GLACIAL HYDROLOGICAL SYSTEM IN WANDA GLACIER ABLATION AREA, KING GEORGE ISLAND, ANTARCTICA, USING GROUND PENETRATING RADAR

Sistema hidrológico glacial na área de ablação na geleira Wanda, usando radar de Penetração no Solo

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ABSTRACT

This paper aims to determine the configuration of the drainage system and water storage in Wanda Glacier, located in King George Island (KGI), South Shetland Islands (61°54’ – 62°16’S and 57°35’ – 59°02’W), Antarctic Peninsula, using data obtained by 100 MHz GPR (Ground Penetration Radar) survey. This site is characterized by accelerated retraction and melting processes as consequence of a recent regional warming. Topography data were used to generate transversal and longitudinal sections and a three-dimensional model (DSM) of the glacier surface. The GPR system was able to deliver information about the internal structure and about the meltwater drainage configuration. GPR internal reflections are attributed to basal water films and intraglacial and subglacial water channels in the Wanda Glacier. The abundance of internal diffractions is considered an indicative of temperate ice with high liquid water content. Similar internal structures are observed in other glaciers in KGI. The application of GPR to Wanda Glacier study showed the dielectric contrasts, internal layering and englacial structure, glacier bed condition and the distribution of individual channels in the glacier and the englacial and subglacial routing of meltwater. Probably the configuration of a subglacial drainage and water liquid exerts an influence on the sediment evacuation by basal meltwater, subglacial erosion and the proglacial deposition pattern.

Keywords: Hydrology. **G**round-penetration radar. Glacial drainage system. Temperate glacier.

RESUMO

O artigo objetiva determinar a configuração do sistema de drenagem e a presença de água líquida na geleira Wanda, localizada na Ilha Rei George, Shetlands do Sul (61°54’ – 62°16’S w 57°35’ – 59°02’W), Península Antártica, através do uso de dados obtidos por Radar de Penetração no Solo de 100 MHz. Esta área de estudo é caracterizada pela retração e processos de fusão acelerados como consequência do recente aquecimento regional. Dados topográficos foram usados para gerar perfis transversais e longitudinais e o modelo tridimensional da superfície da geleira. O sistema de radar resultou em informações sobre a estrutura interna e sobre a configuração do sistema de drenagem da geleira. Os refletores internos de radar são atribuídos a uma camada basal de água líquida e a canais de água de degelo intraglaciais e subglaciais na geleira Wanda. A abundância de difrações internas é considerada um indicativo do gelo temperado com água liquida percolando na geleira. Estruturas internas similares são observadas em outras geleiras da Ilha Rei George. A aplicação dos estudos de GPR na geleira Wanda evidenciou os contrastes dielétricos, a estrutura englacial, a distribuição de canais individuais e condições da base da geleira e ainda o escoamento da drenagem de água de degelo em canais englaciais e subglaciais. Provavelmente, a configuração da drenagem subglacial e a água de degelo presente exerce influência no transporte sedimentar subglacial, erosão subglacial e o padrão de deposição marginal ao gelo.

Palavras-chave: Hidrologia. Radar de Penetração no Solo. Sistema de drenagem glacial. Geleira temperada.

1 INTRODUCTION

Water in glaciers originates from surface melting, liquid precipitation, groundwater, run-off from surrounding slopes and firn areas, as well as melting from dissipative heating, and geothermal heat flux. Water flows down the glacier body through infiltration of the snow/firn layer and inflow throughout crevasses, channels, moulins and fracture zones (GOLUBEV, 1976). According to Lliboutry (1968) water content and distribution depend on the thermal regime. The glacial drainage network develops during the summer, when melting of ice and snow, and the subglacial system, together with rainfalls, supply of water to the ablation zone (HOCK and HOOKE, 1993; MURRAY et al., 2000). Water within glaciers occupies many possible locations: within voids and conduits, as well as interstitial spaces and veins between ice grains (Fountain and Walder, 1998). In an ice-bed interface, flow can be distributed in the form of a thin film of water (WEERTEMAN, 1972; WALDER, 1982) through channels incised in bedrock (Nye) or into the ice (Rothlisberger) or a combination of both (CLARKE, 1996; BENN and EVANS, 2010). Systems and distributed channeled flows differ markedly in terms of hydraulic efficiency (ALLEY et al., 1997). The development and configuration of hydraulic systems within the glacier depends largely on the type, the morphology and topography of the ice mass, the mass balance, the ice flow velocity, the basal conditions, the amount of debris and the discharge of meltwater (FOUNTAIN and WALDER, 1998). According to studies by Alley et al. (2003) and Swift et al. (2005) the configuration of a subglacial drainage exerts a strong control on the sediment transport rate by basal meltwater, subglacial erosion and the marginal ice sedimentation pattern.

Understanding drainage systems in a glacier is fundamental to several critical issues in glaciology, including glacier dynamics (LLIBOUTRY, 1968; IKEN, 1981; HANSON, 1995; HUBBARD et al., 1998). The hydrological system characteristics affect the rate of sliding in glaciers (FOUNTAIN and WALDER, 1998; ZWALLY et al., 2002) and exert some kind of control over many others subglacial processes (SUGDEN and JOHN, 1976; COLLINS, 1979; HOOKE et al., 1983; MACGREGOR et al., 2000; ALLEY et al., 2003; SWIFT et al., 2005; EYLES, 2006). Unfortunately, the difficult access to subglacial and englacial hydrological networks does not contribute to this study.

Ground-penetrating radar (GPR) is a widespread technique for hydrological applications in glacial environments due to the relatively large dielectric constant of liquid water (BRADFORD and HARPER, 2005; MURRAY et al., 2007).

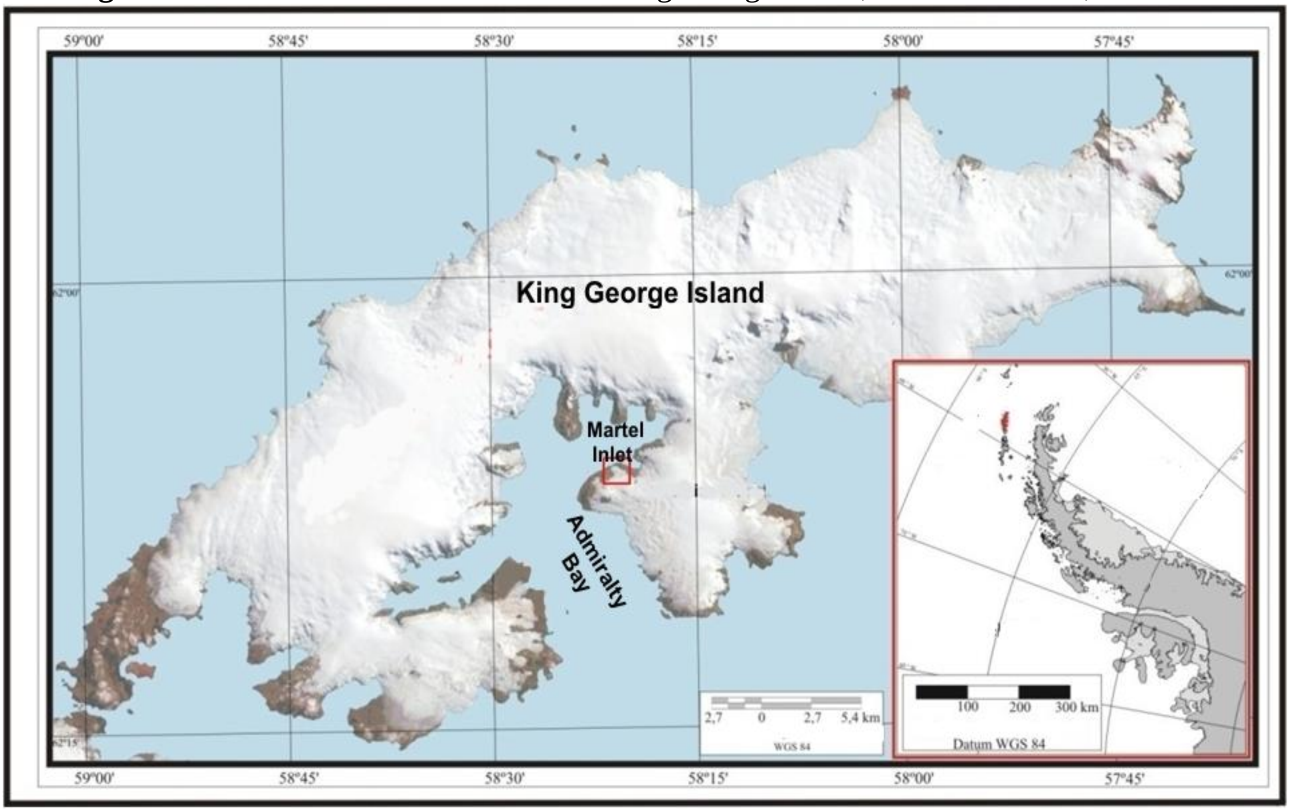
GPR system is a high resolution subsurface imaging technique and consists mainly of a transmitter dipole and a receiver dipole antenna. The transmitter sends out a short broadband electromagnetic (EM) pulse into the subsurface. The application of GPR to glaciological research relies upon these dielectric contrasts and includes investigations of internal layering and englacial structure, profiling of the glacier bed, and also studies on the distribution of individual channels in the glacier and the englacial and subglacial routing of meltwater (ARCONE et al., 1995; MURRAY et al., 1997; MOORMAN and MICHEL, 2000; ARCONE et al., 2004; WOODWARD and BURKE, 2007).

The objective of this study is to examine the hydrological system near the terminus of Wanda Glacier through the use of GPR. This study is important for understanding the implications of the hydrological system on Wanda glacier dynamics, glacier water storage, sediment transport, and formation of landforms.

2 STUDY AREA

Wanda Glacier, located on King George Island (KGI) (61°54' – 62°16'S and 57°35' – 59°02'W), South Shetlands archipelago, in the northwestern sector of the Antarctic Peninsula region (Figures 1 and 2), is characterized by its land front and small area (about 1.5 km²). Ice-temperature measurements have indicated that ice masses in the accumulation areas of KGI are near or at pressure melting points (MACHERET et al., 1997; PFENDER, 1999; SIMÕES et al., 2004; TRAVASSOS and SIMÕES, 2004). The abundant amount of fine sediments in the Wanda Glacier proglacial channels shows the presence of meltwater in the ice-bed interface and indicates a wet basal thermal regime.

Figura 1 – Location of Wanda Glacier in King George Island, South Shetlands, Antártica



Fonte: Centro Polar e Climático (CPC) (SPOT, 2000).

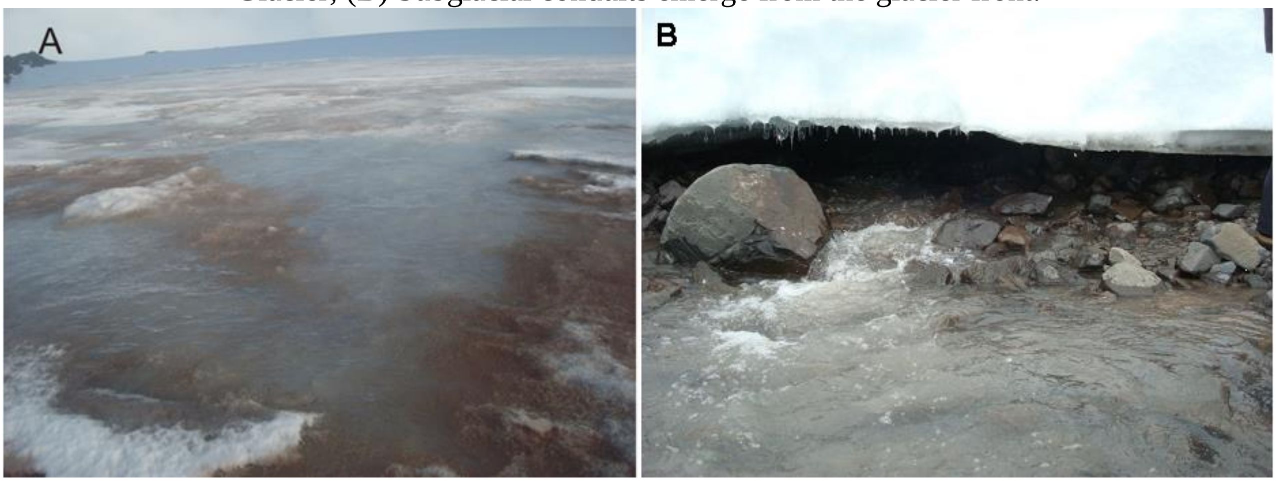
Data indicate that Wanda Glacier has been receding since 1956 (SIMÕES and BREMER, 1995; ROSA et al., 2009). The retreat of this glacier may be related to the atmospheric warming recorded over the last 60 years (BLINDOW et al., 2010). Over the past 30 years, the number of days with liquid precipitation has increased in the summer, accelerating the snowmelt of local glaciers (FERRANDO et al., 2009).

Wanda glacier is characterized by a proglacial lagoon, which results from glacial melting. Subglacial conduits emerge at the front of the glacier (Figure 3) and large flutings moraines extend out from the terminus of the glacier.

Figura 2 – Wanda Glacier viewed from Admiralty Bay

Fonte: Kátia Kellem da Rosa (2011).

Figura 3 – (A) Interconnected supraglacial melting pools located in the eastern margin of Wanda Glacier; (B) Subglacial conduits emerge from the glacier front.



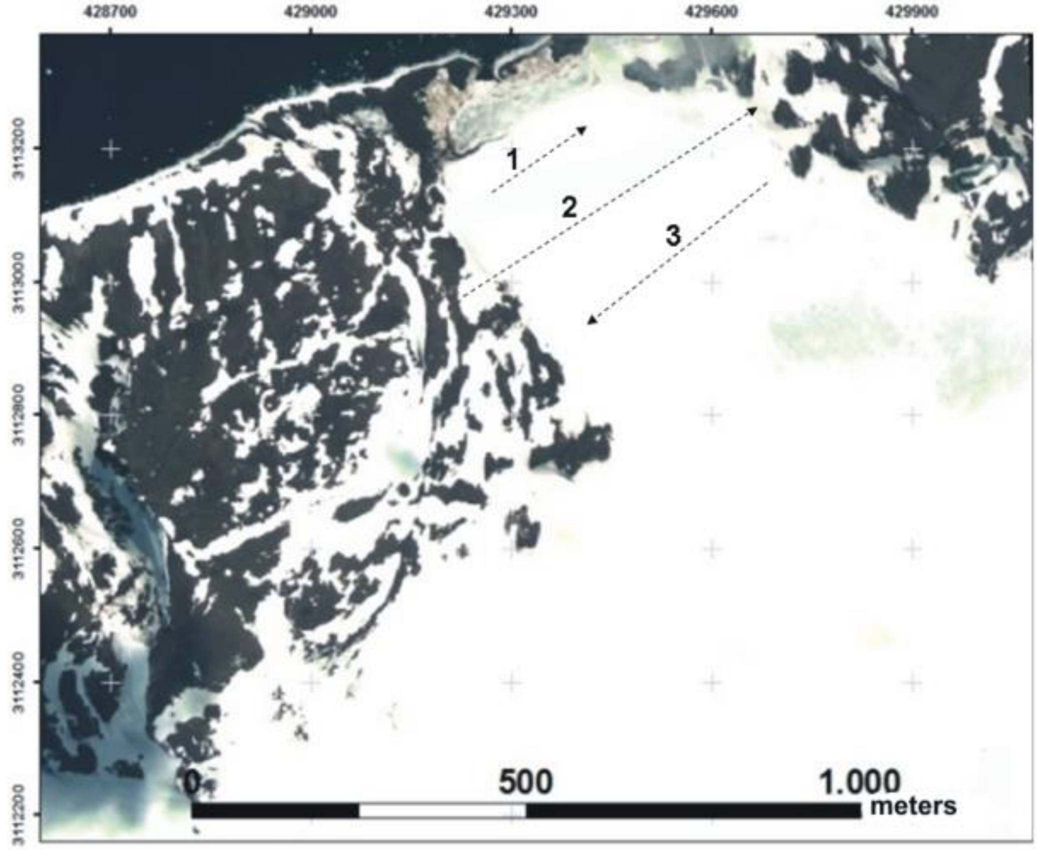
Fonte: Kátia Kellem da Rosa (2011).

3 MATERIALS AND METHODS

In late January 2011, fixed offset GPR data was recorded along a transversal profile in the Wanda Glacier (Figures 4 and 5). The profiles were carried out on the ablation area (near the snout) of the glacier, using a GSSI (Geophysical Survey Systems, Inc.) 100 MHz in monostatic single antenna. All data had a time window of 2040 ns and common-off-set mode. Positions were acquired with Differential Global Positioning System (GPS) TechGeo.

Sampling was based on continuous data acquisition adjusted to the topographical profile using a Leica Total Station. GPR data were processed using the RADAN™ 6.5, a software package from GSSI. Background removal, vertical and horizontal bandpass filtering and automatic gain control were applied to the data. For interpretation, the profiles were vertically exaggerated and topographically corrected.

Figura 4 – Location of the GPR radar profiles on the Wanda Glacier. The profiles were carried out on the ablation area (near the snout) of the glacier



Fonte: Kátia Kellem da Rosa (2011) in ASTER image data (October, 2003).

4 RESULTS

We analyzed a small selection of our large data set, comprising 3 profiles that illustrate the most important results. Profile 1 (Figure 5) crosses the Wanda Glacier from W to E along 140 meters and is located near the front zone of the glacier (15 meters thick).

The profile (Figure 5) shows a strong continuous horizontal reflector on subsurface that indicates a water table from supraglacial melting. Below, the presence of interbedded ice reflects an inhomogeneous firn. Hyperboles diffractions are indicated in H1, and opposite polarity reflections represent a crevasse with presence of air and water. This zone can obscure the reflections below. There are other diffractions in the englacial zone indicating meltwater intrusions into channels.

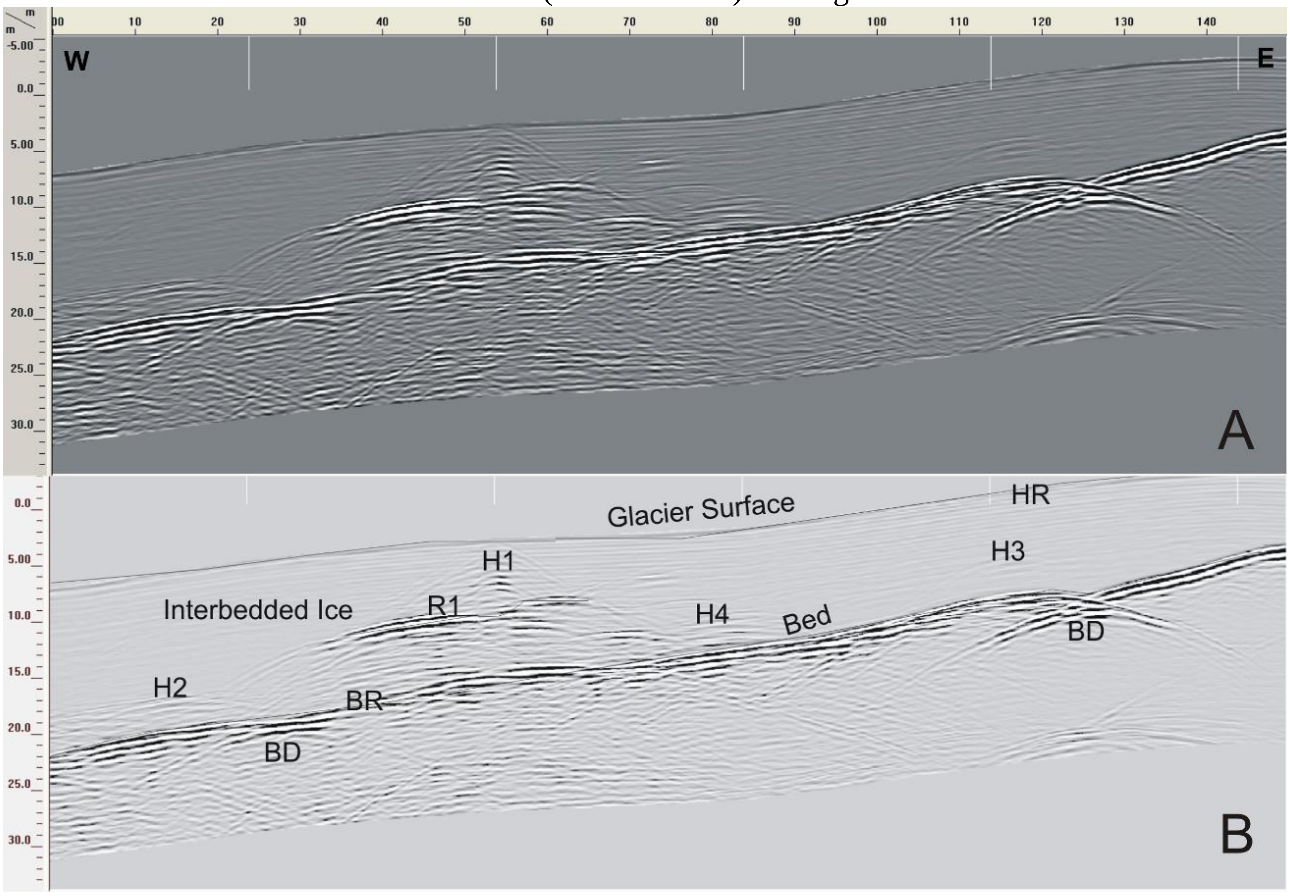
The strong non-continuous reflector R1 (Figure 5) indicates percolation of water in the crevasse zone. A free liquid water (BR) without frozen sediments in contact with the basal ice was identified by diffuse horizontal reflector. Water filled conduits or boulders deposited in the ice-bed interface are identified as BD. Below the strong basal sub horizontal reflectors (BR), are crossed pattern zones due to interference of the water table above this layer. Under BD in the final portion of the profile there is a no coherent reflectors area.

Continuous horizontal reflections (HR) near the surface (Profile 2, Figure 6) indicative a water table. This layering could obscure the firn-ice interface. Interbedded ice occurs in the englacial zone. Hyperbole diffractions (H1 and H2) (Figure 6) near the surface can be interpreted as crevasses that are filled with liquid water.

Field observations suggest the presence of both water filled and air filled voids in the crevasses, which receive supraglacial fusion water that can reach the basal zone and then connects with subglacial drainage.

Abundant diffractions within ice (ID) (Figure 6) may be caused by inclusions of subglacial melting water in basal channels. These can be supplied from the surface water through interconnected drainage. Below this area, there are sub-horizontal reflections with continuity dowlappping that suggest BR bed reflection with percolating water table in contact with the ice.

Figura 5 – (A) Processed transversal GPR profile from W to E along 140 meters shows a continuous reflector at approximately 15 meters depth. (B) Unmigrated and elevation corrected profile. Interpretation indicates H Hyperbole diffractions; ID diffraction within ice; BR bed reflection; BD bed diffractions and HR horizontal reflections. The profiles were carried out on the ablation area (near the snout) of the glacier



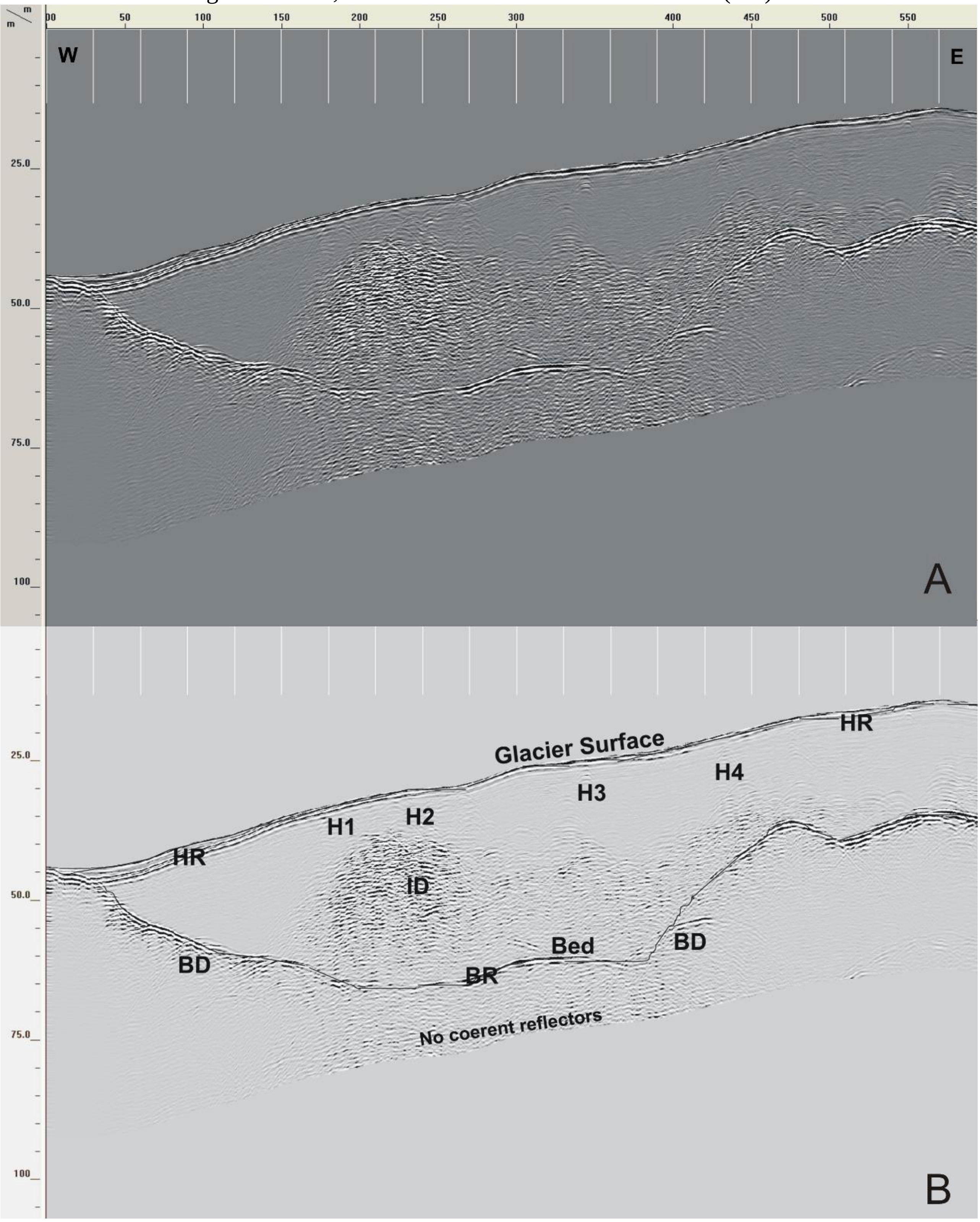
Fonte: Kátia Kellem da Rosa. RADAN layout.

BD diffractions located below this layer (Figure 6) are indicating the presence of water filled channels, subglacial sediment deposition and boulders. There are coherent reflectors below the BR reflection due the high liquid water content of layer. The strong noise near the bed is an indicator of water storage.

According to GPR profiles, water is stored in a number of ways in the Wanda Glacier: in surface ice and firn, crevasses, surface pools, englacial and subglacial drainage network, and in basal sediments. The profiles were carried out on the ablation area (near the snout) of the glacier.

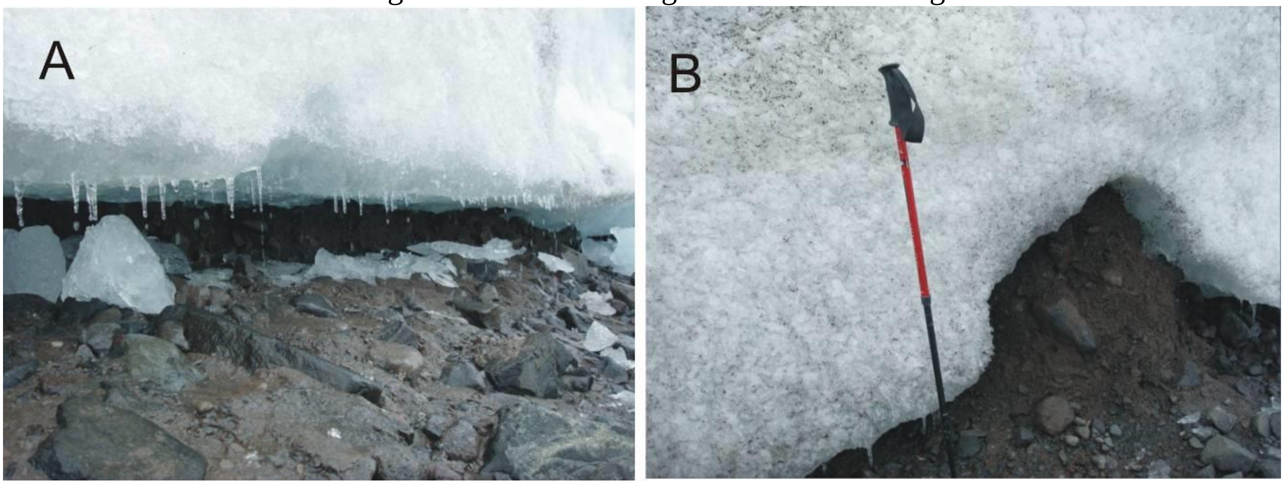
Subglacial sediment deposition in front of the glacier reveal glacial transport and channels in the bed of the glacier (Figure 7).

Figure 6 – (A) Processed transversal profile running W - E along 570 meters. Interpreted profile (B) shows HR horizontal reflections in the upper layer that reflect one direct airwave and one direct ground wave, and a continuous horizontal reflection (HR)



Fonte: Kátia Kellem da Rosa. RADAN layout

Figure 7 – (A) No frozen sediments in the subglacial zone at front of Wanda Glacier. (B) Sediment filled subglacial conduits emerge at the front of the glacier



Fonte: Kátia Kellem da Rosa (2011).

5 DISCUSSION

The application of GPR to Wanda Glacier study showed the dielectric contrasts, internal layering and englacial structure, glacier bed condition and the distribution of individual channels in the glacier and the englacial and subglacial routing of meltwater.

The noise in near-surface GPR profiles is caused by water storage on supraglacial streams. According to Hooke et al. (1989), these are typical conditions during the ablation season in temperate glaciers. The hydraulic system developed through interconnected pools, as observed in field activities in the glacier (Figure 3) due the presence of the pores in permeable firn (NYE and FRANK, 1973; HANTZ and LLIBOUTRY, 1983). Thus, these surface pools of water located at the eastern margin of the ablation zone are an indicative of the relative impermeability of the ice below the firn in several points in the Wanda glacier.

Our GPR profiles show that the percolating water content are high in glacial internal structure. The supraglacial water can also be transported along channels, which can be enlarged by solar radiation and reach englacial interconnected channels and the subglacial drainage system.

Crevasses are observed on the glacier surface, which connects with subglacial conduits in the ablation area where meltwater flows englacially via conduits and penetrates downward to the subglacial zone. Water-filled crevasses indicates a strong melting process. The liquid precipitation also can percolate through the drainage system in the glacier.

Mapped glacial diffraction patterns within the profiles indicate discrete reflections along horizons within the ice. Features (point diffractions) interpreted in the profiles suggest the development of a channelized and distributed (basal melting) drainage configuration. According to Swift et al. (2005), the channelized drainage forms an efficient hydraulic systems with transport high discharge values. Our profiles point to basal ice incised channels (Röthlisberger channels) and subglacial sediment incised channels (Nye channels). This pattern can be inferred from the high sediment content in basal zone as observed at the glacier front. According to Drewry (1986), Sharp et al. (1989), and Walder and Hallet (1979), the presence of Nye channels in one glacier is attributed to its high topographic gradient sectors.

The GPR profiles indicated substrate sectors with slow topographic gradient that provide conditions for slow ice flow velocity, and sediment transport, for water storage and the absence of frozen sediments in the temperate ice zone near the bed of the glacier. Thus, local topography should control the water storage, and the drainage development pattern. The presence of subglacial sediments (Figure 7) in Wanda Glacier can be associated to its less accessible zones by the hydraulic system of the glacier. The profiles indicated a slow subglacial sediment deposition and increased basal liquid water, both percolating toward the glacier terminus (e.g. Profile 1).

The sediments transported through subglacial drainage are deposited in the marginal zone and flow toward a Wanda Glacier proglacial environment (Figure 7).

According to Brennand (1994) and Benn and Evans (2010), if sediment filled conduits survive through the last ablation season, they with make eskers or flutes. Subglacial sediment filled channels were observed emerging in front of the glacier (Figure 7) and flutings in the Wanda Glacier proglacial area. According to Eyles (2006) this feature is an evidence of the development of subglacial melting and thus, provided information about the drainage routing in the glaciers. Results suggest the storage of a substantial volume of water within the glacier ice, which has implications for glacier hydrology and basal sliding dynamics.

Probably the configuration of a subglacial drainage and water liquid exerts an influence on the sediment evacuation by basal meltwater, subglacial erosion and the proglacial deposition pattern.

6. CONCLUSION

The applicability of ground-penetrating radar (GPR) for hydrological investigations was tested and it's suitable for glacial environment. The GPR system was able to deliver information about the internal structure and provide insights into the character of the hydrological system within the Wanda Glacier environment.

The use of GPR allowed the identification of internal reflections that were attributed to water table, intraglacial and subglacial water channels in Wanda Glacier.

The abundance of internal diffractions is considered an indicative of temperate ice. Due to its small size, englacial structure and thermal conditions, the Wanda Glacier probably have a rapidly response to climatic changes.

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