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Insights into deglaciation of the largest ice-free area in the South Shetland Islands (Antarctica) from quantitative analysis of the drainage system

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A B S T R A C T

A quantitative geomorphic analysis of the drainage system on Byers Peninsula, Livingston Island, has been carried out in order to study the relief evolution, glacial history and possible neotectonic influence on the largest ice-free area of the South Shetlands archipelago. Aerial photographs, SAR data from RADARSAT-2 satellite, field work, a digital elevation model and GIS spatial analysis have been used to identify, map and study the existing drainage basins. A series of morphometric parameters have been studied in 30 selected basins in order to characterize their shape as well as the drainage network. Results in morphometric parameters reveal elongation trends in the shape of basins and a limited hierarchical network, common of a youthful stage of landscape evolution models.
Several morphometric indexes (hypsometric integral, hypsometric curves, SL index, transverse topographical drainage basin asymmetry-T-Factor) have been used to study possible controls on drainage development. Results have been discussed in relation to relief and drainage evolution linked to the spatial distribution of lithological units and structural framework. T-Factor shows an apparently disorganized pattern and absence of tectonic influence. However, there are local values of second order basin asymmetry directions and magnitudes, which could reflect a succession of master rills through time, related to the changes in water supply during the deglaciation history of Byers Peninsula. Hypsometric values and curves of basins are also mainly related to a young stage of landscape evolution. Analysis of hypsometric integrals together with T-Factor index has allowed us to establish a possible deglaciation model on Byers Peninsula, which successfully explains the results. Areas of different landscape evolution stage are linked in space and support the hypothesis of local glacial centers during the ice cover retreat process. SL index results do not show the same pattern in results, which could be due to differences between incision and lateral shifting ratios.
Quantitative geomorphic analysis indicates that during the deglaciation of Byers Peninsula, at least three areas acted as local glacial centers (NW, central and Rotch Dome area). Changes in index results clearly show a different behavior between two areas; distal areas and proximal areas close to the glacial centers. Morphometric indexes have demonstrated their being useful tools to provide information on the glacial history in recently deglaciated Antarctic areas.

1. Introduction

Although less than 0.5% of the Antarctic emerged surface is ice-free in summer, fluvial drainage systems play an important role in processes with important consequences in the landscape evolution and environment. Ice and snow melting produce water circulation within glacial margins, but also below and above the glaciers. The study of the Antarctic fluvial drainage networks provides information on hydrological and geomorphological processes and can also contribute to understanding the relief history and to outline scenarios connected with changes in glacial melting, permafrost and sea level.

The scarcity of ice-free surfaces and the difficulties of accessibility to complete drainage basins is a limitation for a direct observation of drainage processes that have consequences for the glacial balance and for ecosystems. Recent discoveries have pointed out the crucial role of subglacial water in the movement and stability of ice-sheets.

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Episodic drainage of large subglacial lakes along bedrock channels is a mechanism that can affect rapid ice flow, as has been shown in the subglacial lakes of Recovery region in East Antarctica (Bell et al., 2007).

The study of mechanisms and processes connected with water flow from glaciers is especially interesting in the Antarctic Peninsula region which is experiencing one of the most rapid warming phases on Earth in the last decades (Turner et al., 2005; Mulvaney et al., 2012). In this region such circumstances are producing glacier mass loss, collapse of ice shelves and acceleration of glaciers (Vaughan et al., 2003; Bentley et al., 2009).

Moreover, the study of drainage systems can provide useful information to reconstruct past phases of glacial fluctuations and episodes in the relief evolution. A study on Antarctic fluvial drainage systems in a large ice-free area has been carried out in northern Victoria Land (Baroni et al., 2005), providing data on fluvial erosion in connection with the glacial, tectonic and denudation history of the Transantarctic Mountains.

In the area studied in this work, previous research of the drainage system has been carried out focusing on the geomorphic role of snow meltwater (Birnie and Gordon, 1980) and on the description of the geomorphological features of the drainage system (López-Martínez et al., 1996a). The development of modern techniques of digital representation and treatment of relief, the availability of current satellite images and the possibility of applying different geomorphic indexes allow exploration and quantification of aspects of the drainage system and the relief not previously studied on Byers Peninsula or elsewhere in the region.

The analysis of terrain and drainage networks is a powerful tool to detect areas of active geomorphological processes (Keller and Pinter, 1996; Burbank and Anderson, 2001) as rivers and their drainage basins are sensitive to changes in the parameters (lithology, climate and neotectonics) that control their shape and spatial distribution. Therefore, geomorphic indexes based on terrain and river parameters such as stream gradient, relief, shape of drainage network, morphometry of watersheds, etc., can provide significant information on the geomorphological Quaternary evolution. The use of geomorphic indexes could allow us to understand the evolution of glacial terrains, in this case with respect to deglaciation.

This study provides an insight into early drainage formation from different sources of superficial water and on fluvial processes, such as channel migration or stream captures. It aims to evaluate the main factors controlling the origin and evolution of the drainage system on Byers Peninsula. The objective is to detect how the drainage system has contributed to build the peninsula's relief and to find evidence of the recent geomorphological, tectonic and glacial history of Byers Peninsula, a representative area in the South Shetlands archipelago, Antarctic Peninsula region.

1.1. Study area

Byers Peninsula is located in Livingston Island between latitudes 62°34′35″ and 62°40′35″S, and longitudes 60°54′14″ and 61°13′7″W. With a surface of about 60 km^2, the peninsula is the largest ice-free area in the South Shetland Islands (Fig. 1A, B). The highest area and more abrupt relief is the northwestern sector (maximum altitude 265 m a.s.l., known as Start Hill). The general landscape is dominated by a series of extensive platforms at altitudes up to above 100 m a.s.l. and higher isolated hills such as Chester Cone, Cerro Negro and others (Fig. 1C). Rocks outcropping on Byers Peninsula are mainly Jurassic to Cretaceous volcanoclastic and detrital sedimentary rocks, with late Cretaceous sills, plugs and other intrusive bodies (Fig. 1D). Most of the 71 km long coastal area of the peninsula is occupied by present and Holocene raised beaches (Thomson and López-Martínez, 1996) (Fig. 1C, D). Byers Peninsula has been the object of many geological and geomorphological studies (for details see López-Martínez et al., 1996b) and a geomorphological map at 1:25,000 scale is available (López-Martínez et al., 1996c). There is a well-developed drainage network including around 110 lakes and pools, which has been the object of descriptive studies (Birnie and Gordon, 1980; López-Martínez et al., 1996a).

In addition to the geological and geomorphological interest, Byers Peninsula is an important area for ecological and limnological studies (e.g. Björck et al., 1996; Quesada et al., 2006, 2009; Toro et al., 2013). Since 1967, Byers Peninsula has been a protected area within the Antarctic Treaty System due to its scientific values and currently is listed as the Antarctic Specially Protected Area no. 126.

Meteorological data of Byers Peninsula are available only for short periods (e.g. 2001–2004, Rochera et al., 2010; 2002–2010, Bañón et al., 2013). Mean annual temperature is −2.8 °C and summer mean temperatures between 1 and 3 °C, with daily maxima up to 10 °C and daily minima down to −10 °C, according to data from the Juan Carlos I station, located on the same island a distance of about 40 km away Mean annual precipitation can be estimated as higher than 500 mm (Bañón, 2001; Rochera et al., 2010; Bañón et al., 2013). The peninsula is snow-covered for much of the year, but is usually snow-free by the end of the summer. Wind and associated processes are important factors controlling snow accumulation and its distribution (Fassnacht et al., 2010).

Under the mentioned climatic conditions, soils in the study area are Cryosols (FAO, ISRIC, IUSS, 2006) and their composition is closely related to the parent material. In general, soils in the region and on Byers Peninsula are low in organic matter and organic carbon content, and physical weathering is much more active than chemical weathering (Navas et al., 2005, 2006, 2008; Balks et al., 2013). Permafrost and periglacial processes have been widely described and mapped in the Antarctic Peninsula region (Bockheim et al., 2008; Vieira et al., 2010; López-Martínez et al., 2012; Bockheim et al., 2013). On Byers Peninsula, thermal records, field observations and soundings have revealed extensive periglacial processes and an active layer from about 30 cm to more than 1 m depth at altitudes above 20 m a.s.l. (Serrano et al., 1996; Bockheim et al., 2008; Serrano et al., 2008; Vieira et al., 2010; López-Martínez et al., 2012; Bockheim et al., 2013).

The melting of snow and fusion of the ice from the glacier dome in early mid-summer leads to an additional water supply, increasing the normal water volume flowing during the rest of the year. The release of these water flows also increases the available energy of fluvial processes that cause altering actions on the drainage channels during a few months a year.

The geomorphological history and the mentioned conditions have led to the presence of numerous drainage channels, lakes and ponds on Byers Peninsula (Fig. 2). The analysis of this drainage system is the main object of this study.

1.1.1. Relief and drainage system

Byers Peninsula, located on the western part of Livingston Island, forms a Y-shaped area open to the west, with coastlines facing toward three preferential directions, north, west and south and where the eastern sector is directly connected to a glacial dome (Rotch Dome) that extends towards the rest of the island (Fig. 1). Two main processes, coupled together, have played a dominant role configuring the present relief on Byers Peninsula. Marine and glacial landforms influence the main morphological shape of the peninsula.

Although it is possible that the deglaciation started about 9000 yBP (Hall, 2009), it seems that most of Byers Peninsula has been probably ice-free, since the last retreat of the glaciers, around 5000–4000 yBP (Björck et al., 1993, 1996; Toro et al., 2013). The Rotch Dome is at present the major glacial feature in the area but glacial activity has left its imprints on the pre-existing marine landforms as can be observed by numerous evidence still present (Martínez de Pisón et al., 1996a; López-Martínez et al., 1996c). The history of the deglaciation and ice fluctuations of Byers Peninsula is complex, as is the relative sea-level record of the South Shetland Islands. These latter records reflect transgressions at approx. 6000–7000 and approx. 400 cal yBP that