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COMPILATION OF GEOMORPHOLOGICAL MAP FOR RECONSTRUCTING THE DEGLACIATION OF ICE-FREE AREAS IN THE MARTEL INLET, KING GEORGE ISLAND, ANTARCTICA

ELABORAÇÃO DE MAPA GEOMORFOLÓGICO PARA A RECONSTRUÇÃO DA DEGLACIAÇÃO DAS ÁREAS LIVRES DE GELO NA ENSEADA MARTEL, ILHA REI GEORGE, ANTÁRTICA

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Abstract

We compiled a geomorphological map and a reconstruction map of glacier extension and ice-free areas in the Martel Inlet, located in King George Island, South Shetlands, Antarctica. Glacier extension data were derived from a digitized orthophotomosaic (2003), SPOT (February, 1988; March, 1995 and 2000), Quickbird (October, 2006) and Cosmo-Skymed (February, 2011) images. This mapping was supported by field data collection carried out in the summers of 2007, 2010 and 2011, and by topographic surveys and geomorphological mapping of proglacial area. Several types of glacial deposits were identified in the study area, such as frontal and lateral moraines, flutes, meltwater channels and erosional features like rock moutonnées, striations and U-shaped valleys. These features allowed reconstructing the evolution of the deglaciation environment in the Martel Inlet ice-free areas, which has been affected by a regional climate warming trend. The mapped data indicated the glaciers in study area lost about 6.64 km² of their ice masses (13.2% of the total area), without any advances during

1979-2011. Since those years these glaciers receded by an average of 0.25 km a^{-1}. These ice-free areas were susceptible to rapid post-depositional changes.

Resumo

Este estudo apresenta o mapa geomorfológico e mapa de reconstrução da extensão das geleiras e áreas sem cobertura de gelo na Enseada Martel, localizada na ilha Rei George, Shetlands do Sul, Antártica. Os dados das áreas das geleiras foram obtidos através de um ortofotomosaico gerado (2003), imagens SPOT (Fevereiro de 1988; Março de 1995 e 2000), Quickbird (Outubro de 2006) e Cosmo-SkyMed (Fevereiro de 2011). Este mapa foi baseado em dados de campo obtidos nos verões de 2007, 2010 e 2011, e pelos dados topográficos e mapa geomorfológico gerado neste estudo. Diversos tipos de depósitos glaciais foram identificados na área de estudos, tais como morainas laterais e frontais, *flutings*, canais de água de degelo e feições erosivas tais como rochas *moutonnées* e vales em forma de U. Estas feições permitiram reconstruir a evolução do ambiente de deglaciação das áreas sem cobertura de gelo da enseada Martel, que tem sido influenciada pela tendência de aquecimento regional. Os dados mapeados indicam que as geleiras da área de estudo perderam aproximadamente 6,64 km² de suas áreas (13,2% do total), sem reavanços durante o período entre 1979-2011. Estas geleiras têm retraído em uma média de 0,25 Quilômetros por ano. Estas áreas recentemente deglaciarizadas são susceptíveis a rápidas mudanças pós deposicionais.

Introduction

Several studies indicated that glaciers in the Antarctica Peninsula have showed rapid dynamic responses to environmental changes (OERLEMANS, 1994; ABDALATI and STEFFEN, 2001; PAUL *et al*., 2004; BOLCH and KAMP, 2006). In order to detect changes in glacier frontal positions in this continent, most of these studies have used cartographic, photogrammetric and remote sensing data.

The analysis of spatial distribution of glacial landforms is an important approach to better understand the landform genesis, and for revealing the area, thickness, ice flow direction and retreat dynamics of glaciers (BOULTON *et al.,* 1985; HARBOR, 1993; PUNKARI, 1995; Clark*, 1997;* COLGAN and PRINCIPATO, 1998; KLEMAN and HATTESTRAND, 1999; CUFFEY *et al.,* 2000; MARTINI *et al.,* 2001; BOULTON *et al.,* 2001; STOKES and CLARK, 2003). Furthermore, the spatial distribution of glacial landforms such as end moraines (in ice-marginal position) have been analyzed to reconstruct glacier extent (KLEMAN *et al*., 1997; CLARK *et al*., 2000; BOULTON *et al.,* 2001).

Photogrammetric and remote sensing data can provide information about location and distribution of ice marginal landforms (BOLCH and KAMP, 2006). In the process of image acquisition, aerial surveys have greater flexibility than orbital remote sensing, and aerial photographs are an important source of data to compile geomorphological maps and to generate highly accurate Digital Elevation Models (DEM) (CHANDLER, 1999; DIXON *et al*., 2003; SMITH *et al*., 2006) and the Geographic Information System (GIS) is another technique that can be used to support studies of glacial landforms and landscape evolution.

This paper aims to compile a new geomorphological map of ice-free areas in the Martel Inlet, located in Admiralty Bay, King George Island (KGI), South Shetlands, Antarctica, using remote sensing and GIS techniques, in order to reconstruct the evolution and configuration of local glaciers, their ice-flow and retreat patterns of present deglaciation.

Study area

MarteI Inlet is located in the northern sector of Admiralty Bay, KGI, South Shetlands archipelago (between 61°54’ - 62°16’S and 57°35’ - 59°02’W), Antarctica (Figure 1). The South Shetlands are an island arc with Mesozoic and Tertiary volcanic and sedimentary rocks (CURL, 1980). The KGI is divided along its southern margins by three major fjord-like features, located at Maxwell Bay, Admiralty Bay and King George Bay. Most part of Martel Inlet is surrounded by tidewater glaciers with steep slopes, highly crevassed and fast ice-flow. Some of these glaciers have termini on land, such as Wanda, Dragon and Professor glaciers.

The maritime subpolar climate in the South Shetland Islands is often affected by storms generated in the Pacific Ocean, responsible for high rates of local precipitation. The mean summer air temperature can reach 2.8ºC, which result in high meltwater production during the summer months (SIMÕES *et al*., 1999).

During the Last Glacial Maximum (LGM), large glaciers covered fjords in KGI (JOHN and SUGDEN, 1971; YOON *et al*., 1997). This glaciation process resulted in several marine terraces, erosional platforms and glacial landforms (EVERETT, 1971; JOHN and SUGDEN, 1971; BIRKENMAJER 1981; LEVENTER *et al*., 1996; HJORT *et al*., 1998; HALL, 2003). Since the LGM, the South Shetland Islands have experienced progressive postglacial warming, with a few minor limited cooling events, associated with glacier advances (HALL, 2007). About 9 ka BP, this glacier ice retreated to the heads of the smaller tributary fjords and the terrestrial portions of KGI started to become ice-free (MÄUSBACHER et al., 1989). At least one or possibly two ice readvances may have occurred since 9 ka BP (CURL, 1980; HALL, 2007). Several studies suggested that deglaciation on the ice-free areas of KGI comprises the early-middle Holocene (MÄUSBACHER, 1991) to the middle-late Holocene (BJÖRCK *et al*. 1991, 1993, 1995). According to Yoon *et al*. (1997), glacial deposition records (subglacial till) indicated that Martel Inlet was covered by glaciers, about 2.3 ka BP. Glacimarine sediments in the Martel Inlet indicated that the study area was deglaciated after 1.9 ka BP. Several studies have showed evidences of glacier retreat in the Martel Inlet since the mid-twentieth century in King George Island (SIMÕES and BREMER, 1995; BREMER, 1998; PARK *et al*., 1998; SIMÕES *et al*., 1999; BRAUN and GOSSMANN, 2002).

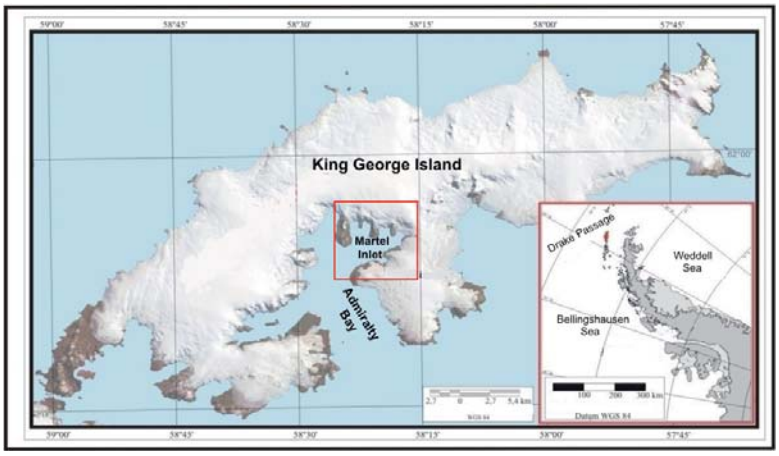

Figure 1 – Martel Inlet location in King George lsland, Antarctica.

Methods

A geomorphologic map of ice-free areas in the Martel Inlet was compiled with multitemporal remote sensing data processed in a GIS environment, supported by reconnaissance of the glacial landforms and landscapes during field data collection, in order to reconstruct the patterns of ice-recession during deglaciation.

Sediment samples were collected during three fieldworks carried out in the summers of 2007, 2010 and 2011, over proglacial areas for geomorphological interpretation, covering different microenvironments and geomorphic features in proglacial environment. We analyzed the shape and roundness of these samples at the Laboratory of Sedimentology of CECO (Center for Marine and Coastal Studies at UFRGS). In addition, topographical surveys were carried out using a Total Station (Leica Geosystems TPS1200), to measure transversal and perpendicular transects on the proglacial area.

An orthophotomosaic was generated from panchromatic vertical aerial photographies at scale of 1:50.000, taken on 22nd January, 2003, provided by the Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA). The planialtimetric points generated automatically by LPS software (Leica Photogrammetry Suite) were interpolated in ArcGIS™ software (ESRI, Inc.), to generate a DEM with spatial resolution of 0.7 m, using Kriging as geostatistical method.

Some glacial landforms that indicated the frontal position of former glacier during retreat processes were investigated and mapped. The geomorphologial mapping of subglacial and ice-marginal landforms was based on glacial lineaments and moraine ridges, and the aspects of morphology were described following suggestions of Glasser and Jansson (2005), Gustavsson *et al*. (2006) and Benn and Evans (2010).

The area of glaciers in 1979 was based in a study of Arigony-Neto (2001) (orthophotomosaic of 1979). The identification of geographical distribution of glacial marginal landforms was based on fieldwork, topographic profiles surveyed and on visual interpretation of Quickbird images (0.6 m spatial resolution, acquired in October, 2006) and of the orthophotomosaic produced in this study. The geomorphological mapping of glacial landforms from remote sensing data is a fundamental technique for reconstructing palaeoenvironments, and it was also used for reconstructing the pattern and style of deglaciation of ice-free areas in Martel Inlet. The extent and position reached by these glaciers were quantified using SPOT (20 m spatial resolution, acquired on February, 1988, and on March, 1995 and 2000) and COSMO-SkyMed orthorectified images (in spotlight mode, with 1 m spatial resolution, acquired on February, 2011). Striations, subglacial meltwater channels and fluting deposits indicated the pattern of ice discharge in glaciers.

Results

As a consequence of the glacier retreat processes in the study area, large glaciarized areas became ice-free, exposing glacially eroded landforms and till deposits, which recorded the former glacier configuration and the deglaciation history. We observed several eroded bedforms on these ice-free areas, such as rock moutonnées, stoss and lee, striated pavements, arêtes and glacial cirques (Figure 2).

Figure 2 – Striated pavement in Wanda proglacial area (A) and glacial cirques in the Keller Peninsula (B). January, 2011.

Moraine ridges were found near the glacier front. Lateral and end moraines of exposed proglacial area were linked to stages of retreat stabilization (Figure 3 and 4). Frontal moraines are generally curved, reflecting the shape of the glacier´s front edge in a previous position. Subaquatic depositional systems as morainal banks were identified in topographic profiles surveyed in the Wanda proglacial area (Figure 3). These latter features can reveal information about local patterns of deglaciation.

Landforms of glacial meltwater erosion include both subglacial and ice-marginal meltwater channels. Proglacial meltwater channels occur throughout the study area in several spatial scales. Lakes (Figure 3) resulted from meltwater channels near front glaciers with land terminus. Fluting deposits (Figure 3), located on the Wanda proglacial area, are glacial lineations formed parallel to ice-flow direction, and presented a spherical and rounding morphology.

Raised beaches with maximum height of 6 m, composed of well-sorted gravels and defines the marine limit extension in the Holocene, and is determined by the eustatic sea level rise associated with the post-Glacial Maximum deglaciation (JOHN and SUGDEN, 1971).

A transverse topographical profile indicated the presence of an U-shaped valley (Figure 5) in the northern sector of the Martel Inlet. The pattern of ice flows appeared to be influenced by local topography. The presence of steep terrains in recently exposed rocky areas provides favorable conditions for the development of debris flow processes in moraine deposits.

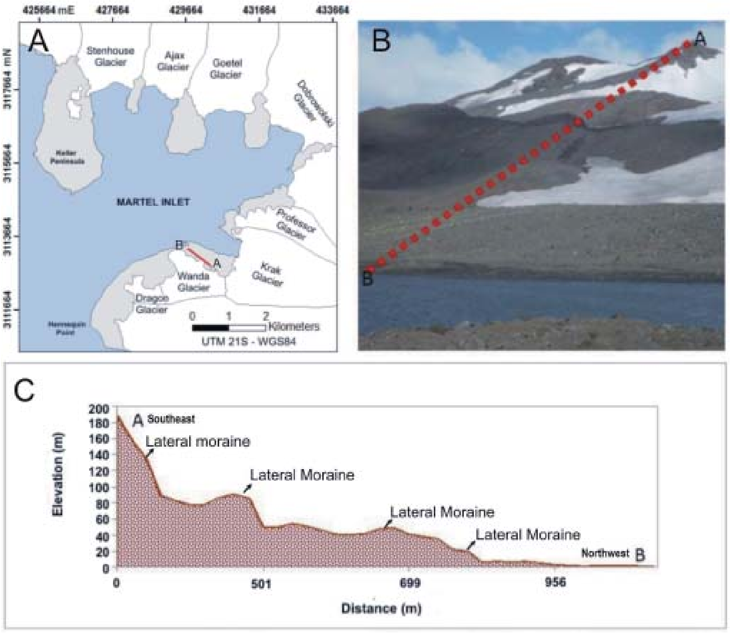

Figure 4 – Topographical profile A-B (dashed line – Figure B) shows morainic ridges in Wanda Glacier (Figure A) marginal area (Figure C).

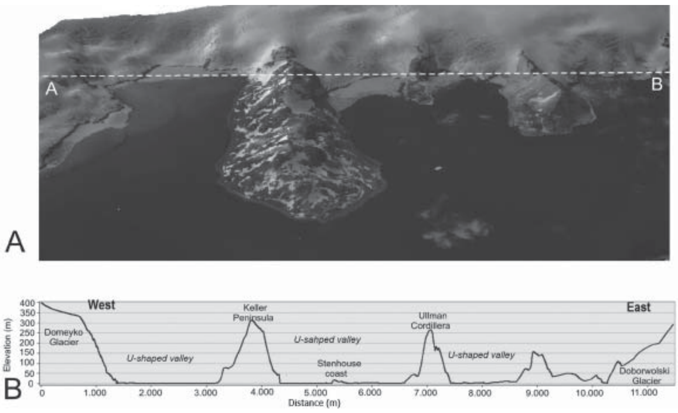

Figure 5 – Transverse topographical profile (white dashed line in the perspective view scene – Figura B) indicates the presence of an U-shaped valley in the northern sector (Figura A) of the Martel Inlet.

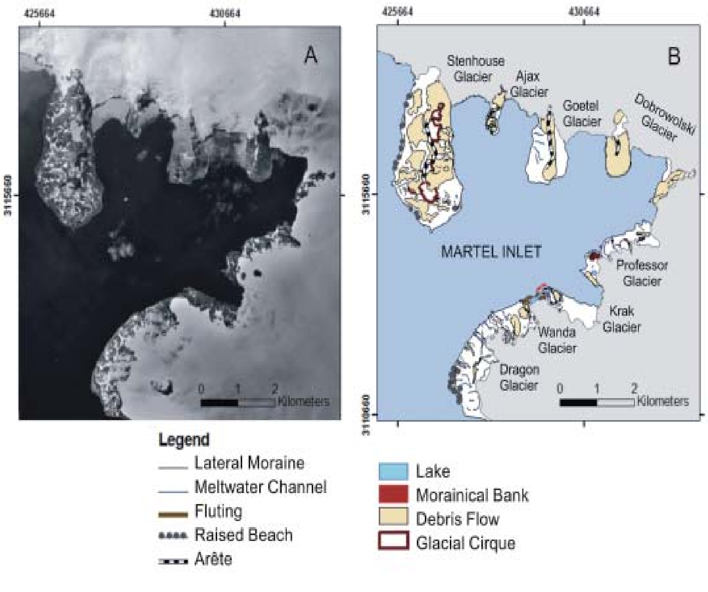

Figure 3 – Orhophotomosaic (right figure) (A) and geomorphological map (last figure) (B) of the Martel Inlet ice-free areas (based on Quickbird (2006), orthophotomosaic produced in this study and COSMO-SkyMed orthorectified images (2011).

The reconstruction map of glacier extension in Martel Inlet ice-free areas is presented in Figure 6. During the period 1979-2011, glacier retreat amounted to 13.2% (6.64 km² - Table 1) of the total area. The tidewater glacier Dobrowolski (0,076 km^2a^{-1}) presented the highest annual retreat rate and has 17.27% of the area loss. The land terminus glaciers Wanda (31.27%), Dragon (53.84%) and Professor (39.71%) presented the highest area loss during the period. Other glaciers have 11.7% (Krak), 7.6% (Ajax), 6.1% (Stenhouse) and 6.98% (Goetel). Thus, in those years glaciers in the study area have retreated by an average of 0.25 km a^{-1}.

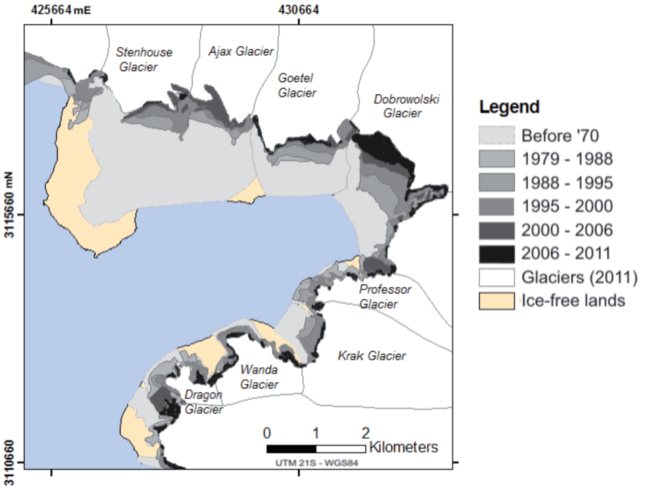

Figure 6 – Glacial retreat in the Martel Inlet. Glacier extend data were derived from lateral and bank morainal positions and orthophotomosaic (1979), SPOT (February of 1988; March of 1995 and 2000), Quickbird (October, 2006) and Cosmo-Skymed (February of 2011) orthorectified images.

Table 1 – Glacier retreat rates from 1979 to 2011.

Glacier	Area in 1979 (km²)	Area loss (km²) 1979-1988	Area loss (km²) 1988-1995	Area Loss (km²) 1995-2000	Area loss km²) 2000-06	Area loss (km²) 2006-2011	Area in 2011 (km²)	Total area loss %	Retreat rate km²a⁻¹
Stenhouse	9.70	0	0.20	0.2	0.18	0.02	9.10	6.18	0.019
Goetel	9.30	0.06	0.26	0.18	0.06	0.09	8.65	6.98	0.020
Ajax	6.94	0.01	0.16	0.12	0.23	0.01	6.41	7.63	0.017
Dobrowolski	14.07	0.54	0.57	0.56	0.22	0.54	11.64	17.27	0.076
Professor	1.41	0.23	0.08	0.13	0.06	0.06	0.85	39.71	0.018
Krak	5.73	0.29	0.11	0.21	0	0.06	5.06	11.70	0.021
Wanda	2.27	0.25	0.09	0.30	0.05	0.02	1.56	31.27	0.022
Dragon	0.91	0.28	0.08	0.06	0.05	0.02	0.42	53.84	0.016

Discussion

The distribution of distal moraine systems and patterns of glacial lineations, identified in satellite images, fieldwork and topographic surveys, were used to reconstruct the glacier retreat processes since the mid-twentieth century. A complex series of lateral and terminal moraines marked the past glacier extent. These retreat processes were evidenced by Arigony-Neto (2001) and Bremer (1998), who highlighted a substantial glacier area loss between 1979 and 2000.

These glacier retreats are linked to an atmospheric warming trend (about 3°C) observed since 1940 in Antarctic Peninsula (PARK *et al.*, 1998, BLINDOW *et al.*, 2010).

The glacier retreat rates presented for glaciers in study area can be considered very high if compared to other KGI ice masses, as Collins and Lange glaciers. In their current phase, these glaciers are continuously and fast retreating.

We observed that glaciers in Martel Inlet had small drainage basins and high retreat rates by fusion processes, if compared to other ice masses in KGI. Due to its small size and thermal conditions, these glaciers responded rapidly to environment changes and thus can be considered a relevant glacier for environmental studies.

The Dobrowolski glacier has the highest retreat rate. Its stepped topography and loss of anchorage can influence the velocity ice flow and calving process. Last stability position of this terminus was determined by the morainical bank (Figure 6, Photos a and b) observed in lower tide condition. In this phase its terminus was anchorage. Similar retreat pattern also explain high retreat rate for others glaciers, as the Wanda and Dragon glaciers, actually with land terminus. The actual topography anchorage terminus of the Goetel Ajax and Stenhouse glaciers determine lower front retreat in the last decades.

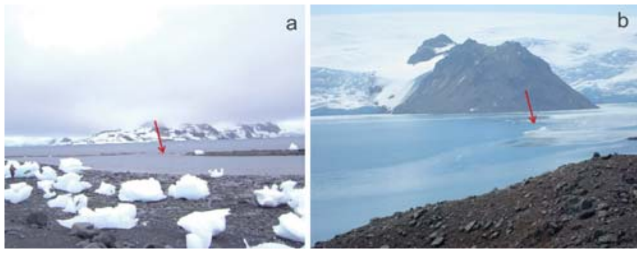

Figure 6 – Morainical banks in latest stability positions of the Wanda (a) and Dobrowolki (b) glaciers, Rosa Photo, 2013.

Multitemporal satellite images, topographic surveys and geomorphological mapping proved to be useful techniques for monitoring glacial changes in study area. The regular monitoring of glaciers in the KGI is important for improving our knowledge about their responses to climate change.

The glacial landform data provided greater understanding of landscape evolution of study area during the Holocene, while the geomorphological mapping gave us further information about glacial erosional and depositional processes and their interactions with glacial dynamics. The study area is characterized by great varieties of glaciofluvial, lacustrine, glacimarine and paraglacial deposicional and erosional landforms. Glacier retreat exhibited a landscape susceptible to rapid post-depositional changes. Terrains recently deglaciarized, such as moraine deposits, have undergone processes of reworking by water streams from seasonal snowmelt, by gravitational and melting processes, and through tide and wave actions. There is no continuity of frontal morainic ridges due to wind erosion and by seasonal snowmelt streams. Debris flows are characterized by abundant clasts with accelerated mechanical mechanisms of weathering. These deposits have different characteristics from the till deposits. Chemical weathering processes in rocks are observed in proglacial area related with high air temperature and liquid precipitation in the summer months. According to Ballantyne (2002), these processes can be considered as the first effects of environmental changes.

Landforms of glacial erosion and the presence of merging subglacial channels evidenced temperate basal thermal conditions for glaciers in the study area.

Conclusions

The spatial distribution of landforms and geomorphological maps produced in this study contributed to reconstructing the pattern and style of deglaciation of ice free-lands in the Martel Inlet.

This work showed the reduction degree of glaciated area in Martel Inlet over the last three decades (1979-2011); the glacier total area loss 6.64 km² was about 13.2% from the total area, without any advances during this period. Thus, since those years the glaciers in study area have receded by an average of 0.25 km a^{-1}. Martel Inlet glaciers have small drainage basins and high retreat rates through fusion processes if compared to others ice masses in KGI. Due to its small size and thermal conditions, Wanda Glacier responded rapidly to environment changes and it is considered relevant for environmental monitoring studies.

Geomorphological interpretations of marginal glaciation provided glacier dynamics information. Glacier type and its proglacial area are sensitive to climatic conditions and may be greatly impacted by recent patterns of climate variability. Furthermore, geomorphological mapping may be used for monitoring paraglacial and glacial changes observed in study area.

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