacial dynamics. (C) Deglaciation of the Byers Peninsula and widespread periglacial processes. Legend: (1) Bedrock. (2) Glacial ice. (3) Snow patch. (4) Lake. (5) Moraine. (6) Talus cones. (7) Blockstreams. (8) Stone field. (9) Sorted stone circles.

Maximum Glacial Expansion

Several studies have inferred a phase of maximum glacial advance for the AP and the SSI around 18–20 k.y. B.P. (RAISED Consortium, 2014). During this time, a large ice cap extended continuously across all the islands of the SSI, physically connected with the continent (Ó Cofaigh et al., 2014). Therefore, the Rotch Dome Glacier probably occupied the entire extent of the Byers Peninsula. It is likely that only the uppermost parts of Cerro Negro were exposed above the glacier ice constituting a nunatak (Fig. 4, part a), as it probably occurred with other volcanic plugs distributed across the peninsula reaching elevations of 140–250 m (e.g., Start Hill, Chester Cone). Therefore, during this phase, periglacial processes were geographically very restricted on Byers Peninsula, limited only to reshaping the few ice-free areas (i.e., the walls and rocky ridges of the nunataks). These would be affected by permafrost conditions, such as occurs today in most of the nunataks in continental Antarctica (Vieira et al., 2010).

Holocene Glacial Retreat, Lake Formation, and Intense Periglacial Dynamics

Warmer conditions during the Early Holocene promoted the onset of deglaciation on Byers Peninsula (Oliva et al., 2016). The gradual loss of ice thickness of the Rotch Dome Glacier may have established a center of glacial dispersion on the Cerro Negro (López-Martínez et al., 1996). The moraine adjoining the northern slope of the Cerro Negro suggests a second stage of environmental evolution. The loss of ice thickness of the Rotch Dome Glacier resulted in the formation of both the Cerro Negro lake and the smaller lake located above the moraine. A recent luminescence dating of its basal lacustrine sediments indicates that it formed around 7.5 ± 2.5 ka B.P. (Oliva et al., 2016), much older than the age of 2700 cal. yr B.P. reported in former studies (Björck et al., 1996). Therefore, this lake formed while most of the central plateau was still glaciated, confirming that the Cerro Negro hill protruded above the ice as a nunatak during most of the Holocene. The lower elevation of the moraine relative to the lakes suggests that it probably formed during a phase of glacier stabilization dur-

ing the Mid Holocene, as observed in other areas across the AP region (Ó Cofaigh et al., 2014).

The moraine of Cerro Negro was partially dismantled by slope processes, which must have been very active particularly during the paraglacial stage. The increase of the ice-free surface in the Cerro Negro exposed areas of moderate slope on the northern side (Fig. 4, part b). Intense frost shattering of the basaltic outcrops of the Cerro Negro generated rock fragments that were mobilized downslope to form widespread blockstreams. These landforms have also been mapped in other areas of the SSI, such as Hurd Peninsula and Barnard Point (Livingston Island), Coppermine Peninsula (Robert Island), Stanbury Point (Nelson Island), and Barton, Keller, and Weaver peninsulas (King George Island; López-Martínez et al., 2012). Blockstreams require permafrost conditions for their formation (French, 2007); at present, blockstreams are active in the Arctic and in mid-latitude high mountain environments with very low negative mean annual temperatures (Washburn, 1979). Therefore, by analogy it would appear that significantly colder conditions than at present prevailed on Byers Peninsula during the formation of these landforms.

This loss of ice thickness occurred in parallel to extensive glacial retreat, which generated new ice-free environments in the central-western half of the peninsula. In these areas, tens of lakes formed due to the lack of an organized drainage system (Mink et al., 2014). For the entire AP region, the onset of glacial retreat dates to 14–15 ka with massive ice loss and sea level rise until 6 ka (Ingólfsson et al., 2003; Weber et al., 2014). For the specific case of the SSI, previous studies have revealed that warmer conditions during the Early Holocene led to the beginning of deglaciation in King George Island occurring between 11 and 9 ka in Fildes Peninsula (Watcham et al., 2011), between 11.9 and 7.6 ka in Barton Peninsula, and starting in 8.8 ka in the highest areas of the nearby Weaver Peninsula (Seong et al., 2009). The ages obtained by Toro et al. (2013) and Oliva et al. (2016) confirm that deglaciation of the westernmost fringe of Livingston Island occurred during the Holocene; the datings of the base of the sedimentary cores of Limnopolar, Chester, and Escondido lakes show times for the onset of deglaciation ranging between 8.3 and 5.9 ka. Toro et al. (2013) detected increased organic sedimenta-

tion during the Mid Holocene in the Limnopolar Lake, in parallel to warmer conditions recorded in the SSI between 8.2 and 5.9 ka (Milliken et al., 2009). The chronological differences existing for ages of formation of these lakes may be related to the persistence of residual glacial centers on Byers Peninsula during the long-term eastward retreat of Rotch Dome Glacier (Oliva et al., 2016). This is also confirmed by the configuration of the drainage system in the central plateau of the Byers Peninsula (Mink et al., 2014), although there are still uncertainties about the location of these local glacial centers (Oliva et al., 2016).

Recent Deglaciation of the Byers Peninsula and Widespread Periglacial Processes

In the third and final environmental phase, which continues to the present day, the area surrounding Cerro Negro is completely deglaciated (Fig. 4, part c). Following deglaciation, the paraglacial dynamics affected the ice-free landscape through a wide range of processes, such as intense rockfall dynamics, establishment of an incipient drainage system, increasing activity of eolian processes mobilizing the fine sediments generated by the glaciers, development of periglacial landforms on newly exposed land, reworking of glacial sediments, and increased frost action and frost shattering. Present-day geomorphological processes are similar to those occurring today in other maritime polar environments, such as in Svalbard (Matsuoka et al., 2004) or other regions in the AP region (Davies et al., 2013).

As a response to ice disappearance, rockfall activity must have been particularly intense during the paraglacial adjustment on the southern face of the Cerro Negro hill due to decompression of the slope caused by the recession of the glacial ice (Ballantyne, 2002a, 2002b; Mercier, 2008). This process was enhanced by the columnar jointing of the basaltic volcanic plug. Rockfalls still occur today during the summer season feeding the talus cones observed there.

The new ice-free areas generated during this stage are affected by periglacial dynamics, though less intense today than during the previous period. Geomorphic evidence of this pattern is inferred from the inactivity of the blockstreams, as revealed by the abundance of lichens colonizing the exposed surfaces of these landforms. At present, the most widespread active periglacial landforms are sorted stone circles and stone stripes (Fig. 2), which are broadly distributed in ice-free areas on the SSI (López-Martínez et al., 2012). Cryoturbation processes responsible for the formation of these landforms are more intense in moist areas, where patterned ground features are better developed. The slopes with larger water supply at the foot of long-lying snow patches are affected by solifluction processes, particularly active in saturated areas composed of fine-grained sediments. The effect of this slow mass-wasting process is also seen in the frost-shattered pebbles moving downslope. The combined action of periglacial and deflation processes in wind-exposed environments generates abundant stone fields.

The fluvial system formed after the deglaciation and is therefore at an early stage of development. On the southern side of Cerro Negro there are several seasonal streams fed by snow melt, summer rain, and melting ground ice that flow downslope toward the beach. The sequence of marine terraces is cut perpendicularly by stream incision. Several active periglacial features have been identified on the Holocene marine terraces, such as the existence of incipient ice-wedge polygonal terrain. In contrast to the widespread occurrence of these polygons in the Arctic (e.g., Fortier and Allard, 2004; Oliva et al., 2014), these landforms have only been observed in a few sites in Antarctica (Salvatore et al., 1997; Raffi and Stenni, 2011; López-Martínez et al., 2012). Patterned ground features are better developed in moist environments of the highest terraces than in the lowest, indicating an older origin of those located higher. The glacio-isostatic adjustment in the SSI (Watcham et al., 2011) is similar in terms of altitude and age to that reconstructed for the NE side of the Antarctic Peninsula (Roberts et al., 2011; Sterken et al., 2012). The highest dated marine terraces in the Byers Peninsula (9–10 m elevation) have been dated to 1.8 ka (John and Sugden, 1971; Hansom, 1979; Hall and Perry, 2004), those at 7.6 m have reported ages of 1.2 ka (Curl, 1980), and the lowest (<6 m) have developed only over the past 500 yr B.P. (Hall and Perry, 2004). Therefore, time is the main factor controlling the formation of these patterned ground features. They

developed between 1.2 and 1.8 ka, but they did not have enough time to form during the past 500 years. Similarly, in the nearby peninsula of Elephant Point, Oliva and Ruiz-Fernández (2014) found that patterned ground was well developed on the highest terraces and was inexistent on the lowest raised beaches.

Ventifacts polished by the bombardment of fine particles blown by the prevailing westerly winds are distributed on the highest marine terraces. The exotic boulders observed on the Holocene marine terraces on Byers Peninsula have been described in former studies as ice-rafted debris probably brought in at high tide by icebergs during the Late Holocene (Hall and Perry, 2004).

The present-day geomorphological dynamics in the area of Cerro Negro are conditioned by the presence of permafrost and active layer dynamics. On Byers Peninsula, at an altitude of 70 m, de Pablo et al. (2014) estimated the active layer thickness as about 1.3 m. On the SSI, permafrost is sporadic or discontinuous until 25–30 m a.s.l. but continuous above these elevations (Vieira et al., 2010; López-Martínez et al., 2012). In the study area, the lowest marine terraces with presence of incipient polygonal terrain features are placed at 9–10 m a.s.l., which indicates the altitudinal limit of permafrost distribution on this part of the Byers Peninsula. On the lower terraces, the lack of polygons is indicative of the absence of permanently frozen soil conditions in these areas. The small elevation difference between the marine terraces may suggest that permafrost distribution is not conditioned by the altitude, but may be related to the age of exposure. While permafrost on the highest terraces must have formed over the past 1.8 k.y., on the lowest terraces recently exposed to external climatic oscillations (ca. 500 yr B.P.), permafrost conditions may not have had sufficient time to develop.

Conclusions

Cerro Negro is a volcanic plug located on the southeast deglaciated margin of the Byers Peninsula, the largest ice-free area on the SSI. Its summit stands between the Holocene marine terraces in the south and the central plateau on its northern flank. In this paper, we have presented a detailed geomorphological mapping of Cerro Negro and its surroundings, based on fieldwork undertaken in the area in January 2014. Accurate mapping of the geomorphological processes and landforms occurring in this area has provided insights into the paleoenvironmental evolution during deglaciation of the Byers Peninsula. We have identified four different geomorphological environments in the area: hill, north slope, southern escarpment, and marine terraces and present-day beach.

The geomorphological processes and landforms observed on the Cerro Negro area are similar to those observed in other deglaciated areas in the SSI. Despite the small size of the study area, a wide range of periglacial processes is present and shows intense activity. Most abundant are the landforms resulting from cryoturbation processes, such as micropolygons, sorted stone circles, stone stripes, and blockstreams. In contact with the central plateau of the Byers Peninsula, there is a moraine encircling the northern slope of Cerro Negro, while in the steep southern escarpment several rockfalls and talus cones are situated, some of them fed by snow avalanche channels. There are also several levels of Holocene marine terraces, which are cut by a network of streams. On the flat surfaces of the terraces, there are poorly drained areas with ephemeral and permanent lagoons. In the highest raised beaches, frost cracking has resulted in the development of ice-wedge polygonal terrain, which suggests the altitudinal limit of permafrost conditions in this area.

Considering the morphostratigraphic relationships among the different landforms, as well as their formation processes, we have inferred a sequence of three paleoenvironmental stages: (1) glacial maximum expansion; (2) Holocene glacial retreat, lake formation, and very intense periglacial dynamics; and (3) deglaciation of the Byers Peninsula and widespread periglacial processes. During the LGM, most of the Byers Peninsula was covered by a large ice dome extending across the SSI, with only a few nunataks protruding above the ice (as was most likely the case for Cerro Negro). The moraine adjoining the northern slope of Cerro Negro suggests a second environmental phase characterized by the loss of ice thickness, the formation of the Cerro Negro Lake and the existence of intense periglacial dynamics that generated blockstreams on the newly exposed ice-free ground. However, these periglacial conditions were spatially restricted, because most

of the center-east of the Byers Peninsula was occupied by glacier ice during the Mid-Late Holocene. Subsequent paleoenvironmental evolution saw the confinement of the Rotch Dome Glacier toward the east, where it remains to the present day. Since then, the Cerro Negro area has remained completely deglaciated. In these deglaciated areas periglacial processes are widespread, although less intense than in the previous phase of glacial retreat. The blockstreams are inactive nowadays, and are mostly covered by lichens.

The detailed geomorphological research presented in this paper develops further our understanding of the past and present geomorphological dynamics, not only in the area of Cerro Negro but in the entire peninsula. This knowledge will provide an invaluable environmental context from which to assess the climatic significance of events identified within sediment cores from the Cerro Negro Lake, which is the subject of ongoing research.

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