ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

v. 6, nº 2 (2020)

https://doi.org/10.21680/2447-3359.2020v6n2ID19301

RECENT CHANGES IN GLACIERS AND PARAGLACIAL SYSTEMS, ANTARCTIC MARITIME

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Abstract

The article investigates changes in paraglacial systems and interconnections with glacial shrinkage on King George Island, Maritime Antarctica. The proglacial environment, as a result of recent deglaciation, was analyzed, and the types of landforms and at different scales were identified. These records are useful for successive evolutionary stages paraglacial system reconstruction. Glaciers and paraglacial systems showed rapid changes and new landscapes were detected on King George Island. Glaciers presented an important change between 2000 and 2018, where its classification has changed from marine-terminating to land-terminating glacier (no-marine). There are currently 21 glaciers land-terminating on King George Island (corresponding to 31% of the glaciers) and 11 are present in Admiralty Bay. 25% of these glaciers were marine in 2000. The new paraglacial environments (since 2000) has 1.7 km^2 of the total area. Ecology, Wanda, Windy, Anna South and Baranowski Glaciers showed outwash plain, talus slopes and fluvial channels landforms in recent paraglacial system. Geomorphological mapping shows that paraglacial processes which differ between environments marginal to glacier ice are not standardized.

Keywords: Glacial geomorphological processes; Ice free-land areas; Climate change.

RECENTES ALTERAÇÕES NAS GELEIRAS E NOS SISTEMAS PARAGLACIAIS, ANTÁRTICA MARÍTIMA

Resumo

O artigo investiga alterações nos sistemas paraglaciais e interconexões com a retração glacial em setores da ilha Rei George, Antártica Marítima. Foi analisado o ambiente proglacial, resultado da deglaciação recente, e identificados os tipos de formas de relevo em suas diferentes escalas. Estes registros são úteis para a reconstrução de estágios sucessivos evolutivos do sistema paraglacial. Os resultados demonstraram que o ambiente marginal às geleiras e sistemas paraglaciais estão evoluindo na ilha Rei George e há novas paisagens. Algumas geleiras apresentaram uma mudança importante entre 2000 e 2019, onde sua classificação mudou de geleira de terminação marinha para geleira de terminação terrestre (não-marinha). Atualmente há 21 geleiras com término em terra na ilha Rei George (correspondendo a 31% das geleiras) e 11 destas estão localizadas na Baía do Almirantado. 25% destas geleiras eram marinhas em 2000. Os novos ambientes paraglaciais (desde 2000) têm 1,7 km^2 ao total de área. Os ambientes marginais às geleiras (como as geleiras Ecology, Wanda, Windy, Anna Sul e Baranowski) mostraram formas de gênese não glacial, como planície de lavagem, depositos de tálus, ravinas e canais fluviais no sistema paraglacial recente. O mapeamento geomorfológico evidencia que os processos paraglaciais se diferenciam entre os ambientes marginais ao gelo das geleiras, não são padronizados.

Palavras-chave: Processos geomorfológicos glaciais; Áreas livres de gelo; Mudanças climáticas.

RECIENTES CAMBIOS EN GLACIARES Y SISTEMAS PARAGLACIARES, ANTÁRTICA MARÍTIMA

Resumen

El artículo investiga los cambios en los sistemas paraglaciares y las interconexiones con la retracción de los glaciares en la isla Rey Jorge, Antártica Marítima. Se analizó el ambiente proglacial, resultado de la deglaciación reciente, y se identificaron los tipos de formas de relieve en sus diferentes escalas. Estos registros son útiles para la reconstrucción de sucesivas etapas evolutivas en el sistema paraglacial. Los glaciares y los sistemas paraglaciares están evolucionando rápidamente y se están detectando nuevos paisajes en la isla Rey Jorge. Los glaciares mostraron un cambio importante entre 2000 y 2018, donde su clasificación cambió de glaciar de terminación marina a glaciar de terminación terrestre (no marino). Actualmente hay 21 glaciares de terminación terrestres en la isla Rey Jorge (que corresponden al 31% de los glaciares) y 11 están presentes en la Bahía del Almirantazgo. El 25% de estos glaciares eran marinos en 2000. Los nuevos entornos paraglaciares (desde 2000) cubren 1,7 km2 del área total. Los glaciares Ecology, Wanda, Windy, Anna Sul y Baranowski mostraron formas de llanuras de lavado, depósitos de tálus, barrancos y flujos superficiales fluviais en el sistema paraglacial reciente. El mapeo geomorfológico muestra que los procesos paraglaciares que difieren entre ambientes marginales al hielo glaciar no están estandarizados.

Palabras-Clave: Procesos geomorfológicos glaciares; Áreas libres de hielo; Cambio climático.

1. INTRODUCTION

The glaciers and the ice-marginal environments are particularly sensitive to climate change (COWIE; MOORE; HASSAN, 2014; CARRIVICK, 2015). To quantify current and recent changes in Wanda glacier, Ferrando, Rosa and Vieira (2009) showed that the liquid precipitation could trigger the high melting of the snow surface on glaciers and the melting water interconnect the moulins and crevasses and to accelerate the ice flow of the glacier in the summer.

Proglacial environments are defined located close to the ice front of a glacier, ice cap or ice sheet (PENCK; BRUCKNER, 1909). Such environments are adjusted to the average regime of fluvial and lacustrine processes that occur in ice-marginal sector (SLAYMAKER, 2009). The hydrology of proglacial rivers exhibits a distinctive pattern of flow, both seasonally and diurnally, and glacifluvial and glacial forms are present (CHURCH; GILBERT, 1975; EVANS; CLARK; MITCHELL, 2005; BENN; EVANS, 2010). There are glacial sedimentary deposits, as subglacial and marginal landforms, and glaciofluvial and glaciolacustrine landforms (BENN; EVANS, 2010). The proglacial landscapes could be viewed as quasi-equilibrium adjustments to the processes of erosion, sediment transport and deposition associated with ice-marginal fluctuations (SLAYMAKER, 2009).

The continued glacier recession reveal the recent ice-free land areas with intense geomorphic, hydrological and ecological changes (KLAAR et al., 2015). These areas are susceptible to rapid changes due the paraglacial processes (BALLANTYNE, 2002). In recent paraglacial activity, there are landscape modification and the sedimentary production is higher (BALLANTYNE, 2002). The nonglacial processes that are directly conditioned by glacier margin (CHURCH; RYDER, 1972; BALLANTYNE, 2002) and there are a reworking of the physical characteristics of the glacial sedimentary deposits in proglacial environment (BALLANTYNE, 2002a; BENN; EVANS, 2010).

The paraglacial term is defined by Slaymaker (2009) as nonglacial processes that are directly conditioned by glaciation. The paraglacial landscape could be characterized by rate of changes and by change trajectory in environment. The author discuss that almost all paraglacial landforms and paraglacial landscapes are transient and transitional. An interesting challenge of paraglacial landscapes is then to determine their rates of change; how far they have advanced along the trajectory from glacial to non-glacial; and how to recognize empirically the temporal and spatial relationships between proglacial, periglacial, paraglacial and fluvial landscapes (SLAYMAKER, 2009).

Implications of this approach for paraglacial landscapes are discussed for their relation to historical and dynamic geomorphology by several authors. Machado et al. (2019) summarizes that the paraglacial landscape is defined neither by processes nor by its location, but by the trajectory of landscape resettling, adopting time as its criterion. Paraglacial environments are influenced by non-glacial factors, such as wind and drainage, which act to remobilize sediments (BALLANTYNE, 2002b).

The geomorphological development followed by the glacial retraction is influenced by the high sedimentary load originating from glacial deposits, such as moraines, tills, eskers, and flutings. The processes of such modification involve mass movement, menting and refreezing, fluvial processes, among others. According to Petsch, Rosa, Simões and Simões (2018), as a glacier retracts, it exposes land features that are reworked by weather as well as by glaciofluvial and glaciomarine processes.

Due to the high variability of sedimentary mobilization and increased glaciofluvial activity, paraglacial landscapes become dynamic and there is an adjustment period that ends when there is reduced glacial influence conditioned by the lack of glacial sediments input or the stability of reworking processes (BALLANTYNE, 2002b).

The evolution of proglacial environment with paraglacial processes reflects the shrinkage of the glacier. The identification of the environmental changes of the glaciers on King George Island will make it possible to understand how this area of Antarctica has been reflecting climate change since the last century, a region that has, as well as the entire Antarctic Peninsula, climatic interconnections with southern Brazil.

The article investigates changes in paraglacial systems and their interconnections with glacial shrinkage since seven decades on King George Island, Maritime Antarctica (Figure 01).

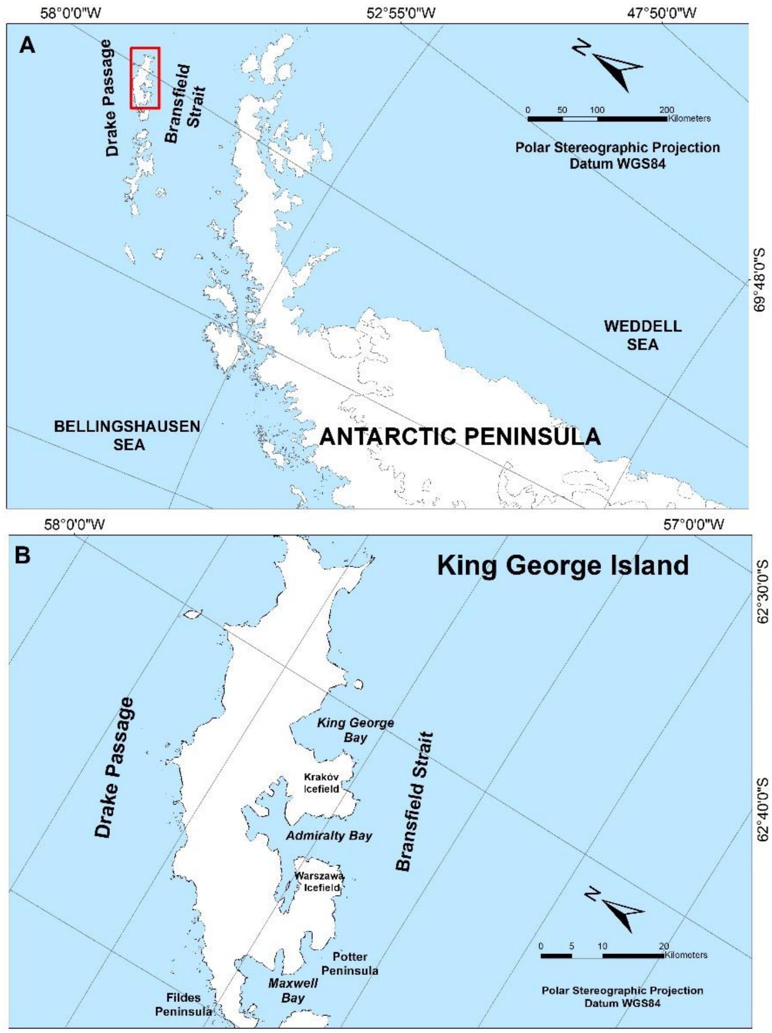


Figure 01- Localization map. A) Location of King George Island in the northwest of the Antarctic Peninsula. B) King George island location. Data: Quantárctica.

2. METHODOLOGY

The evolution of the ice-marginal systems and the configuration of terminating of the glaciers (marine/terrestrial and presence of lagoon of contact with the ice) was investigated through the geomorphological processes interpretation and the the glacial landforms comparison based on previous studies (e.g ROSA *et al*., 2009; PETSCH, ROSA, SIMÕES and SIMÕES, 2018; PERONDI, ROSA and VIEIRA, 2019, and ROSA *et al*., 2020).

The results shown observations performed in field during 2007/2008, 2010, 2011, 2013, 2014 e 2015 years in King George forelands. The laboratorial sedimentar analysis (granulometrical and morfoscopical parametres) results by Rosa et al. (2009) e Petsch, Rosa, Simões e Simões (2018) were considered.

Were used COSMO-SkyMed (Constellation of Small Satellites for Mediterranean Basin Observation), TerraSar-X, Wordview-2, Sentinel 1 and 2, ASTER, Landsat, SPOT, ortoimagens, REMA, TanDEM-X, PlanetScope satellital imagens. The images Landsat ETM+ imagens were acquired in

January 2007, Sentinel-2 was acquired in March 2018, PlanetScope was acquired in February 2018, and WorldView-2 was acquired in March 2014. Orthorectified WorldView-2 images have a spatial resolution of 0.5×2 m in their panchromatic and multispectral channels (eight bands). The Sentinel-2 Multispectral Instrument (MSI) data consist of 13 spectral bands, four of which have a spatial resolution of 10 m in the wavelength range 490–842 nm (European Space Agency 2017). The Sentinel-2 images used in this study were obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/) at no cost. Frontal variation data, obtained using SPOT (1988–1995 and 2000) imagery, were additionally considered in this study. The GLIMS (Global Land Ice Measurements from Space) shapefiles too were used in mapping. The glacier area loss data for the 1956–2019 period were available for the glaciers (obtained using aerial photographs) at the Polar and Climatic Centre of the Federal University of Rio Grande do Sul, Brazil.

The Rosa (2012), Rosa *et al.* (2014), Petsch (2019), Gonçalves *et al*. (2019), and Perondi, Rosa and Vieira (2019) data were used in this study for paraglacial and glacial processes and landforms comparison for each proglacial environment. This comparison was based on the Benn and Evans (2010) terminologies and Heckmann and Morche (2019) paraglacial concepts.

Was analyzed the proglacial environment, and the types of landforms and at different scales were identified according to Napieralski, Harbor e Li (2007) and Benn and Evans (2010). These records are useful for successive proglacial evolutionary stages reconstruction. The case study method involves a definition of proglacial areas as the area between the LIA glacier extent and a contemporary glacier margin (HECKMANN et al., 2012) and has been championed because it has utility for defining a specific relation to glacier retreat and to subsequent paraglacial dynamics.

The proglacial systems are classified into different zones according to glacial landform and geomorphic intensity (glacial and paraglacial sediment supply, deposition, and reworking) based on the Perondi, Rosa and Vieira (2019), and ROSA *et al*. (2020).

3. RESULTS AND DISCUSSION

3.1. The glacial system

Temporal analysis of glaciers and the recognition of glacial and paraglacial features and geomorphological processes show recent changes in glaciers. There are implications of changes in tidal glaciers, such as a possible decrease in the rate of shrinkage. Rosa et al. (2020) points out that glaciers with terrestrial termination had lower shrinkage than glaciers with marine termination when analyzing a sector of the Admiralty bay, King George Island. Other characteristics of glaciers also influence their response to ongoing climate changes.

Changes in the glacier shrinkage pattern are also highlighted by other authors in other areas. Sole et al. (2008) found high shrinkage rates in marine glaciers (GARDNER et al., 2011) and found no significant difference in the frontal shrinkage of marine glaciers when researching glaciers in the Arctic. There is also an interpretation that the dynamics of tidal glaciers are mainly controlled by the temperature of the oceans (CARR; STOKES; VIELI, 2013).

The reconstruction model for one of the sample sectors (Figure 02) reveals a rapid evolution of paraglacial systems related to different stages of decadal glacial shrinkage. Proglacial lakes and glacial geoforms have recently emerged associated with the new conditions for marine to terrestrial glaciers.

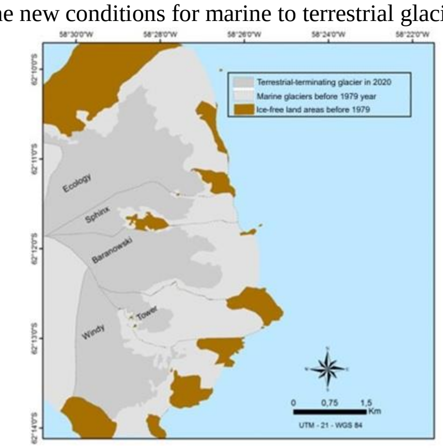


Figure 02. Changes in marine and land-terminating glaciers in southwest sector of the Admiralty Bay. Modificado de: Perondi, Rosa e Vieira (2019).

Changes in shrinkage pattern and responses in shapes and geomorphological processes were evidenced with the distance from the current glacial margin, thus presenting the mapping of glaciers that show changes in their frontal areas between 1979-2018 (Figure 03).

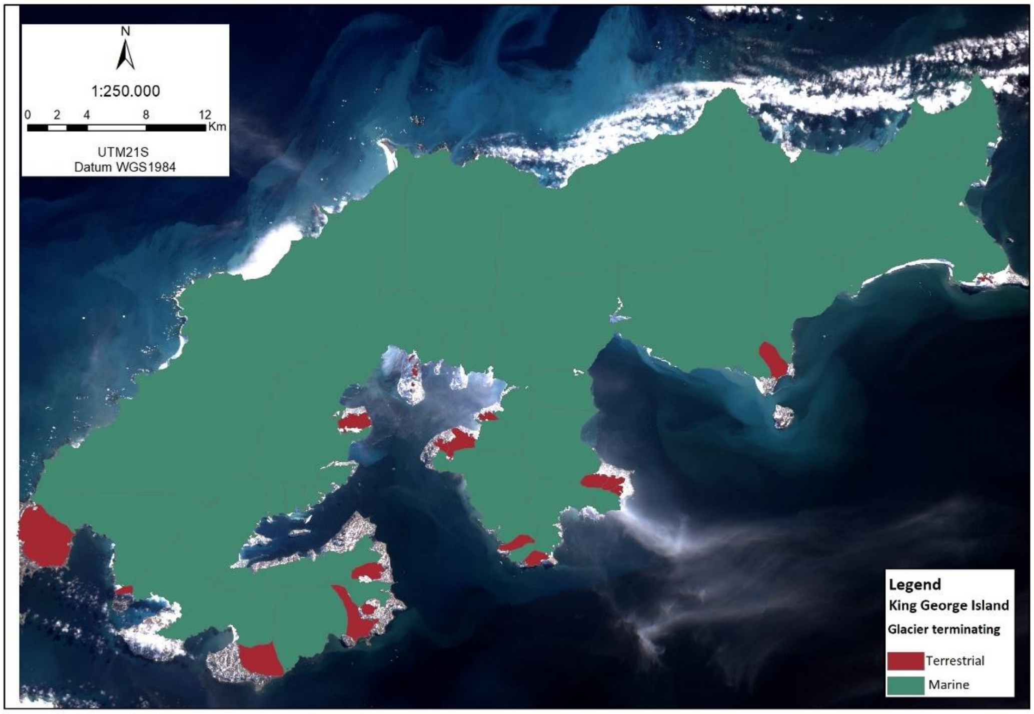


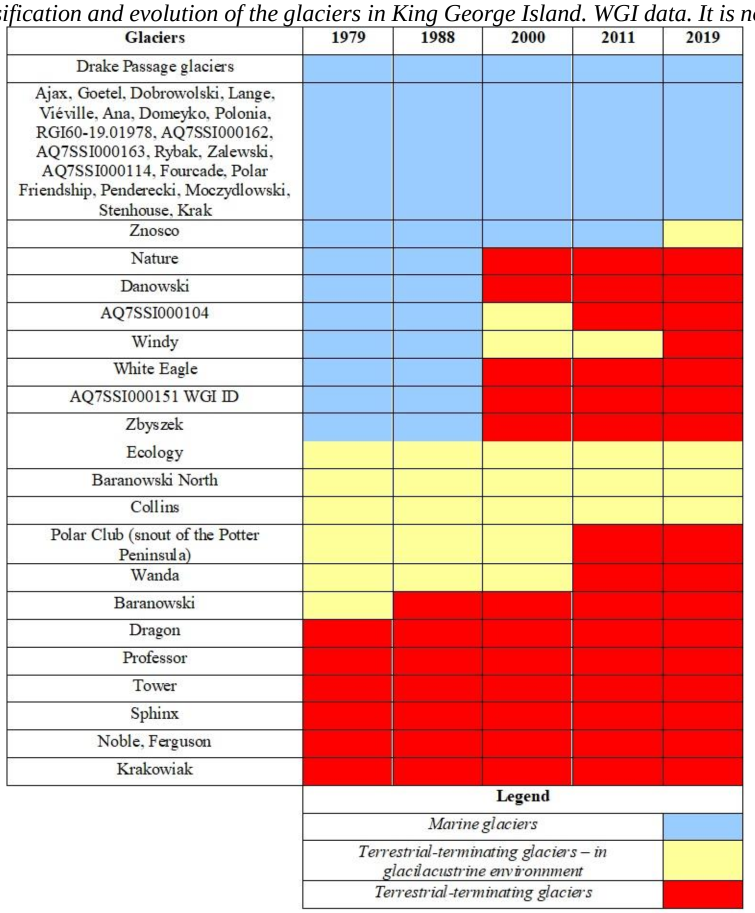
Figure 03. Terrestrial glaciers in King George Island. Sentinel-2 data (02/02/2018). Source of the Sentinel 2. Data: USGS.

Glaciers and paraglacial systems showed rapid changes and new landscapes were detected on King George Island. Glaciers presented an important change between 2000 and 2018, where its classification has changed from marine-terminating to land-terminating glacier (no-marine). There are currently 21 glaciers land-terminating on King George Island (corresponding to 31% of the glaciers) and 11 are present in Admiralty Bay. 25% of these glaciers were marine in 2000. The new paraglacial environments (since 2000) has 1.7 km^2 of the total area. There are not new terrestrial glaciers in Drake Passage sector of the island between 2000 and 2018.

3.2. The paraglacial system

The identification of types of landforms and different scales were useful for the reconstruction of successive evolutionary stages in the paraglacial system. Recent formation of proglacial lakes directly connected with the glacier is observed, after changing the conditions of the marine glacier (Figure 03 and Table 01) for a land –based glacier.

Table 01. Classification and evolution of the glaciers in King George Island. WGI data. It is not considered the Icefalls in this analysis.



Geomorphological mapping showed that paraglacial processes differ between environments marginal to glacier ice and there are evolutionary stages that develop with the shrinking of glaciers (Table 2). Proglacial environments that have areas in stage 4 correspond to the marginal environment of contact with ice. Glaciers that have passed from marine to terrestrial termination are only Stage 4. Stage 1 currently occurs to older sectors for land-based glaciers.

Table 2- Evolution stages of the paraglacial system during glacier retreat processes for King George sectors.

Response to continuous glacial retreat or shrinkage and changed to terrestrial glacial landsystem	Formed subaerial environment	Preserved glacial features	Erosion and sediment production glacifluvial and paraglacial	Proglacial drainage pattern	Transition in time and space
STAGE 1	Paraglacial; Periglacial; Non proglacial	Arêtes, horns and valleys with denudation	Low; Higher stability leads to greater coverage of mosses and lichens	Non proglacial lakes and fluvial channels	Thousands and hundreds of years
STAGE 2	Paraglacial; periglacial; Proglacial-distal	Moraines of higher extension	Low;	Interlaced channels can connect the farthest lakes from the glacier	Hundreds of years (since the Little Ice Age)
STAGE 3	Paraglacial; periglacial; Proglacial: proximal	Larger glacial deposits	Average;	Lakes may lose direct contact with the glacier	Multi-year/ decadal
STAGE 4	Paraglacial; Periglacial; Proglacial: Ice-marginal,	All recent glacial deposits	High; There is marginal glacial deposition	Channels and lakes ice-contact	Newly exposed by multi-year retraction

Paraglacial systems that have the first successional stage, are characterized by the gradual formation for a diversified environment with a predominance of paraglacial and periglacial activity in relation to the decreasing glacial influence. Mass movements, chemical weathering, freezing activity and permafrost melting are also evident, as in the other stages. Shorter length lakes and interlaced channels, mainly fed by melting snow and stagnant ice, are formed where there was part of the body of the active glacier. Interlaced channels are interconnected to proglacial lakes and wetlands of lesser extent. Along the interconnected channels and lakes, fed essentially by the melting of snow when far from the glacial margin, there is the formation of humid areas with organic activity, as well as colonization by moss and lichen.

In the second stage, in the ice-free area there is a greater area with a predominance of modifications by paraglacial activity than in the previous stage, as there is a transition from glacial to periglacial successively with a greater stability in the reworking processes of glacial landforms. When the area is exposed for the longest time, paraglacial processes are evidenced in association with the periglacial ones. Interconnected lakes and channels, fed by snow and melting ice flow, are formed where there was part of the body of the active glacier and are interconnected to wetlands and proglacial lakes of lesser extent. Lakes decrease in area and volume as the distance from the glacial margin increases. Reworked colluvium and glacial deposits in the previous stages are eroded in sectors where the flow of snowmelt becomes concentrated in rapid episodes throughout summer.

In a third stage there is the formation of a sector that is marginal to the ice, but does not contact it. We can still notice, as in the previous stage, that shapes suffer rapid and intense changes due to paraglacial activity. The proglacial lake keeps on receiving subglacial snowmelt flow, but through connecting proglacial channels (Figure 04). Proglacial channels help to rework exposed deposits in the previous phase and also on the loss of their connectivity. Greater sedimentary removal can be evidenced by snowmelt than by ice transport as the front of the glacier is distanced. Mass movements in steeper areas from older morainic deposits generate talus deposits. In these sectors at the base of the slopes, greater deposition may occur than transport by paraglacial processes.

In the fourth stage there is an environment recently exposed by shrinkage and directly connected to the glacier. Deposits of moraines of recession are formed in the frontal and lateral position of the glacier and are subject to the beginning of paraglacial activity, as well as the deposits of flutings and eskers. There is a high intensity in paraglacial processes, such as mass movements, chemical weathering, among others. Channels of snowmelt and surface ice, subglacial as well, emerge in the marginal environment from the newly formed ice and there is a large supply of liquid water in the summer. Proglacial lakes and lagoons are directly connected to the glacier (Figure 04).

Figure 04. Proglacial channels connected, the evolving proglacial lake and reworking of till deposits, flutings and moraines of recession.

Wanda glacier, located on King George Island, is on stage 4 in the following sectors: lateral and latero-frontal areas. In the older sectors, the glacial forms show that there was active glacial transport and deposition of boulders and large rocky blocks, a high proportion of till and flutings deposition. Subglacial sediments in this sector are morphologically faceted and display striations, showing greater glacier dynamics (flow velocity and basal sliding). Sedimentary transport in conditions of a possibly more active flow rather than the current one deposited marginal and frontal moraines of recession of greater sedimentary thickness than those exposed in stage 4.

Stages presented here can be synthesized in a proposal that admits 3 environments, one proximal, in contact with the ice, and two distal ones. For the glacial deposits on the edge of the Wanda and Ecology glaciers it is possible to apply this zoning. The ice-free environment due to shrinkage in recent years is related to a greater sedimentary modification, but the front moraines of recession have more fine sediments than the older ones. The processes of sediment transport by wind and snowmelt can take finer sediments to sectors downstream in the slope. The farther from the current glacial margin and the older its exposure due to glacial retreat, we can notice greater stability of deposits due to the presence of moss and lichen in less steep sectors. At the same time, it is evident that each environment marginal to the ice is distinguished in several aspects, such as the availability of snowmelt, the shape of its slope, besides the greater or lesser influence of glaciers and marine action, among other aspects.

Monitoring and analysis on and post field activity made it possible to assess the relationship between processes and forms with the occurring shrinkage. In the most recently formed landscape, all processes evidence glacial recession, with no increase in recent decades. The increase in snowmelt channels along the glacier margin, connectivity with proglacial lakes and the formation of a terrain susceptible to alteration by paraglacial processes mark the initial phases of a paraglacial system with the least glacial influence, in a transitory relationship of processes and forms, as stated by Heckmann and Morche (2019).

Recent paraglacial sectors (created since 2000) are characterized by new proglacial lakes, glacial and glaciofluvial mesoscale landforms (Stoss and Lee, moraines of recession and flutings). Ecology, Wanda, Windy, Anna Sul and Baranowski glaciers showed non-glacial landforms such as outwash plains, talus deposits, ravines and river channels in the recent paraglacial system.

These newly formed paraglacial environments are important targets for monitoring. Several glaciers and recent paraglacial systems are evolving rapidly and new landscapes are emerging on King George Island due to changes in glacier types and the destabilization of some landforms, erosion by snowmelt, and other active paraglacial processes. Glaciofluvial processes also make these environments unfavorable to the preservation of (small-metric) landforms.

4. CONCLUSIONS

The paraglacial comparison reveal successive evolutionary stages for paraglacial system in short-term.

Glaciers and paraglacial systems showed rapid changes and new landscapes were detected on King George Island. Glaciers presented an important change between 2000 and 2018, where its classification has changed from marine-terminating to land-terminating glacier (no-marine).

Geomorphological mapping shows that paraglacial processes which differ between environments marginal to glacier ice are not standardized. Location in slope values, spatial layout in the valley and its location in the environment marginal to the ice as well as the degree of disturbance of the environment and the drainage pattern by geomorphological mapping could be synthetized in future proposal. Their parameters should also be criteria to be identified in the continuous monitoring of changes in geomorphological and evolution features of the marginal environment to ice. The expansion of data in the field to other latitudes, in aid to the identification of the evolutionary stage of the depositional environment, in response to glacial shrinkage. And may enable the detailing of the evolution of these Antarctic paraglacial systems and the extraction of predictive scenarios of evolution, in face of the projection of an increase of the average surface temperature for the next decades in the polar regions.

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6. ACKNOWLEDGMENTS

The authors express gratitude to all institution that provide us the support for this study: Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), CAPES, PROANTAR and Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS).

Received in: 20/11/2019
Accepted for publication in: 04/12/2020