# Glacial landforms and glaciological processes of the temperate Wanda Glacier, South Shetlands

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## ABSTRACT

This paper presents the geomorphic mapping of the Wanda Glacier proglacial environment, King George Island, South Shetlands. All together investigates the glaciological dynamics related to the glacial landforms in the study area. The mapping was based on field analysis and image interpretation. The interpretation was also made by mean of identification and interpretation of the samples in laboratoty. Glaciofluvial, glaciomarine and subglacial processes predominate in the study area. As a result from the recent glacial retreat, several landforms and proglacial deposits, such as flutes, morainic ridges, striated rocks, have been exposed. Abraded and subglacially transported sediments predominate in the deglaciation environments, with meltwater flow in the bed. The generated map contributes in improving the knowledge about the processes that influence the glacial geomorphology and geodynamics. Furthermore this study serves as support to monitoring environmental change facing the glacier retreat processes as effect of climate variability verified in the study area.

**Keywords:** geomorphic mapping, image interpretation, proglacial environmental, glacial geomorphology.

# Formas glaciales y procesos glaciológicos del glaciar templado Wanda, Shetland del Sur

## RESUMEN

Este trabajo presenta la cartografía geomorfológica del ambiente proglacial del glaciar Wanda, Isla Rey Jorge, Shetland del Sur. Conjuntamente, se investiga la dinámica glaciológica de los rasgos glaciales en el área de estudio. El mapeo se basa en el análisis de terreno y en la interpretación de imágenes. La interpretación se hizo además con la identificación y posterior interpretación de las muestras de sedimentos en laboratorio. En el área de estudio predominan los procesos glaciofluviales, glaciomarinos y subglaciales. Como resultado del reciente retroceso de los glaciares, varios depósitos proglaciales, como *flutes*, cordones morénicos y rocas estriadas, han sido expuestos. Sedimentos erosionados y transportados subglacialmente predominan en el ambiente de deglaciación, con flujo de agua de deshielo en la base del glaciar. El mapa generado contribuye a mejorar el conocimiento sobre los procesos que influyen en la geomorfología glacial y la geodinámica de la zona de estudio. Además, este estudio sirve de apoyo al monitoreo de cambios ambientales frente a los procesos de recesión de los glaciares como efecto de la variabilidad climática verificada en el área de estudio.

**Palabras clave**: mapeo geomorfológico, interpretación de imágenes, ambiente proglacial, geomorfologia glacial

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## INTRODUCTION

The glacial depositional and erosional systems produces important insights into the dynamics of former glaciers, including the patterns of deglaciation, periods of rising meltwater runoff, direction and ice flow velocity (BENN & EVANS 2010).

As a consequence of glaciers retreat, several instability processes have been investigated recently in glacial environments, such as increasing of debris flow deposits originated from moraine ridges, which are considered as one of the first effects of environmental changes (BALLANTYNE 2002).

This paper aims, by the use of geomorphological characterization and mapping, to identify different types of landforms in the proglacial area of Wanda Glacier, located in King George Island, Southern Shetland Islands, Antarctica, and analyze the glacial dynamics through depositional and erosional processes.

## MATERIALS AND METHODS

### Study area

Wanda glacier (Figs. 1 and 2) is a land terminus glacier located in King George Island, South Shetlands comprising 1.56 km² (based in a QUICKBIRD image obtained in 2006), has a thin glacier front (maximum of 4 meters thick). This glacier transports sediments towards Martel inlet through a channel and a proglacial lagoon. The proglacial lagoon was formed as consequence of recent glacier melting.

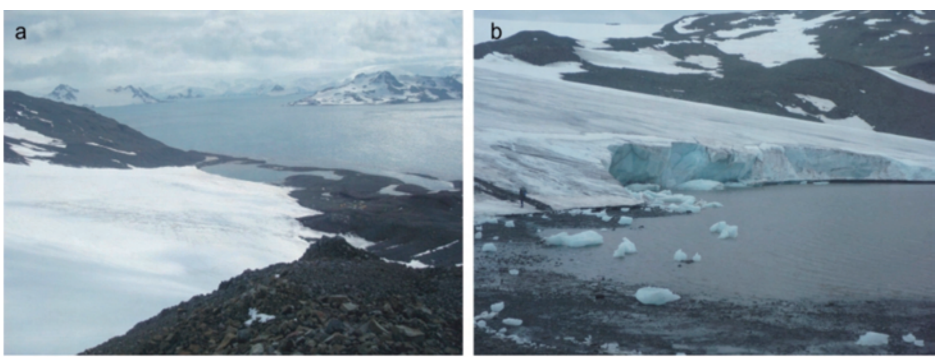


**Fig. 1. Wanda Glacier (a) and its proglacial front close to the proglacial lagoon (b).**

**Fig. 1. Glaciar Wanda (a) y su frente proglacial junto a la laguna proglacial (b).**

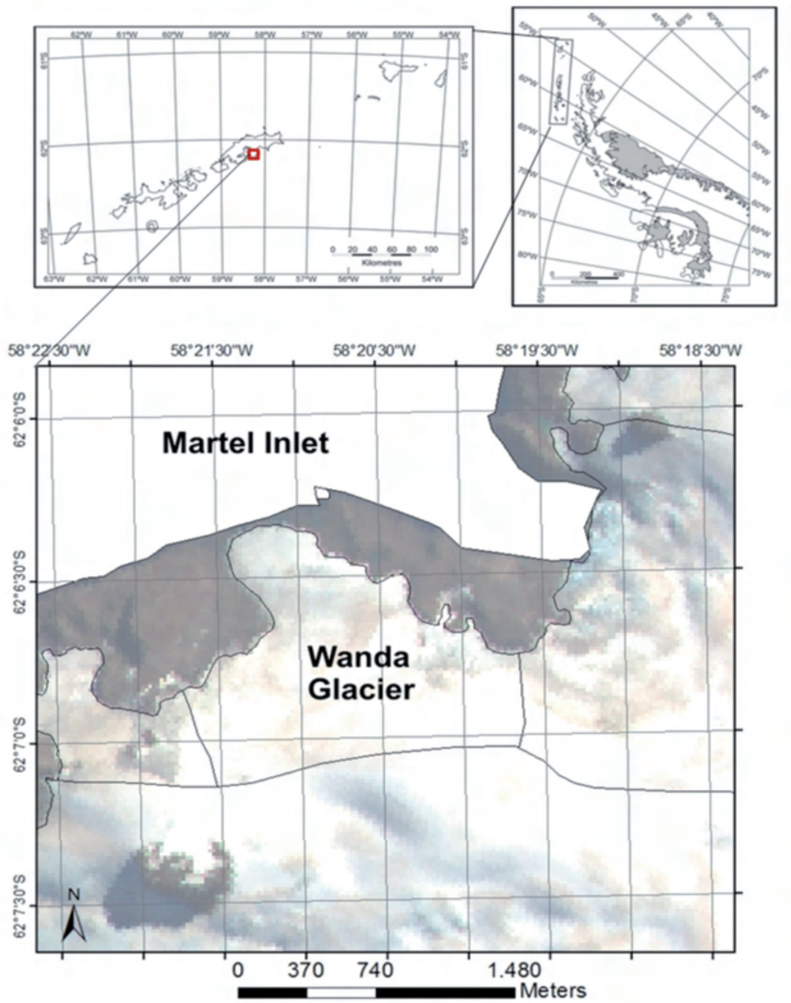


**Fig. 2. Situation of the study area.**

**Fig. 2. Ubicación del área de estudio.**

Wanda glacier has retreated in the last decades. The retreat is related to the atmospheric warming recorded in the northern Antarctic Peninsula area since 1940 (PARK et al. 1998, SIMÕES *et al*. 2004; COOK et al. 2005). According to BRAUN *et al*. (2001) over the past 30 years, the number of days with liquid precipitation has increased in the summer, accompanied by the number of days with mean air temperature exceeded 0°C. These processes have accelerated the snowmelt and increased the negative mass balance of the local glaciers. Generation and exposition of deposits and landforms have accompanied each phase of retreat.

## Methods

Sediment samples were collected during three summer field seasons (2007, 2010 and 2011) in the Wanda glacier proglacial area, at 16 selected points covering different microenvironments and geomorphic features. The samples were analyzed at the Laboratory of Sedimentology of CECO (Center for Marine and Coastal Studies – Uviversidade Federal do Rio Grande do Sul, URFGS).

Subglacial conditions were determined by analyzing shape and roundness of sediments using the $C_{40}$ index (percentage of clasts with *c*-ratio ≤ 0.4) in the form of scatter plots (BENN & BALLANTYNE 1994; GLASSER & HAMBREY 2001; ADAM & KNIGHT 2003). This method allows the quantification of actively and passively transported sediments and also the distinction between them (BENNET *et al*. 1997). Therefore, it is useful for the discrimination of glacial environments (BENN & BALLANTYNE 1994). Directions of the striations at exposed rocks were plotted on diagrams by the program ROSE Rosetta 2.0.

Topographical surveys were carried out using Leica Geosystems Total Station TPS1200 series through transversal and perpendicular transects on the proglacial area of the glacier.

Geomorphologic mapping was done at 1:8.000 scale through the interpretation of sedimentary records, topographical profiles and geomorphologic interpretation of Quickbird satellite image (obtained on October, 2006). Quickbird satellite image has 0.61 meters of spatial resolution in panchromatic and 2.4 meters in multispectral mode. The identification and mapping of landforms were based on morphology aspects and sedimentary characteristics according to GLASSER and JANSSON (2005), GLASSER et al. (2005), SMITH &CLARK (2005), GUSTAVSSON *et al*. (2006) and BENN &EVANS (2010).

## RESULTS

### General view

The geomorphological map (Figs. 3 and 4) shows flutes, morainic ridges, stoss and lee clasts and multiple proglacial channels.Topographic profiles along the proglacial area (Figs. 6, 7 and 8) provided the geomorphical characterization of the Wanda glacier study area and indicate a environment of deglaciation with an extension of approximately 200 m from the glacier terminus to the shoreline. In this part there is an barrier-lagoon system developed at the lower area of the valley sculped by glacial action when the glacier front was tidewater (Figs. 5 and 7a and c). The formation of the proglacial lagoon is a consequence of meltwater flows from snow and ice. Except the proglacial lagoon, topographic profiles of the ice-free shoreline do not show other barrier-lagoon systems (Fig. 7f).

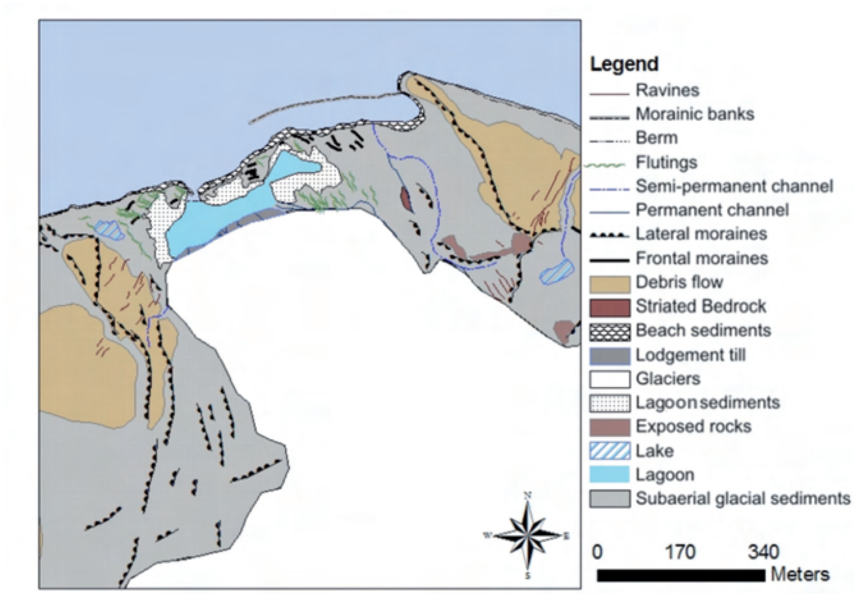


**Fig. 3. Geomorphological map of Wanda glacier.**

**Fig. 3. Mapa geomorfológico del glaciar Wanda.**

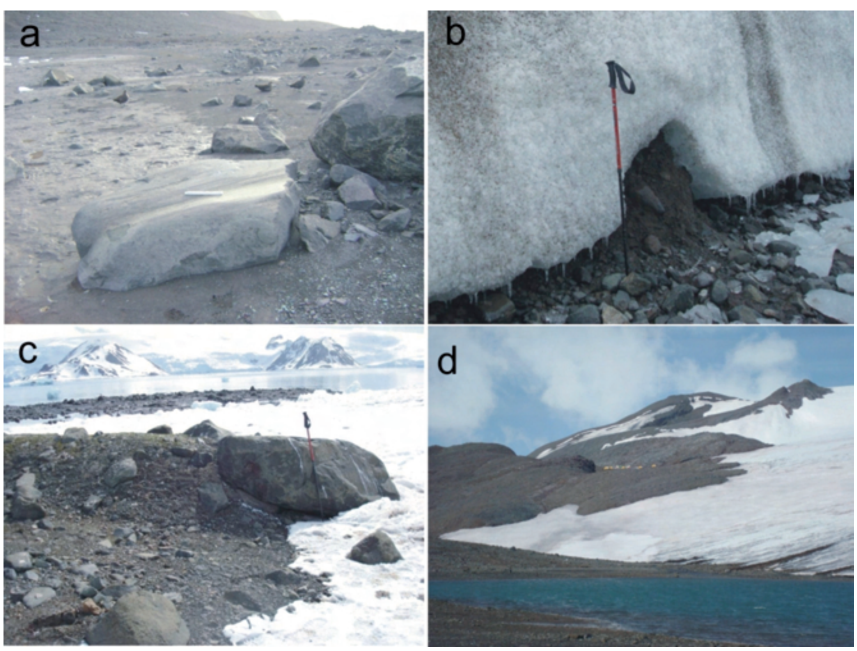


**Fig. 4. Surface striated stoss and lee clasts (a); subglacial fluting deposition (b); flutes (c) and lateral morainic ridges of different positions and elevations indicating the different positions reached by the glacier during the retreat process.**

**Fig. 4. Superficie estriada de clastos tipo stoss and lee (a); depósitos tipo flutes en la base del glaciar (b); flutes (c); cinturón de morrenas laterales en diferentes ubicaciones y elevaciones indicando las posiciones alcanzadas por el glaciar durante el retroceso (d).**

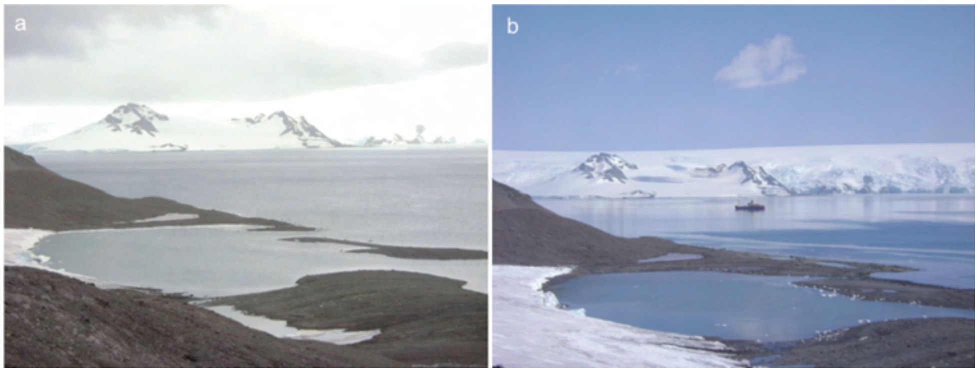


**Fig. 5. Terminal moraines form a lagoon system at Wanda glacier proglacial area. The barrier undergoes processes of reworking during high (a) and low tides (b) fluctuations.**

**Fig. 5. Morrenas frontales forman un sistema lagunar en la zona proglacial del glaciar Wanda. Las barreras sufren (re) trabajo durante las fluctuaciones de las mareas: alta (a) y baja (b).**

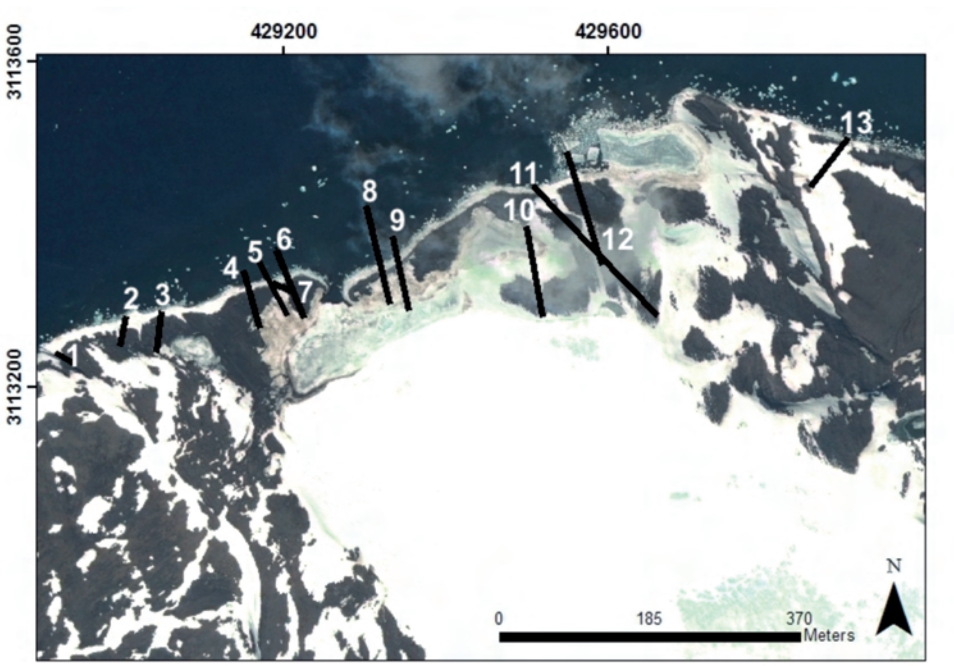


**Fig. 6. Location of topographical profiles at the Wanda glacier proglacial area. Profiles 1-6 are represented in Figure 7 by letters a-f; profiles 7-13 are represented in Figure 8 by letters a-f.**

**Fig. 6. Ubicacion de los perfiles topográficos de la zona proglacial del glaciar Wanda. Perfiles 1-6 son representados en la Figura 7 por las letras a-f; perfiles 7-13 son representados en la Figura 6 por las letras a-f.**

According to topographical profiles (Figs. 7 and 8), the ridges in shoreline indicate the presence of recessional moraines at glacier front area. These are often discontinuous due to paraglacial reworking by meltwater channels and tides and waves action. Small melt ponds, supplied by meltwater channels, are found amidst moraines ridges.

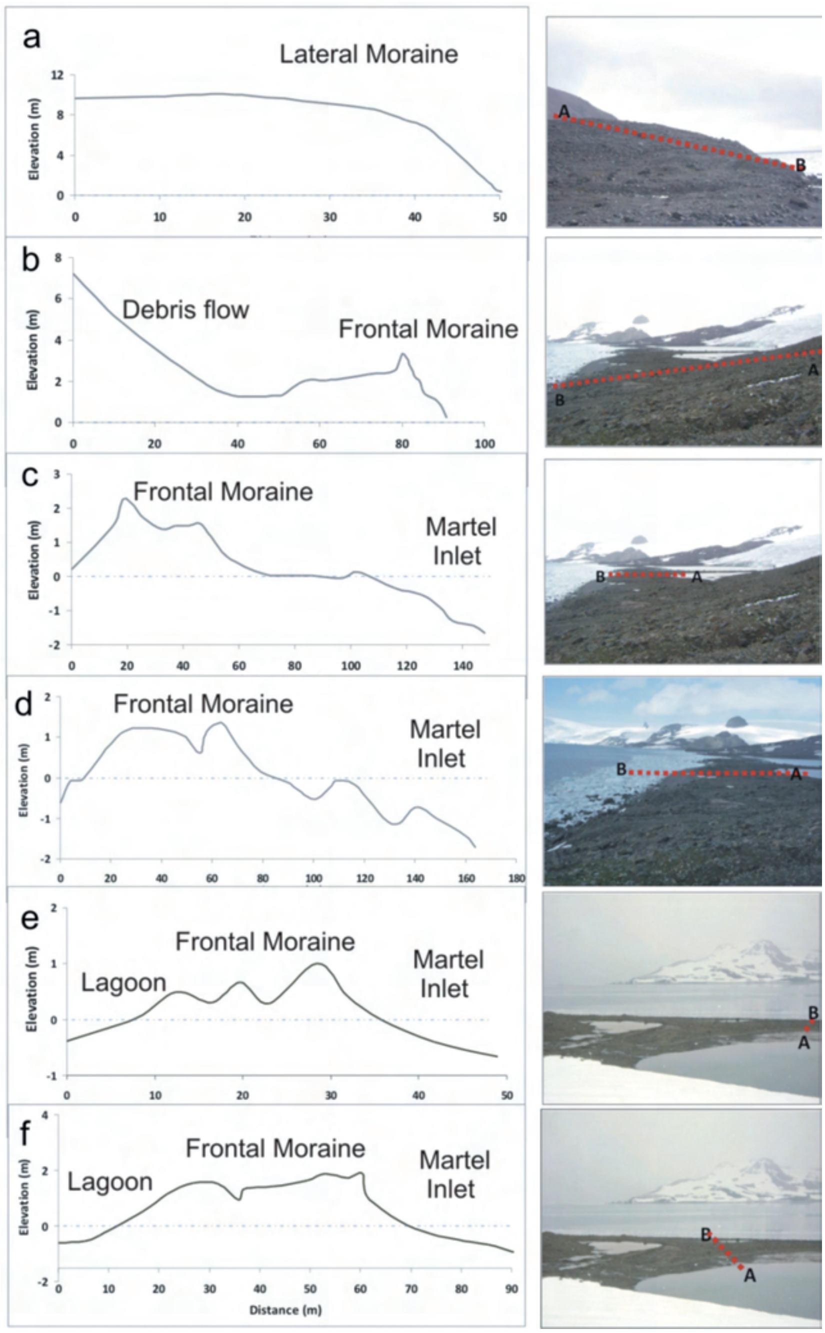


**Fig. 7. Topographic profiles located in the western area of the Wanda glacier proglacial zone.**

**Fig. 7. Perfiles topográficos ubicados en el área oeste de la zona proglacial del glaciar Wanda.**

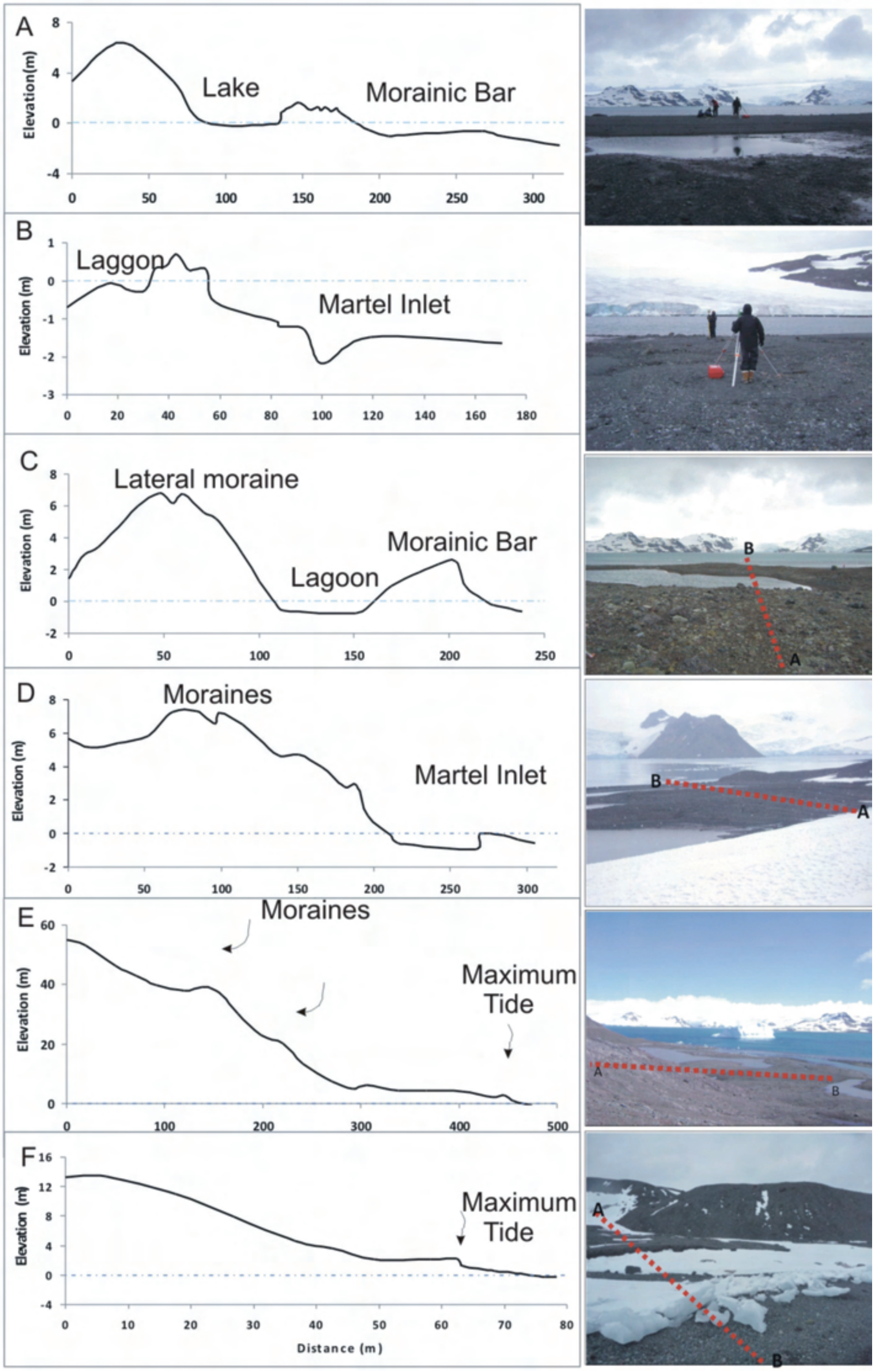


**Fig. 8. Topographic profiles in the eastern area of Wanda glacier proglacial area.**

**Fig. 8. Perfiles topográficos en el área este de la zona proglacial del glaciar Wanda.**

Reconstructing the lagoon system evolution (Fig. 9) its origin is associated with the exposition of frontal morainic ridges, which represent the glacier front at the end of 1990s. Recent exposed recession moraines at Wanda glacier proglacial area are linked to events of stabilization of retreats since the late 90's, when the glacier has become land-based terminus. Morainic banks (Fig. 3) observed during low tide phases, can be formed when the glacier front position still showed tidewater terminus characteristics in the 1980's and 1990's.

Meltwater channels erosion and tidal and wave activities characterize the study area. Debrisflow on steeper slopes of moraine deposition were observed in proglacial area. Features formed by rain events and meltwater flow from snow surface, such as ravines, can be also found along these slopes.

Scatter plot representing the $C_{40}$ index (Fig. 10a) shows that most of the samples from the proglacial area of Wanda glacier have values lower than 40, indicating a major wastage of the grain during the predominantly subglacial transport. Orientation measurements of striate on the bedrocks exposed (Fig. 11) are expressed in the rose diagram (Fig. 10b), and indicate that the predominant direction of ice flow was from 45° NE.

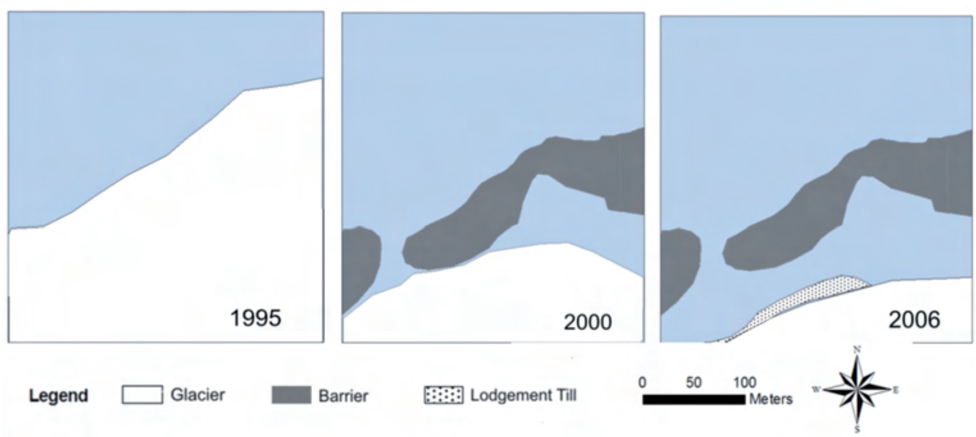


**Fig. 9. Evolution of the barrier-lagoon system during retreat stages.**

**Fig. 9. Evolución del sistema barrera-laguna durante el retroceso.**

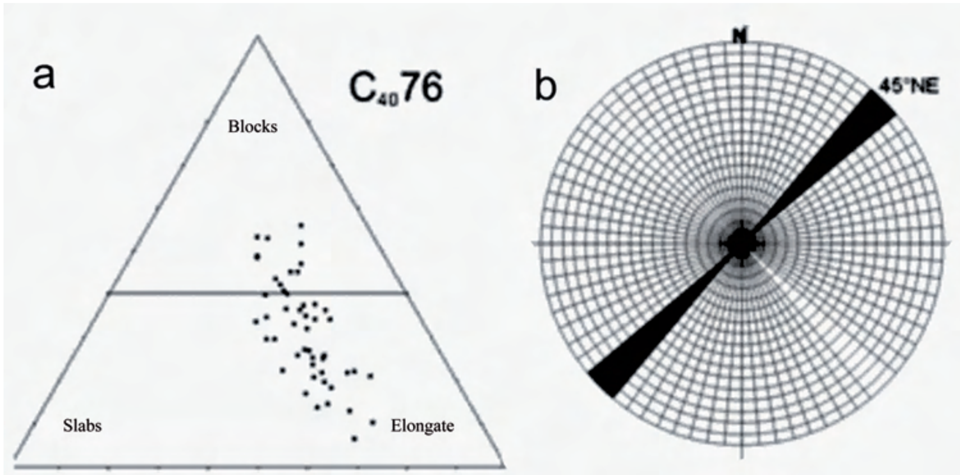


**Fig. 10. Scatter plot representing the C40 index (a) and predominant orientation of striate and striated bedrocks exposed (b).**

**Fig. 10. Diagrama de dispersión representando índice C40 (a) y orientación predominante de las estrías y de los bloques estriados expuestos (b).**

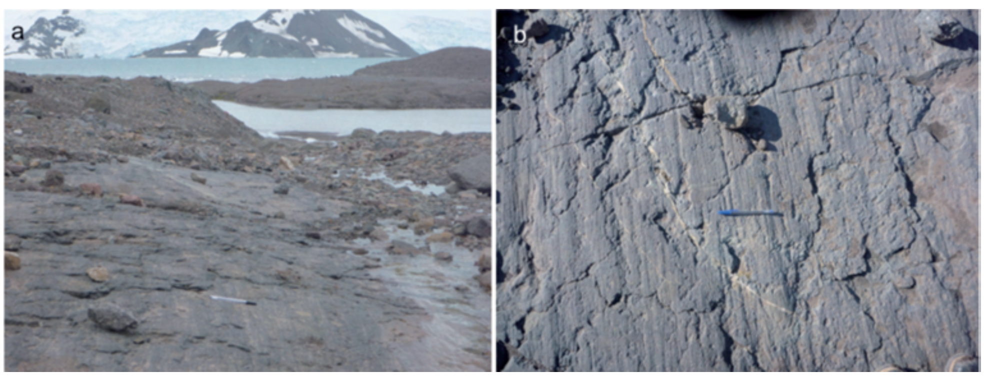


**Fig. 11. Striations exposed on the rock indicate the predominant direction of ice flow - 45° Northeast.**

**Fig. 11. Estrías expuestas sobre la roca indican la dirección predominante del flujo de hielo - 45° Noreste.**

## DISCUSSION

### Geomorphic characterization of the proglacial area of Wanda Glacier

Subglacial deposits dominate the deglaciation environment of Wanda glacier. Typical features of subglacial transport are found in these deposits, such as bimodal and multimodal grain size distribution, high roundness of the grains, tendency to be more spherical and the presence of faceted and striated rocks.

The abundance of landforms of glacial abrasion such as stoss and lee forms (Fig. 4a), striated bedrocks and meltwater features in the proglacial zone provide evidence for the action of subglacial meltwater, and warm-based ice. These features also reflect the ice flow direction. According to GLASSER & BENNET (2004), the stoss and lee features reflect relatively high sliding velocities, with thin ice and low effective normal pressure, and striated bedrock indicate subglacial sediment sliding over bedrock or by individual clasts contained within the ice.

Thus, in the study area the pattern for landforms shows that the operation of the three major processes of glacial erosion in the past (glacial abrasion, glacial quarrying and glacial meltwater erosion) depends on the release of meltwater at the glacier bed and on glaciological conditions.

Meltwater channels located in the proglacial area flow according to NE direction of the Wanda glacier. According to GLASSER & BENNET (2004), the significance of proglacial channels to reconstructions of former ice sheets is that they help to define a marginal meltwater system that can be used to locate the former ice margin position and changes in their location over time. Detailed mapping of the distribution of these features on bedrock surfaces allowed inferences about former subglacial water drainage and glacier velocities of Wanda glacier. The channel distribution indicates development of the drainage systems with capacity of sediment transport.

Fluting deposits (Fig. 4b and 4c) are also landforms of glacial meltwater deposition and are located in the proglacial area of Wanda glacier; also they have recently been exposed. These deposits have the form of an elongated ridge with a parallel alignment to former ice flow direction. Some have a uniform cross section that generally begins with a rocky section. These deposits are composed mainly of sand and gravel. According to GLASSER & BENNET (2004) flutes and channel shape provide information about the paleodischarge and size of material transported within former glacial meltwater channels. These deposits indicate the direction of the ice flow, the presence of the thin ice and a wet basal thermal regime (BENNETT & GLASSER 1996).

Deposits interpreted as lateral moraines (Fig. 4c) indicate positions of the glacier margins during the retreat processes. Frontal moraines are generally curved, reflecting the shape of the front edge of the glacier in a previous position.

Those deposits interpreted as recessional moraines (Fig. 7) were deposited during pauses in the retreat of the glacier Wanda. The dimensions of the landforms indicate a small thickness of the glacier front in recent times.

The retreat of the glacier exhibits a landscape susceptible to rapid post-depositional changes. Terrains recently deglaciarized such as moraine deposits, undergo processes of reworking by streams of water from seasonal snowmelt, by gravitational and melting processes, and through the tides and waves actions. There is no continuity of frontal moraines ridge due to wind erosion and by seasonal snowmelt streams.

As shown in the profiles (Figs. 7 and 8) the reworking processes of tides, waves actions are observed on deposits and subglacial moraines located at the coastal area.

Partially submerged morainic banks form a barrier and lagoons systems (Fig. 8) during tidal variations. These morainic banks indicate the location of the former Wanda glacier tidewater terminus.

## CONCLUSION

The geomorphologic mapping provided information about processes operating in the study area, such as subglacial erosion, glaciofluvial erosion and flow slope causing paraglacial reworking of deposits.

Several glacial geomorphic features in the Wanda glacier proglacial area were identified. It was possible to examine the glacial depositional and erosional processes by which the sediments were submitted, which revealed information on the glacial dynamics and provides the reconstruction of the pattern of deglaciation, as response to the regional climate warming.

A large proportion of fine sediments, striated rocks surfaces, lodgement till and stoss and lee forms, indicate that Wanda glacier is wet based.

Considerable modification of the deposits and paraglacial processes can generate problems of reconstruction and mapping in the study area. These environmental changes are consequence of climate variability and are important for monitoring studies.

## ACKNOWLEDGMENT

The Brazilian National Council for Scientific and Technological Development (CNPq), Center for Studies in Marine and Coastal (CECO/UFRGS), the Geodesia Departament at Federal Rio Grande do Sul University and Brazilian Antarctic Program (PROANTAR) provided the support for this research.

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