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PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS

DINÂMICA GLACIAL, SEDIMENTOLÓGICA E VARIAÇÕES AMBIENTAIS EM GELEIRAS NA ENSEADA MARTEL, ILHA REI GEORGE, SHETLANDS DO SUL

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RESUMO

Esta tese investiga a dinâmica glacial e proglacial relacionada aos processos de retração na enseada Martel, baía do Almirantado, ilha Rei George. Dados geomorfológicos, morfométricos, hidrológicos e obtidos por Geofísica, Sensoriamento Remoto e Sistema de Informações Geográficas revelam o comportamento da dinâmica glacial e sedimentar das geleiras em resposta às variações climáticas. O modelo de reconstrução dos processos de retração das geleiras mostra que a área total com cobertura glacial perdeu aproximadamente 13,2% de sua área original no período entre 1979 e 2011 (total de 50,3 km²). As geleiras Dobrowolski, Wanda, Dragão e Professor, na enseada Martel, apresentaram as maiores perdas anuais (até 75 m^2a^{-1}). Com o processo de retração glacial ocorrem mudanças ambientais perceptíveis, por exemplo, na dinâmica sedimentar da área de estudo. A geleira Wanda mostra uma significativa descarga de sedimentos em suspensão (19,4 x 10^{-3} kg s^{-1}) para o ambiente glacimarinho. Dados de GPR (*Ground Penetration Radar*) (100 MHz) possibilitaram inferir informações sobre a estrutura interna, desenvolvimento do sistema de drenagem e condições de estocagem hídrica líquida na geleira Wanda. A forte presença de difrações nos perfis de GPR é atribuída à presença de canais subglaciais, englaciais e supraglaciais e mostram que a geleira possua regime termal temperado. Como resultado do processo de retração glacial, há a formação de um ambiente de deglaciação com a exposição de várias geoformas erosivas e deposicionais landforms (vales em forma de U, morainas laterais e frontais, *flutings*, aretês, bancos morâinicos). Esta tese apresenta o mapeamento geomorfológico, Modelo Digital de Elevação (resolução de 0,7 m), mapas morfométricos e perfis topográficos para a área de estudo. A aplicação de filtros específicos em imagens COSMO-SkyMed com diferentes polarizações (VV e HH) relevou-se com potencial na aplicação no reconhecimento de feições geomorfológicas glaciais e para o monitoramento de processos paraglaciais. O mapeamento da distribuição espacial das geoformas glaciais foi relevante para inferir a extensão, padrão do fluxo de gelo e dinâmica glacial (direção do fluxo de gelo e condições termais basais) nas geleiras da baía do Almirantado. Foram observadas recentes alterações ambientais na área deglaciarizada, como a ocorrência de atividade paraglacial (como processos de fluxo de detritos).

ABSTRACT

This thesis investigates the glacial and proglacial dynamics related to glacier retreat processes in Martel Inlet, Admiralty Bay, King George Island (KGI). Geomorphic, hydrological, geophysics, Remote Sensing and Geographic Information System data sets reveal the local glacial and sedimentary dynamics as a reflection of the climate variability. A reconstruction map of past glacial extension indicates that glaciers lost nearly 13.2% of its area from 1979 to 2011 (50.3 km^2 total). Dobrowolski, Wanda, Dragon and Professor glaciers, in Martel Inlet, presented the highest annual losses (up to 75 m^2 a^{-1}). Retreat processes generated perceptive environmental changes, for example sedimentary dynamics in the study area. The Wanda Glacier shows significantly suspended sediment discharge for a glaciomarine environment (19.4 x 10^{-3} kg s^{-1}). GPR (Ground Penetration Radar) data (100 MHz) provided information about internal structure, drainage system development and liquid water storage in the Wanda Glacier. The strong scattering of the radio waves are attributed to supraglacial, englacial and subglacial meltwater channels and constitutes further evidence that the ice in the ablation area of this glacier is temperate. As a consequence of the general glacier retreat, large glaciarized areas became ice-free, exposing glacially eroded and deposits landforms (U shaped valleys, lateral and end moraines, flutings, aretes, morainal bank). This work presents a geomorphologic mapping, Digital Elevation Model (DEM) (0.7 m of the resolution), morphometric maps and topographic profiles for the study area. The application of several filters in COSMO-SkyMed images, at HH and VV polarizations, was suitable for recognizing glacial geomorphological features and monitoring of paraglacial processes. A spatial distribution mapping of glacial landforms is important to infer about glaciarized former areas, ice retreat pattern and glacial dynamics (e.g. ice flow direction and basal thermal conditions) of the Admiralty Bay glaciers. Recent environmental changes are also observed in deglaciated areas as paraglacial activities (e.g. flow debris).

SUMÁRIO

APRESENTAÇÃO

A Península Antártica e as ilhas no entorno estão em uma das áreas que registrou as maiores tendências de aquecimento regional nas últimas décadas. Em decorrência de sua localização geográfica, as geleiras das ilhas antárticas, como a ilha Rei George, são sensíveis às rápidas variações ambientais. Como consequência, aumenta a preocupação entre os pesquisadores de tentar entender a dinâmica das geleiras subpolares em condições marítimas em resposta à tendência desse aquecimento regional. Também é relevante monitorar diversos processos que podem revelar alterações nestes ambientes, tais como a dinâmica sedimentar e hidrológica das geleiras e as suas interligações existentes, a nível local, com o ambiente proglacial e glacimarinho.

A presente tese apresenta investigações da dinâmica glacial e geomorfológica e mecanismos que condicionam a erosão e produção sedimentar glacial das geleiras que fluem para a enseada Martel (capítulos 2 a 5), ilha Rei George, Shetlands do Sul, Antártica, dando ênfase à geleira Wanda (capítulos 6 a 11). Esta tem término terrestre e uma ampla área proglacial. O trabalho apresenta considerações sobre os processos glaciais e sedimentares da área de estudo, assim como sobre recentes mudanças ambientais e suas interconexões entre diversas variáveis que compõe o sistema glacial, proglacial e glacimarinho. Discute-se as técnicas de investigação geomorfológica, sedimentológica, hidrológicas, geofísicas e utilização de dados de Sensoriamento Remoto e Sistema de Informação Geográfica para o ambiente glacial e proglacial.

A tese está organizada no formato de artigos, conforme normas do Programa de Pós-Graduação em Geociências, do Instituto de Geociências da Universidade Federal do Rio Grande do Sul. Apresentando um capítulo inicial introdutório, os capítulos 2 a 11 são artigos submetidos ou aceitos seguidos de um capítulo com considerações finais.

Capítulo 1 - Introdução

1.1 Dinâmica glacial e inter-relações com os processos hidrológicos e sedimentares em ambientes com processo de deglaciação recentes

Ambientes glaciais representam indicadores sensíveis às mudanças climáticas e agem como importantes reguladores do sistema climático (ZEMP *et al*., 2008), pois influenciam no albedo e contribuem para o gradiente térmico global. Massas das geleiras e calotas de gelo localizadas em áreas subpolares da Antártica têm retraído como consequência do aquecimento regional (OERLEMANS, 1994). Vários estudos indicam que essas geleiras mostram uma rápida reposta a mudanças ambientais (ABDALATI e STEFFEN, 2001; PAUL *et al*., 2004; BOLCH e KAMP, 2006), em escalas temporais que variam entre anos e séculos (SIMÕES *et al*., 2011).

A análise das geoformas glaciais, relevadas durante a deglaciação, é relevante para o melhor entendimento dos processos sedimentares glaciais e também para revelar a dinâmica glacial (GLASSER e HAMBREY, 2001; BOULTON *et al*., 2001; ADAM e KNIGHT, 2003). A distribuição espacial de geoformas glaciais podem ser importantes para inferir a extensão, espessura, comportamento da massa de gelo, direção do movimento do gelo e padrão de retração glacial (COLGAN e PRINCIPATO, 1998; KLEMAN e HATTESTRAND, 1999; CLARK; KNIGHT; GRAY, 2000; STOKES e CLARK, 2003; NAPIERALKI *et al*., 2007). Dessa forma, os registros geomorfológicos encontrados nos ambientes de deglaciação são relevantes para a interpretação dos processos erosivos e deposicionais glaciais e fornecem informações sobre as condições termais, dinâmica passada e atual da geleira, assim como podem ser úteis para reconstruir a evolução do ambiente de deglaciação, por exemplo, em resposta ao aquecimento climático regional (BOULTON *et al*., 2001; KLEMAN *et al*., 2006).

No ambiente glacial, os sedimentos sofrem diversas modificações pela ação erosiva durante o processo de transporte e são posteriormente depositados no ambiente glacimarinho através da drenagem glacial ou ainda por gelo marinho e icebergs. Canais de água de degelo ou corpos lagunares proglaciais formados pelo derretimento frontal das geleiras também podem transferir os sedimentos para o sistema glacimarinho. Para entender como a geomorfologia reflete a variabilidade climática, é necessário identificar os fatores controladores do grau de produção de sedimentos, o qual é resultante da ação erosiva e da sua transferência para o ambiente glacimarinho ou proglacial. O entendimento dos processos erosivos subglaciais requer a investigação das características glaciológicas (extensão e espessura da geleira, velocidade do fluxo de gelo, configuração do término, grau de retração e regime termal), topográficas, temporais, litológicas do substrato rochoso e dos detritos transportados, entre outras (SUGDEN e JOHN, 1976; DREWRY, 1986; GURNELL, 1987, BENNETT e GLASSER, 1996; HALLET, HUNTER; BOGEN, 1996; HOWAT *et al*., 2005; KOPPES e HALLET, 2006; KOPPES *et al*., 2010).

A distribuição da temperatura de uma geleira é fundamental para a sua dinâmica, pois controla como o gelo se deforma internamente e o papel da água de degelo na lubrificação do contato rocha/gelo. A distribuição da temperatura em um corpo de gelo é consequência da interação de diversos processos, entre eles, o calor gerado na base da geleira e o gradiente térmico dentro do gelo (PATTERSON, 1994). Geleiras temperadas, que são caracterizadas por terem toda a massa de gelo próxima ou no ponto de fusão sob pressão, são muito sensíveis à variáveis meteorológicas (temperatura do ar, precipitação, etc.) e superficiais (albedo, temperatura superficial, etc.) (PATTERSON, 1994; VINCENT, 2002; HOCK, 2005).

O conteúdo de água e sua distribuição no corpo de gelo dependem do regime termal da geleira, desta forma, este exerce importante influência no deslizamento basal (BENN e EVANS, 2010), assim como no grau de erosão (CUFFEY e ALLEY, 1996; RIIHIMAKI *et al*., 2005). A presença da água na base de uma geleira subpolar com regime termal basal úmido determina a eficiência do fluxo de água de degelo para remover os detritos rochosos erodidos, renovando assim, a superfície abrasiva e aumentando o grau de erosão e produção sedimentar (DREWRY, 1986; SUGDEN e JOHN, 1976; BENNETT e GLASSER, 1996; ELVERHØI; HOOKE; SOLHEIM, 1998; SWIFT *et al*., 2005; BENN e EVANS, 2010). O transporte de sedimentos subglaciais por uma eficiente rede de drenagem subglacial é amplamente considerado como a forma dominante de descarga sedimentar na maioria das geleiras temperadas para ambientes proglaciais. Considera-se que o regime termal basal pode variar ao longo do tempo por modificações na topografia glacial, devido a mudanças na velocidade do fluxo de gelo, e ainda por mudanças climáticas (BENNETT e GLASSER, 1996).

A velocidade do fluxo de gelo está relacionada ao balanço de massa, deformação interna e ao regime termal basal (MENZIES, 1995). A variabilidade no movimento de deslizamento é atribuída a mudanças no mecanismo de transporte pela água basal (MACGREGOR *et al*., 2000). A alta pressão da água é importante na redução da fricção na interface gelo-base e para aumentar deslizamento basal (BENNETT e GLASSER, 1996). Assim, variações no sistema hidráulico subglacial e variações de temperatura, precipitação, descarga de água e flutuação geotermal podem reduzir o arrasto friccional na base do gelo (SUGDEN e JOHN, 1976; MENZIES, 1995; MACGREGOR *et al*., 2000).

Geleiras temperadas comumente mostram episódios de rápido fluxo de gelo devido ao deslizamento basal (MEIER *et al*., 1994) quando tornam-se flutuantes em seu término. Numa posição instável da frente de gelo, a produção sedimentar será em grande parte controlada pelo grau de retração do seu término (POWELL, 1991; SYVITSKI e SHAW, 1995). Observa-se a ocorrência de rápido movimento das geleiras durante períodos de acelerada retração (KOPPES *et al*., 2010), pois podem sofrer um alto grau de degelo em seu término.

A investigação desses processos é importante para o entendimento do grau de produção sedimentar glacial no seu término (ANDERSON e MOLNIA, 1989). Desta forma, os padrões e as taxas de aporte sedimentar para o fiorde são controlados pelo: regime termal, velocidade de fluxo do gelo, grau de retração, configuração do término, configuração do sistema de drenagem, entre outros (SYVITSKI; BURREL; SKER, 1987).

A produção de sedimentos se mostra diferente em vários tipos de geleiras (HALLET, HUNTER; BOGEN, 1996). De acordo com estimativas de Powell e Molnia (1989), o material em suspensão transportado pela descarga de água de fusão de geleiras temperadas em retração é maior do que o volume de aporte sedimentar na frente de geleiras de maré ou em término terrestre (SYVITSKI, 1989; COWAN e POWELL, 1991).

Processos de descarga de água de degelo para o ambiente proglacial possuem considerável variação sazonal e diurna (DREWRY, 1986; BOGEN e BØNSNES, 2003; RIIHIMAKI *et al*., 2005; BENN e EVANS, 2010), relacionados com o desenvolvimento do sistema de canais de água de degelo em direção a área de ablação (HUBBARD e GLASSER, 2005). O entendimento dos sistemas de drenagens glaciais é fundamental para várias questões que envolvem a glaciologia, incluindo a dinâmica glacial (HUBBARD *et al*., 1998). As características do sistema de drenagem interferem no grau de deslizamento basal das geleiras (FOUNTAIN e WALDER, 1998) e, desta forma, nos processos sublaciais envolvidos (PATERSON, 1994; MACGREGOR *et al*., 2000; SWIFT *et al*. 2005). Altas concentrações de sedimentos em canais proglaciais podem estar relacionadas ao desenvolvimento sazonal de uma eficiente rede de canais de drenagem subglacial (ALLEY *et al*., 1997; RIIHIMAKI *et al*., 2005; SWIFT *et al*., 2005). O desenvolvimento e configuração do sistema hidráulico glacial dependem: do tipo, morfologia e topografia da massa de gelo, das condições termais, do balanço de massa, da velocidade do fluxo de gelo, das condições termais basais e da quantidade de detritos transportada (MENZIES, 1995; FOUNTAIN e WALDER, 1998).

Nas ilhas situadas a noroeste da Península Antártica, como a ilha Rei George, grandes geleiras de maré são em grande parte confinadas em fiordes, sendo a produção sazonal de água de degelo e transporte partículas em suspensão na água um importante componente do ambiente glacimarinho da região (ANDERSON e MOLNIA, 1989). Plumas de sedimentos em suspensão, relacionadas, principalmente, ao aporte de água de degelo proveniente de canais subglaciais foram observadas próximas ao término de geleiras na enseada Martel por Pecherzewski (1980); Gruber (1989); Griffth e Anderson (1989); Domack e Ishman (1993); Yoon *et al. (*1998); Aquino (1999) e Pilchemaier *et al.* (2004). A geleira Wanda gera fluxos de água de degelo por meio de canais proglaciais que deságuam na laguna proglacial, a qual se comunica com a enseada Martel. A sedimentação terrígena em fiordes subpolares do arquipélago das Shetlands do Sul excede os fiordes polares na Península Antártica, devido às plumas de sedimentos em suspensão geradas nas frentes de geleiras de maré (ANDERSON, 1999).

A enseada Martel, localizada na baía do Almirantado, ilha Rei George (IRG), a nordeste da Península Antártica, é considerada um fiorde devido suas características de morfologia de fundo e sua circulação influenciada pela presença de um *sill* em sua desenbocadura, sendo circundada por geleiras de marés ou com frente terrestre. A massa de gelo da ilha Rei George divide-se em domos, os quais são conectados e a partir deles diferentes bacias de drenagem fluem em direção ao ambiente glacimarinho (BREMER; ARIGONY-NETO; SIMÕES, 2004). A calota de gelo que cobre aproximadamente 92,7% da ilha Rei George, possui a altitude máxima entorno de 700 metros (BREMER, 1998). Processos relacionados ao derretimento de neve e gelo controlam fortemente esses ambientes (VOGT e BRAUN, 2004). As geleiras de maré possuem gradiente superficial acentuado, fluxo relativamente rápido e muitas fendas. Algumas geleiras, como a Wanda, Dragão e Professor se caracterizam pela atual frente terrestre.

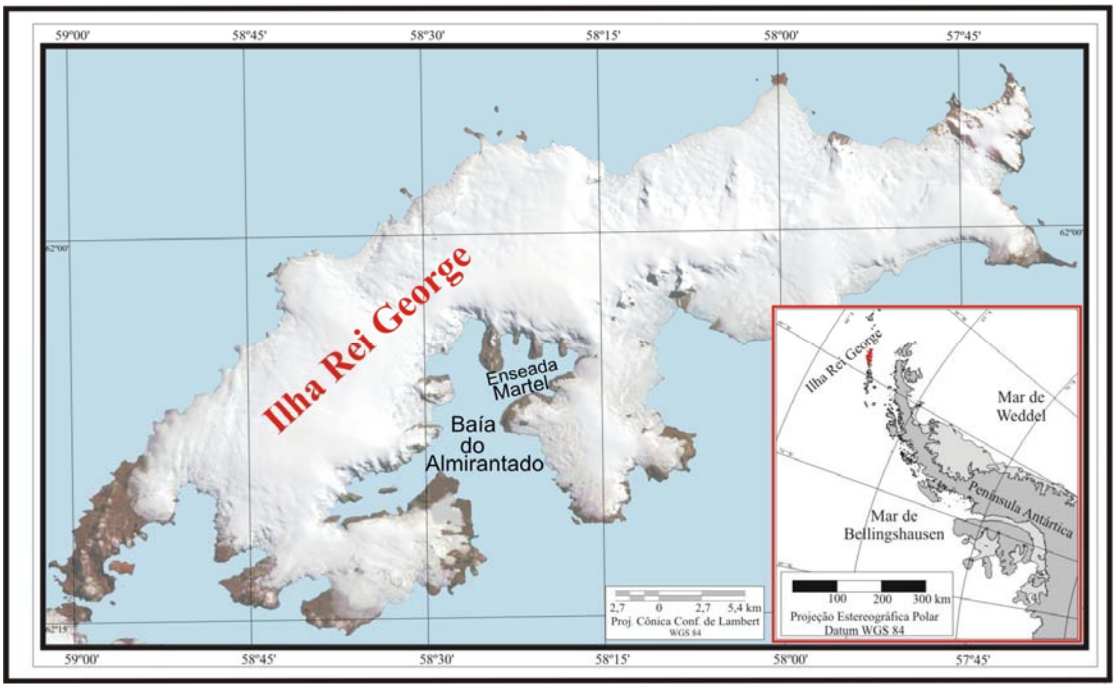

Figura 1 - Localização da enseada Martel.

Vários estudos têm registrado a retração de geleiras na ilha Rei George desde 1956 (SIMÕES e BREMER, 1995; BREMER, 1998; PARK *et al*., 1998; SIMÕES *et al*., 1999; BRAUN e GOSSMANN, 2002). Esssas retrações têm sido ligadas diretamente ao aquecimento regional (3°C) na Península Antártica nas últimas décadas (SIMÕES *et al*, 2004; MONAGHAN *et al*. 2008; TURNER *et al*., 2009; BLINDOW *et al*., 2010). As massas de gelo das ilhas Shetland do Sul são particularmente sensíveis às variações climáticas, em função de sua posição geográfica (Lat. 61°04'S - 63°20'S e Long. 54°00'W - 62°25'W), da pequena espessura de gelo e por estarem muito próximas do ponto de fusão sob pressão (KNAP; OERLEMANS; CADEE; 1996).

Devido à sua localização, as Shetlands do Sul possuem clima tipicamente subpolar marítimo (SETZER e HUNGRIA, 1994). A temperatura média do verão atinge 2,0ºC, resultando em uma produção de água de degelo durante essa estação (DOMACK e ISHMAN, 1993; BRAUN, 2001). Ao longo dos últimos 30 anos, os dias do ano com precipitação líquida no verão aumentaram, juntamente com o número de dias em que a temperatura média ultrapassou os 0°C, esse processo acelera a fusão de neve e gelo e aumenta o balanço de massa negativo das geleiras da ilha (PILCHLMAIER *et al.*, 2004; RAKUSA-SUSZCZEWSKI, 1995; BRAUN *et al*., 2001; FERRANDO.; VIEIRA; ROSA et al., 2009; 2011). Variações na geração de água de degelo influenciam no suprimento de material terrígeno para o ambiente glacimarinho devido à geração de múltiplos canais de água de degelo e lagunas proglaciais (BRAUN *et al.*, 2001).

1.2 Objetivo geral

O objetivo desta tese é investigar a dinâmica glacial e proglacial relacionada aos processos de retração das geleiras que fluem para a enseada Martel, baía do Almirantado, ilha Rei George, usando registros geomorfológicos, morfométricos, hidrosedimentológicos e dados obtidos por Geofísica, Sensoriamento Remoto e SIG.

1.2.1 Metas

a) Investigar as características do sistema hidrológico subglacial, englacial e supraglacial e mecanismos de transporte sedimentar da geleira Wanda, relacionando-os à dinâmica glacial, condições termais basais e a variabilidade da estocagem hídrica e produção sedimentar pela geleira.

b) Aplicar modelo numérico de estimativa de graus de produção de sedimentos glaciais da geleira Wanda para o ambiente glacimarinho, e investigar as variáveis que condicionam sua variabilidade espacial e temporal.

c) Examinar a estrutura termal da geleira Wanda e inferir o regime termal das geleiras da área de estudo relacionando-os com os processos de retração glacial e geração de plumas de turbidez para o ambiente glacimarinho.

d) Analisar as características morfométricas e elaborar perfis topográficos e Modelo Digital de Terreno para o ambiente glacial e proglacial da área de estudo.

e) Elaborar um mapeamento geomorfológico subaéreo que é útil para o monitorar as variações ambientais proglaciais e relação à dinâmica dos processos glaciais e paraglaciais envolvidos, os quais são influenciados pela retração glacial.

f) Reconstruir a evolução da retração das geleiras que fluem para o fiorde baseado em análises de registros geomorfológicos obtidos em campo e de estudos temporais de dados de Sensoriamento Remoto com o uso de SIG.

g) Desenvolver e aprimorar uma metodologia de análise integrada de registros sedimentológicos e aplicação de métodos glaciológicos, hidrológicos, geofísicos, processamento digital de imagens e de Sistema de Informações Geográficas para relacionar o ambiente proglacial com a dinâmica glacial, para detectar variações ambientais temporais e inferir o comportamento das geleiras da área de estudo como reflexo à variabilidade climática.

h) Comparar o padrão de retração glacial entre as geleiras da área de estudo relacionado às suas características de configuração de término, influência da declividade topográfica, velocidade de fluxo de gelo e regimes termais.

1.3 Justificativa

A região da Península Antártica é uma das mais sensíveis às variações climáticas na escala global e tem apresentado significante tendência de aquecimento da temperatura superficial (TURNER *et al*., 2009). As massas de gelo das ilhas da Antártica marítima são de interesse particular para os estudos ambientais devido às suas respostas relativamente rápidas (intervalos de década a centenas de anos) à variabilidade climática regional (IPCC, 2007; SIMÕES *et al.*, 2011). Tal sensibilidade deve-se às pequenas dimensões e menor espessura do gelo se comparadas ao manto de gelo do continente (ANDERSON, 1999; SIMÕES *et al*., 2011).

Com o processo de retração das geleiras, torna-se importante o monitoramento das respostas da dinâmica glacial, hidrológica e sedimentar e as suas interligações existentes, a nível local, com o ambiente glacimarinho e proglacial. Este estudo pode auxiliar na compreensão das consequências das mudanças climáticas para o comportamento e padrão de retração de geleiras localizadas na região marítima antártica. O entendimento desses processos e sua relação com as características do sistema de drenagem glacial, configuração de término, velocidade de fluxo de gelo e regimes termais são relevantes para comparações com outras geleiras de condições semelhantes.

Importantes processos de liberação da água armazenada no sistema glacial dependem da variabilidade da descarga de água de degelo para o ambiente glacimarinho. Com o processo de retração, muitas geleiras têm a estocagem hídrica reduzida e transferindo mais água e sedimentos em suspensão para o fiorde. O monitoramento destes processos é relevante para o estudo das flutuações no nível do mar, da circulação no fiorde, da dinâmica glacial, da produção sedimentar e, ainda, para a formação de geoformas glaciais (JANSSON *et al*., 2003).

De acordo com Griffth e Anderson (1989) e Domack e Ishman (1993), processos importantes ligando sistemas atmosféricos, oceanográficos e a criosfera antártica são a produção sazonal de água de degelo e o transporte de partículas em suspensão na água por geleiras temperadas. A sedimentação terrígena em fiordes do arquipélago das Shetlands do Sul excede os fiordes polares na Península Antártica, devido às plumas de sedimentos em suspensão geradas nas frentes de geleiras de maré (GRIFFITH e ANDERSON, 1989; ANDERSON, 1999). O processo sedimentar está intimamente relacionado com o comportamento climático, pois este controla o regime glacial, o volume de precipitação, a descarga de fluxos de fusão (POWELL e MOLNIA, 1989). Sendo assim, as mudanças ocorridas no padrão sedimentar das geleiras fornecem excelente base para estudos acerca da mudança climática e de suas consequências (GLASSER e HAMBREY, 2001). De acordo com Pichmaier *et al*. (2004), essas alterações relacionadas a deglaciação geram mudanças significativas na dinâmica sedimentar da enseada, e assim, para o ecossistema marinho que habita esses ambientes.

Os dados resultantes desta pesquisa contribuem para o entendimento o contínuo monitoramento dos efeitos das mudanças ambientais na região. Destaca-se o aprimoramento de metodologias que integrem registros sedimentológicos e aplicação de métodos glaciológicos, hidrológicos, geofísicos, processamento digital de imagens e de Sistema de Informações Geográficas para ampliar a compreensão e detectar variações temporais na dinâmica glacial, hidrológica e sedimentar destes ambientes.

A ligação entre a pesquisa glaciológica com o ambiente subaéreo permite estudos dos processos que influenciam a flutuação do sistema glacial, e contribui para o entendimento das mudanças ocorridas nesse sistema, incluindo decréscimo da massa de gelo das geleiras. Investigações dos mecanismos que controlam a produção sedimentar proporcionam maior compreensão dos processos e geoformas resultantes, e possibilita a interpretação das informações registradas em sedimentos glacigênicos.

1.4 Metodologia

A metodologia desenvolvida nesta tese foi realizada de acordo com a seguinte sequência de metas a serem alcançadas: caracterização da dinâmica glacial, hidrológica, sedimentar; elaboração do modelo para estimar a produção sedimentar; interpretação das características e dos processos geomorfológicos glaciais e paraglaciais dos ambientes proglaciais e reconstrução da evolução do ambiente de deglaciação das geleiras que fluem para a enseada Martel.

O desenvolvimento da tese envolveram atividades de campo realizadas nas Operações Antárticas nos anos de 2007 (novembro e dezembro), 2010 e 2011 (janeiro e fevereiro). Durante as atividades de campo na área proglacial da geleira Wanda foram coletadas amostras de sedimentos, perfis topográficos, dados de GPR (*Ground Penetrating Radar*), dados de deslocamento de fluxo superficial de gelo e medidas de concentração de sedimentos em suspensão e descarga de água de degelo em canais proglaciais na geleira.

As características da estrutura interna e configuração da drenagem glacial, o regime termal e as características do contado base-substrato da geleira Wanda são inferidas por dados obtidos por 17 perfis longitudinais e transversais de GPR *Geophysical Survey Systems Inc*. (GSSI) *SIR System control* com uma antena de 100 MHz. O equipamento foi tracionado à mão com configuração *common-off set* e janela de tempo de 600 ns a 800 ns. O posicionamento, para a correção da topografia superficial, foi realizado com DGPS *Global Positioning System TechGeo* e Estação Total. Técnicas de processamento digital com o software RADANTM 6.5 foram desenvolvidas para melhorar as reflexões de radar.

Fluxos de sedimentos em suspensão e descarga de água de degelo foram mensurados durante o mês de janeiro nos verões 2010 e 2011, em canais proglaciais na parte frontal da geleira Wanda, de acordo a metodologia proposta por Bogen (1996). Este procedimento visa investigar o influxo de água de degelo basal e a variabilidade da taxa de transferência do fluxo de água de degelo de sedimentos em suspensão para a enseada Martel de acordo com modelo numérico proposto por Riihimaki *et al.* (2005) e com relação aos dados meteorológicos (radiação, precipitação e temperatura) do período observado. A variabilidade temporal do grau de erosão e produção de sedimentos foi examinada com a aplicação do modelo numérico que relaciona as condições glaciais (grau de retração, velocidade de fluxo da geleira, regime termal, área glaciarizada) e características do substrato rochoso.

O monitoramento da localização dos canais foi realizado por meio de coleta de pontos de controle de GPS e uso de fotografias aéreas e de imagens de satélite para seu mapeamento. O processamento das amostras para determinar a concentração de sedimentos em suspensão foi efetuado através da utilização de um equipamento de filtragem.

A velocidade de fluxo horizontal da superfície do gelo da geleira Wanda foi estimada com base no deslocamento de estacas de velocidade (2007-2011) determinado com o uso de DGPS (*Differential Global Positioning Systems*) e pós processamento dos dados para a correção diferencial, de acordo a metodologia proposta por Anderson *et al*. (2004) e MacGregor *et al*. (2005).

Altitudes ortométricas no ambiente glacial e proglacial na geleira Wanda foram obtidas com a realização de transectos longitudinais e transversais com o uso de *Leica Geosystems Total Station* TPS1200. Adicionalmente, pontos planialtimétricos foram obtidos com dados de DGPS (GTRA) e pós-processados com referência nas coordenadas da antena base de GPS (62°04'58"S e 58°23'39"W; altitude de 57.53 m) instalada na Estação Antártica Comandante Ferraz (EACF) pela Rede Brasileira de Monitoramento Contínuo (RBMC) do IBGE (Instituto Brasileiro de Geografia e Estatística). Os pontos de altitudes elipsoidais foram transformados em altitudes ortométricas, referenciadas pelo Sistema Geodésico Mundial (WGS 84) com o uso do Modelo de Ondulação Geoidal EGM86 (*Earth Gravity Model* 1996), baseado em Hofmannw-Ellenhof *et al*. (1997). As altitudes ortométricas foram interpoladas com o método de Krigagem Ordinária no software SURFER (*Golden Software, Inc.*) para gerar um Modelo Digital do Terreno (MDT) para a geleira Wanda. Adicionalmente, perfis transversais e longitudinais para o ambiente proglacial e para a superfície da geleira, também, foram gerados com estes dados.

Dados morfométricos (mapas hipsométrico, de declividade e aspecto, escala 1:10.000, e modelos de sombreamento analítico e cenas perspectivas tridimensionais) para toda a área do setor norte da baía do Almirantado foram gerados pela da elaboração de ortofotomosaico e MDT (interpolado através do método Vizinho Natural do ARCGIS e com resolução espacial de 0,7 m no terreno) com a utilização do Sistema de Informações Geográficas (SIG). A geração do ortofotomosaico foi realizada a partir de um estereopar de fotografias aéreas pancromáticas na escala 1:50.000, obtidas por câmara fotogramétrica *Leica* modelo RC10, com distância focal de 88,10 mm, durante uma missão de vôo executada no ano de 2003 sobre a Península Antártica pelo *Servicio Hidrográfico y Oceanográfico de La Armada del Chile* (SHOA). O ortofotomosaico foi elaborado a partir da ortorretificação de cinco fotografias aéreas, utilizadas na geração de um MDT. As orientações interior e exterior, bem como a geração e edição do MDT, foram realizadas no software LPS (*Leica Photogrammetry Suite*), adotando-se o sistema de projeção cartográfica *Universal Transversa de Mercator* (UTM), zona 21S, com o elipsóide de referência *World Geodetic System* 1984 (WGS84).

O mapeamento geomorfológico dos ambientes proglaciais das geleiras que fluem para a enseada Martel foi elaborado pela análise de registros sedimentares, perfis topográficos e interpretação geomorfológica de imagens QUICKBIRD (obtida em Outubro, 2006, com 0,61 metros de resolução espacial no modo pancromático e 2,4 metros de resolução no modo espectral), COSMO-SkyMed (4 imagens na banda X, com polarizações HH e VV, obtidas no mesmo período do campo de 2011, e ortorretificadas com 1 metro de resolução, com a aplicação de filtros específicos e analise textural) e ortofotomosaico (0,7 metros de resolução espacial gerado). A identificação das formas foi baseada em Glasser *et al*. (2005), Hubbart e Glasser (2005), Smith e Clark (2005), Gustavsson *et al*. (2006).

O mapeamento da distribuição espacial de depósitos morâinicos de recessão, bancos morâinicos, *flutings* e aretes foram utilizadas para reconstruir o padrão de deglaciação das geleiras que fluem para a enseada Martel. A extensão e posição atingida pelas geleiras em várias fases de retração, assim como o grau de retração anual foi quantificada com a utilização de imagens SPOT (obtidas em Fevereiro de 1988 e em Março de 1995 e 2000), QUICKBIRD (obtida em Outubro de 2006) e COSMO-SkyMed (obtida em Fevereiro de 2011). A estimativa de área das geleiras em 1979 foi baseada em dados de Arigony-Neto (2001).

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Capítulo 2

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USE OF COSMO-SKYMED IMAGERY FOR RECOGNITION OF GEOMORPHOLOGICAL FEATURES IN THE MARTEL INLET ICE-FREE AREAS, KING GEORGE ISLAND, ANTARCTICA

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ABSTRACT

COSMO-SkyMed images in spotlight mode (1-m spatial resolution) were used for recognition of geomorphological features in Martel Inlet ice-free areas, King George Island, South Shetlands, Antarctica. This paper shows results from texture analysis and filtering of four X-band images with HH and VV polarization, acquired during fieldworks carried out in January and February 2011. Based on field checking and visual interpretation techniques, we identified several glacial landforms, such as moraines, flutes, outwash, arêtes, glacial lineations, meltwater channels, lakes, lagoons and shorelines. Some glacial linear features, like lateral moraines, flutings and arêtes are better identified with VV polarization, while supraglacial debris, debris flow and shorelines are better discriminated with HH polarization. Meltwater channels, lakes and lagoons were easily distinguished under both co-polarizations. Focal variance texture analysis and specific kernel size convolution filters yielded the best enhanced images for landforms visual interpretation. For this proposes the Wallis adaptative, morphological Close, Prewitt with northwestern and southeastern directions, and some high-pass filters described in this studies are the best filters. Images processed with these filters can be used for studies of geomorphic processes and for monitoring periglacial changes in Antarctica.

Keywords: Martel Inlet, King George Island, COSMO-SkyMed, glacial landforms.

1. Introduction

Radar remote sensing has brought a new dimension for understanding glacial geomorphological processes. Often cloudy conditions over Antarctic sub-polar maritime regions limit the use of optical images for the monitoring of these areas. On the other and, microwave energy is able to penetrate through clouds and most rain (CCRS, 2002).

Backscatter values variations in radar images results from physical characteristics changes of terrain surfaces illuminated by the radar beam such as sediments, moisture content, surface roughness and its geometry (e.g., local incidence angle), as cited by Sarapirome et al. (1995). The side-looking viewing geometry of imaging radar systems improves the recognition of glacial linear features, such as morainic rigdes, flutings and meltwater channels. Several studies have confirmed the usefulness of RADARSAT, ERS Synthetic Aperture Radar (SAR) and ENVISAT Advanced Synthetic Aperture Radar (ASAR) images (C-band - 5.6 GHz) for geomorphological mapping (Sarapirome et al., 1995; Lewis et al. 1998; Rao, 2002; Jensen, 2007).

The COnstellation of small Satellites for Mediterranean basin Observation (COSMO-SkyMed) provides SAR data and the possibility of observing the Earth surface with high temporal and spatial resolutions at different polarizations. It is the largest Italian investment in space systems for Earth observation, commissioned and funded by Italian Space Agency (ASI). This system consists of four low Earth orbit mid-sized satellites, each one equipped with a multi-mode high-resolution SAR operating at X–band (9.6 GHz), acquiring images every 12 hours for a 600 km swath width. The COSMO-SkyMed satellites allow full global coverage, all weather, day/night acquisition capability, fast revisit/response time and interferometric/polarimetric capabilities. Thus, these high resolutions X - band SAR satellites allow the image interpreter to distinguish more details and can further support glacial geomorphological studies (ASI, 2007; Battazza et al., 2007; Caltagirone et al., 2007; Coletta et al., 2008; Covello et al., 2008).

This paper assesses the use of COSMO-SkyMed imagery at HH and VV polarizations to discriminate glacial landforms in the ice-free areas of the Antarctic region, and their application on geomorphological mapping. The study of landforms development and their spatial distribution are critical to characterize proglacial zones for monitoring the ice-free areas of Antarctica. Landform mapping is also useful for glacier reconstruction (Lowe and Walker, 1997).

2. Regional Setting

In this study we used four COSMO-SkyMed images covering Martel Inlet, located in the northern sector of Admiralty Bay, King George Island (KGI), South Shetlands archipelago (between 61°54’ - 62°16’S and 57°35’ - 59°02’W), off in the northwestern tip of the Antarctic Peninsula (Fig. 1).

Most part of the Martel Inlet is surrounded by tidewater glaciers with steep slopes, high ice flow velocities and extensive crevasse fields. Some glaciers have termini on land, such as Wanda, Dragon and Professor ones (Fig. 2). Glacier retreat processes formed ice-free areas and consequently exposed several landforms (Rosa et al., 2010).

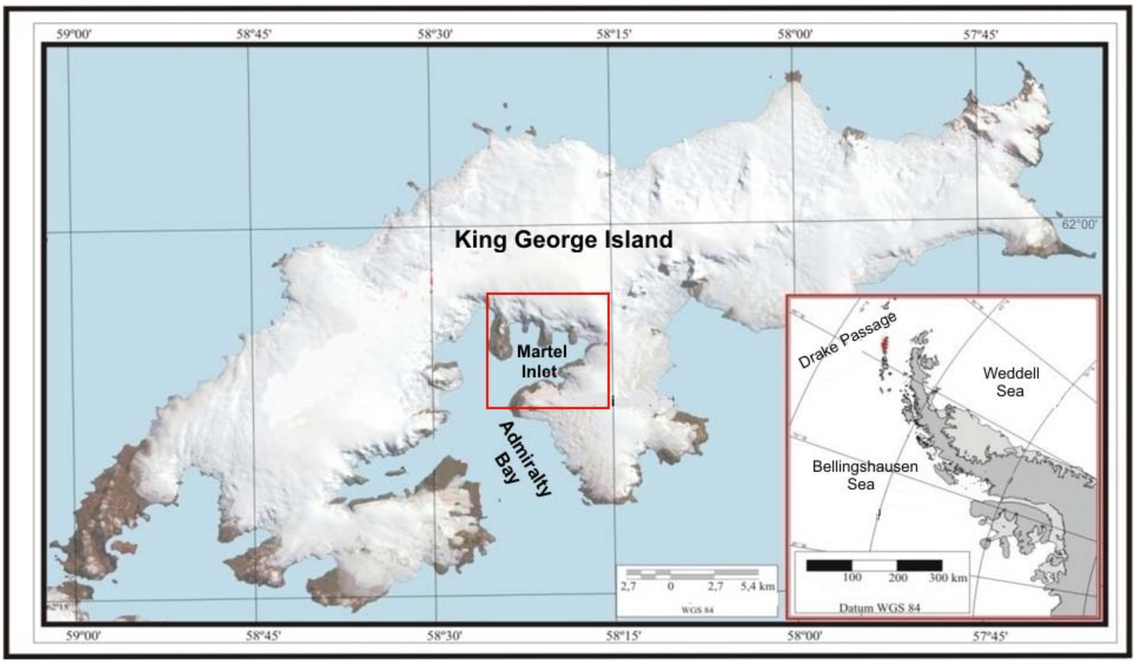

Figure 1 - Martel Inlet location in King George lsland, Antarctica. The red square indicates the ground coverage area of COSMO-SkyMed scenes used in this study.

3. Material and methods

3.1 Dataset characteristics

The imagery used in this study consists of two horizontal-polarized (HH) and two vertical-polarized (VV) COSMO-SkyMed imagery acquired on spotlight mode, with 1-m spatial resolution and approximately 100 km² of ground coverage area. These images were acquired in descending orbits, at the same time of a fieldwork carried out in January and February, 2011. Some characteristics about these images are described in table 1. Sediment samples were collected during three summer field seasons (2007, 2010 and 2011) proglacial area, covering different microenvironments and geomorphic features, for identification and mapping of landforms. The samples were analyzed at the Laboratory of Sedimentology of CECO (Center for Marine and Coastal Studies - UFRGS).

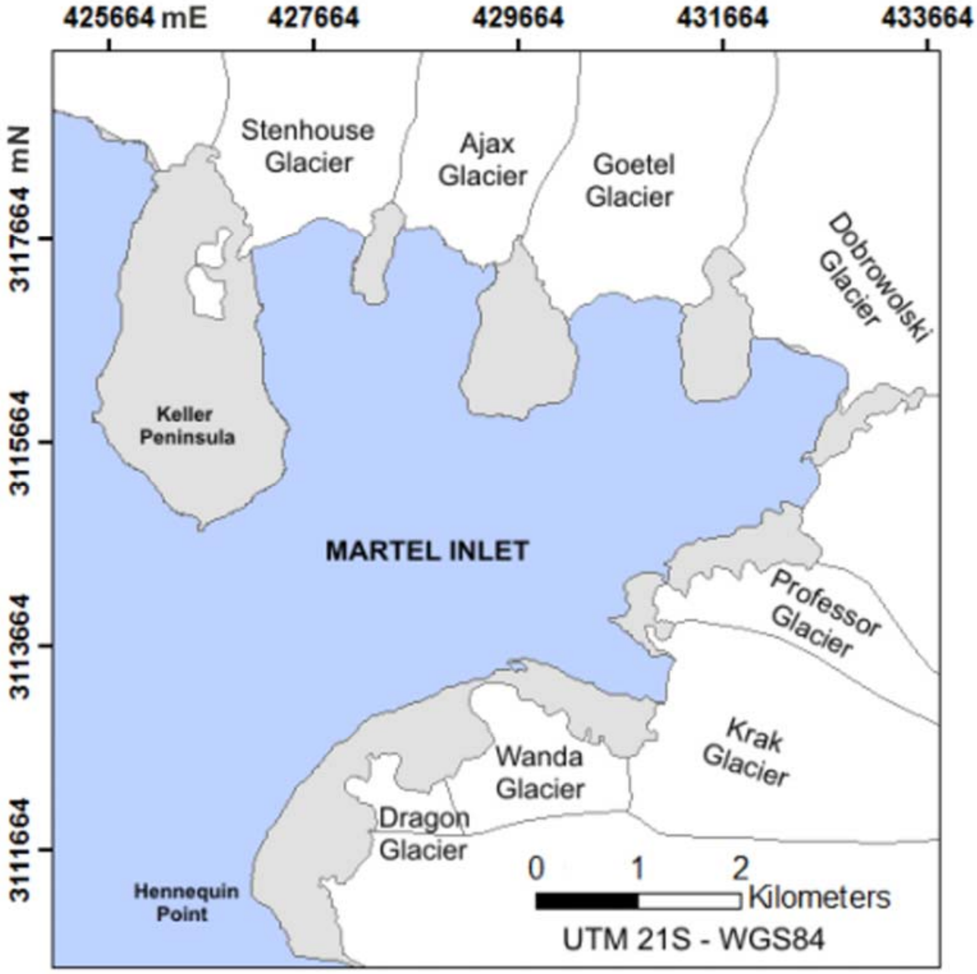

Figure 2 – Glaciers in the Martel Inlet, with their drainage basin boundaries. Data provided by the Admiralty Bay Map Server prototype – Centro Polar e Climático/UFRGS (2011).

Table 1 – Characteristics of COSMO-SkyMed images used in this study.

Acquisition date	Acquisition time (UTC)	Satellite mission	Orbit number	Look angles near – far range	Polarization mode
22/01/2011	19h 58min 45s	CSK3	12142	43.023 – 43.431	VV
25/01/2011	20h 22min 40s	CKS1	19904	28.329 – 28.992	HH
10/02/2011	20h 22min 30s	CSK1	19667	28.295 - 28.958	VV
11/02/2011	19h 52min 34s	CSK2	17193	45.553 – 45.916	HH

3.2 Image processing

We used COSMO-SkyMed level 1A products (also indicated as Single-look Complex Slant - SCS), which consist of focused data, with internal radiometric calibration, in slant range-geometric projection, with associated ancillary data.

Conversion from intensity to amplitude in dB, orthorectification, speckle filtering and statistical evaluation of the COSMO-SkyMed data were performed using the open source software Next ESA SAR Toolbox (NEST – Array Systems Computing, Inc.). The slant-to-ground range correction was performed using image metadata and a high resolution Digital Elevation Model (DEM). We generated a DEM and an orthophotomosaic of the study area using a digital photogrammetric station (model Leica Photogrammetry Suite – Leica Geosystems, Inc.), with control points surveyed by Differential Global Positioning System (DGPS) in the summers 2007 and 2011 and five vertical aerial photographs at scale 1:50.000, acquired on January 2003 by the Servicio Hidrográfico y Oceanográfico de La Armada de Chile (SHOA).

In the orthorectification of COSMO-SkyMed images and SHOA aerial photographs, the original pixel size was resampled to 0.7 m and 1 m, respectively, by using a bilinear interpolation. All data were represented in UTM projection and referenced to the WGS84 ellipsoid.

A median filter (Rees and Satchell, 1997) with 5x5 kernel size was applied for speckle reduction of the COSMO-SkyMed orthorectified images. This filter reduced effectively the speckle noise, preserving edges between homogeneous areas and allowed good identification of geomorphological features. An experimental study carried out by Arigony-Neto (2006) with ERS SAR and ENVISAT ASAR images showed that the median filter is one of the best algorithms for speckle reduction in glacial environments, with high computational efficiency.

3.3 Image enhancement and interpretation

SAR images interpretation was based on visual examination, considering distinct image tones, textures, size, shape and target patterns, radar shadows, topographic position, orientation and the regional geomorphic context. Landforms identification was based on Glasser and Jansson (2005), Glasser et al. (2005), Smith and Clark (2005), Gustavsson et al. (2006) and Benn and Evans (2010), considering information acquired in the field, visual interpretation of COSMO-SkyMed images including comparations with the orthophotomosaic described in section 3.1 and with the co-registered Quickbird fused image acquired in October 2006.

We evaluated the use of COSMO-SkyMed images at HH and VV polarizations to discriminate geomorphological features in the Martel Inlet ice-free areas. Focal variance texture analysis, the Wallis adaptative filter, morphological filter, Prewitt and some high-pass filters were applied to the COSMO-SkyMed dataset to enhance linear structures in those images used to identify geomorphological features. Texture enhancement was performed by focal variance calculation of images (i.e., within a moving window). The Wallis adaptative filter is designed to adjust images contrast stretch using only values within the window size. We applied a linear stretch with two standard deviations to this kernel. We also evaluated filters: the morphological Erode (focal minimum value), Dilate (focal maximum value), Open (Erode followed by dilate) and Close (Dilate followed by erode). Finally, we analyzed th image edge enhancement resulted from the use of high pass and Prewitt directional filters. In table 2, we present the 3 x 3 kernel definition of the high pass and directional filters tested in this study and the filters that better enhance geomorphic features in COSMO–SkyMed images. Tests were also made using 5x5 and 7x7 kernel sizes.

4. Results and discussions

Based on visual interpretation of pre-processed COSMO-SkyMed images, we identified several well-preserved glacial and periglacial landforms, including moraines, flutes, outwash, arêtes, glacial lineations, meltwater channels, lakes and shorelines in the Martel Inlet.

Table 2 – Kernel definition of high pass and Prewitt filters with 3 x 3 pixels tested in this study. Filters that best enhance geomorphic features in COSMO-SkyMed images are gray highlighted.

High pass filters					
-1 -1 -1 -1 8 -1 -1 -1 -1	-1 -1 -1 -1 9 -1 -1 -1 -1	-1 -1 -1 -1 10 -1 -1 -1 -1	-1 -1 -1 -1 17 -1 -1 -1 -1	-1 -1 -1 2 2 2 -1 -1 -1	-1 2 -1 -1 2 -1 -1 2 -1
Edge detect	**High pass**	**Summary**	**Edge enhance**	**Horizontal**	**Vertical**
-1 -2 -1 0 0 0 1 2 1	-1 0 1 -2 0 2 -1 0 1	0 -1 0 -1 0 1 0 1 0	0 1 2 -1 0 1 -2 -1 0	-2 -1 0 -1 0 1 0 1 2	1 4 1 4 -20 4 1 4 1
Horizontal edge	**Vertical edge**	**Cross edge**	**Left diagonal**	**Right diagonal**	**Laplacian edge**

Prewitt directional filter							
1 1 1 1 -2 1 -1 -1 -1	1 1 1 1 -2 -1 1 -1 -1	1 1 -1 1 -2 -1 1 1 -1	1 -1 -1 1 -2 -1 1 1 1	-1 -1 -1 1 -2 1 1 1 1	-1 -1 1 -1 - 2 1 1 1 1	-1 1 1 -1 -2 1 -1 1 1	1 1 1 -1 -2 1 -1 -1 1
North	**Northwest**	**West**	**Southwest**	**South**	**Southeast**	**East**	**Northeast**

Lateral and end moraines composed by single linear and curved ridges with positive relief, are geomorphological evidences of the Wanda Glacier maximum extent (Rosa et al., 2010). Most of these lateral moraines have northeastern orientation, while the ones located on the most recent depositional margins have northwestern orientation. These features were best identified in vertically co-polarized images. In general, VV and HH data correspond to information resulting from surface-scattering contributions (e.g., from morainic deposits on Wanda proglacial area), while HV and VH combinations provide information on polarizations properties resulting largely on volume scattering (Rott and Davis, 1993).

The lateral moraines northeastern orientation points to an ancient Wanda Glacier ice flow, which formed an U-shaped valley (Rosa et al., 2010). These depositional features present low moisture content and they can be identify in COSMO-SkyMed images by medium gray tones, due to their boulder content that increases backscattering and radar shadows (due to their steep slopes that shield radar illumination) and because of their linear morphology.Vertical edge detection and morphological Close filters (with 3 x 3 windows) showed better results for lateral moraines identification (Fig. 3).

A lateral moraine located at a recent ice free area along the Wanda Glacier front is northwestern aligned. The 3 x 3 Prewitt filter with same orientation) enhanced this glacial feature (Fig. 4).

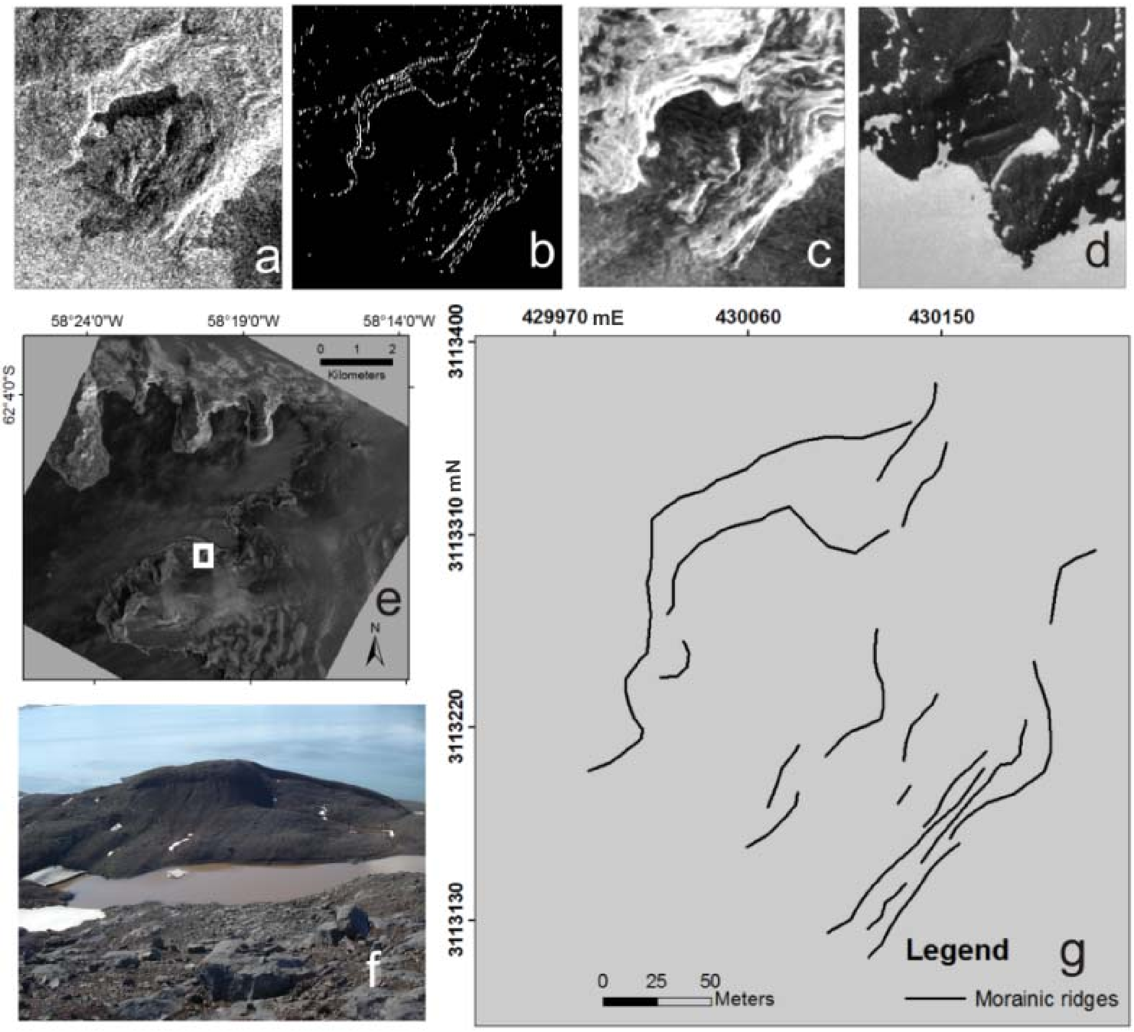

Figure 3 – A lateral moraine on Wanda glacier: (a) Subscene of orthorectified COSMO-Skymed image; (b) Image enhanced by a 3 x 3 vertical edge detection filter; (c) Image enhanced by a 3 x 3 morphological Close filter; (d) Subscene of an orthorectified SHOA aerial photograph acquired on 22/jan/2003; (e) at VV polarization (22/01/2011), speckle-reduced by a 5 x 5 median filter. (f) Photography of a Wanda lateral moraine taken on 17/jan/2011. (g) Geomorphic map of lateral morainic ridges, compiled from figures 3b and 3c.

Meltwater channels and flutings (Fig. 4 and 5) were visually distinguished by their linear forms and medium to dark gray tonalities, because of water content in these deposits. Flutings are parallel features indicating a wet thermal regime and an ancient northwestern ice flow direction for Wanda Glacier (Rosa et al., 2010). Meltwater channels occur at different locations of the proglacial areas. According to Rodhe (1988), these features are most common in the ablation area of glaciers. At Wanda Glacier terminus they appear as small ice-marginal channels that run parallel to ice margins and mark the recent ice retreat. Flutings were better identified at VV polarization, while meltwater channels were easily identified at both HH and VV polarizations. These linear features were better enhanced by a 3 x 3 Prewitt filter with northwestern direction.

Exposed striated pavements at Wanda Glacier proglacial area (Fig. 6) could be identified in COSMO-SkyMed images by their dark gray tones (lower backscattering) due to their smooth surface and basaltic lithology that have a higher dielectric constant (about 12) than adjacent sedimentary deposits composed of dry silt and sand (3.5 and 2.5, respectively).

Coastal features with sand deposition (Fig. 7) showed a smooth surface, low slope and high water content, resulting in low backscattering and dark gray tones in COSMO-SkyMed images. The surface roughness of boulder pavements produces a high backscattering and consequently lighter gray tones in SAR images. These deposits are found parallel to the coastline and were better identified in COSMO-SkyMed images at HH polarization. The 3 x 3 texture analysis and vertical edge detection were the best methods to discriminate these coastal features.

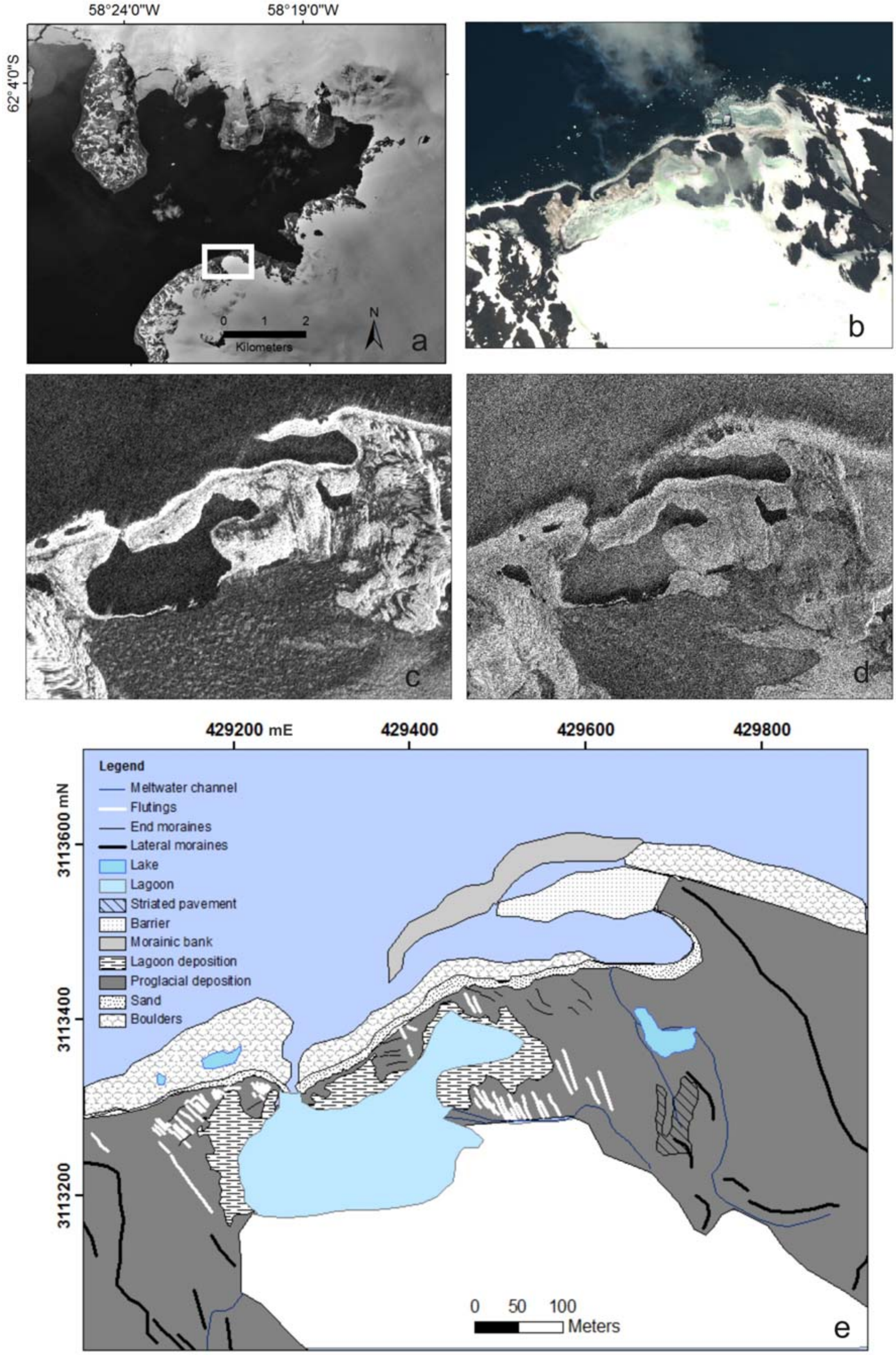

Figure 4 – Recent exposed Wanda Glacier proglacial area. (a) Study area location on an

orthophotomosaic (22/01/2003); (b) Subscene of a Quickbird fused image (October, 2006), corresponding to the area covered by the COSMO-SkyMed images represented in figures 4c and 4d. The former was acquired at HH polarization (25/01/2011) and enhanced by a 3 x 3 vertical edge detection filter, while the latter was acquired at VV polarization (22/01/2011) and processed with a 3 x 3 edge enhance filter; (e) Geomorphic map of landforms on Wanda Glacier proglacial area, compiled from figures 4c and 4d.

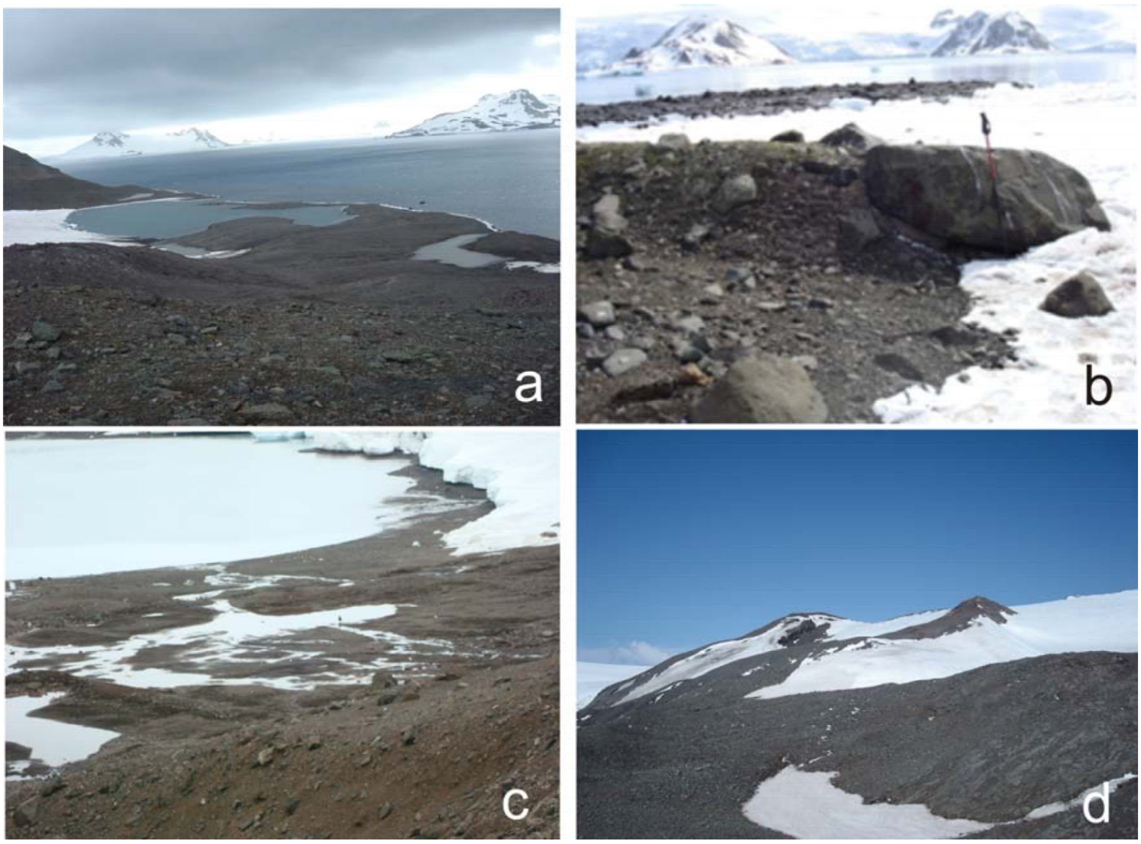

Figure 5 – Wanda Glacier landforms photographs taken on 17/01/2011: (a) lagoon and meltwater channels, (b) flutings, (c) channels exposed on proglacial area; and (d) lagoon deposition and meltwater channels.

The coastline delineation on COSMO-SkyMed imagery could have done even in despeckled images without any high-pass filtering because of land (surface and volume scattering mechanisms) and water (specular reflection mechanism) high contrast in radar return. Besides the frequency and polarization characteristics, the high SAR sensor incidence angles provided more details about glacial features surface roughness. According to Leconte and Pultz (1991) and Lewis et al. (1998), radar data ability to delineate land/water boundary and to map geomorphological features dependents largely on the incident angle. Thus, at low proglacial areas elevation, SAR images acquired at high incident angles (i.e., acquired on 22/01 and 11/02/2011 – table 1) have greater terrain texture contrast than the other ones.

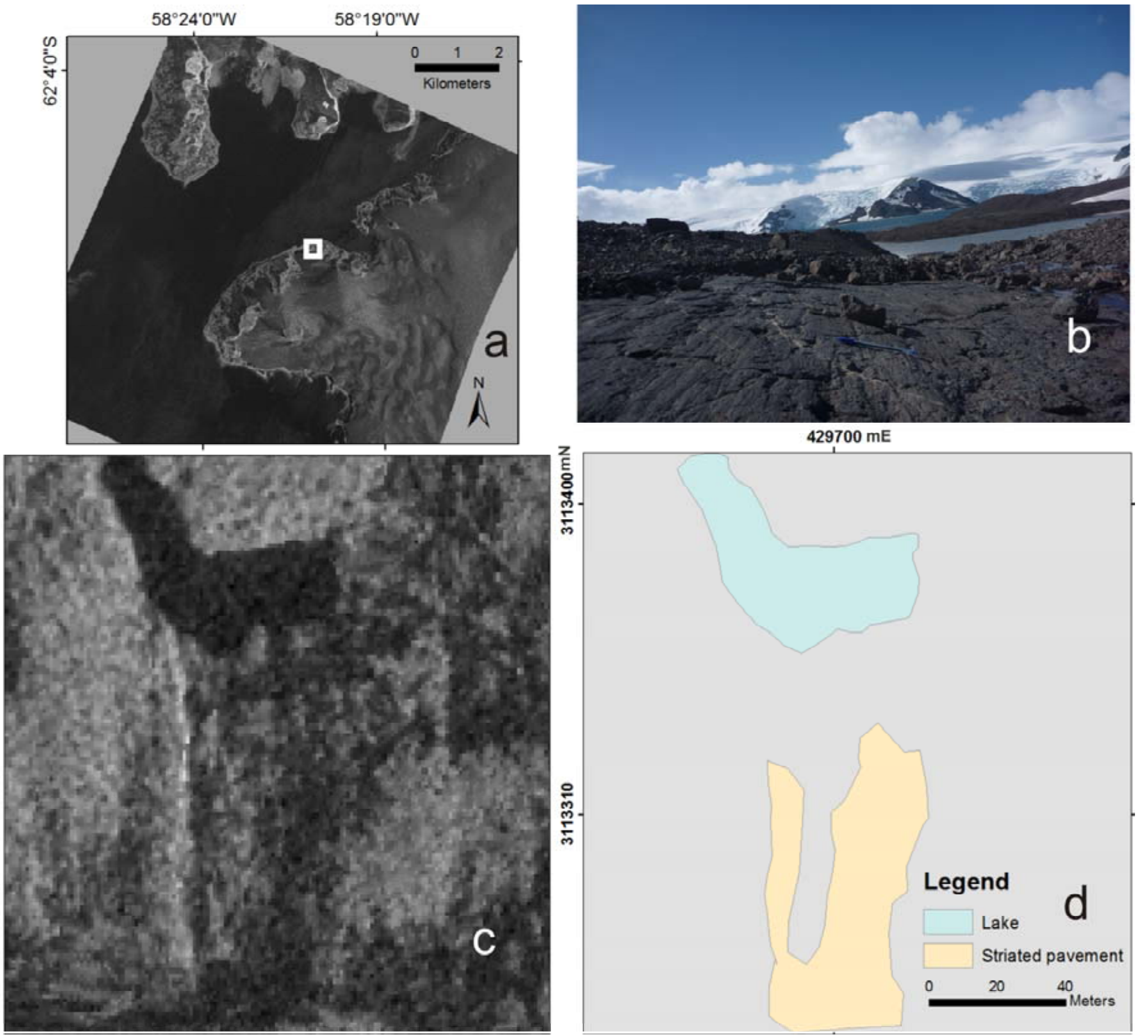

Figure 6 – Exposed striated pavements on Wanda Glacier; a) Orthorectified COSMO-Skymed image (e) at HH polarization (25/01/2011), speckle-reduced by a 5 x 5 median filter. (b) Photography of a striated pavement, taken on 17/01/2011; (c) Subscene of

COSMO-Skymed image (its location is indicated by a small square on figure 6a); (d) Lake and striated pavement geomorphic map, compiled from figure 6c.

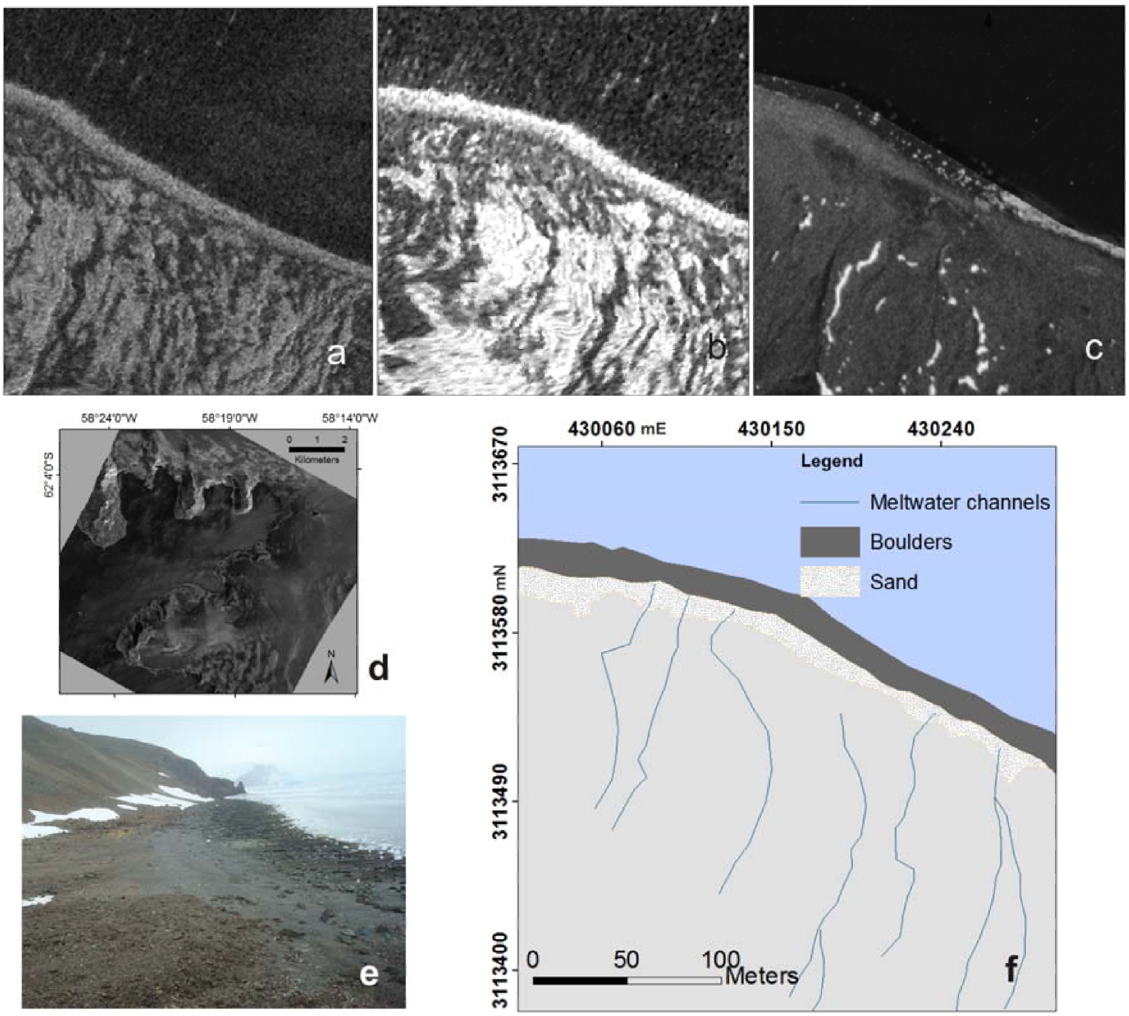

Figure 7 – Coastal features on Dragon Glacier. (a) Subscene of an orthorectified COSMO-SkyMed image; (b) Enhanced image by a 3 x 3 vertical edge detection filter. (c) Image enhanced by texture focal variance of 3 x 3 pixels; (d) at HH polarization (25/01/2011), speckle-reduced by a 5 x 5 median filter; e) Photography of coastal features, taken on 17/01/2011; (f) Geomorphic map of boulders, sand depositions and meltwater channels, compiled from figures 7b and 7c.

Lagoon and lakes at Wanda Glacier proglacial area act like specular reflectors and reflect away most of the incident radar energy. For these reasons, they appear as very dark gray tones in COSMO-SkyMed images (Fig. 4 and 5). Ice-free areas lagoons usually indicate large volumes of glacier meltwater. At he time of image acquisition, Martel Inlet was not very susceptible to wind-induced waves and thus it appeared predominantly in dark gray tones on HH and VV polarizations images. Lacustrine deposits also appear in very dark gray tones (Fig. 4 and 5) due to their high moisture content, fine textured surfaces and low slopes shores. The 3 x 3 texture analysis and edge enhance filter were the best choice for delineating these water bodies.

COSMO-SkyMed images could be used for detecting the underwater morphology, for examples morainic banks. However, high radar signal absorption by deep water during high tides or turbulence precluded the use of these images, only in the COSMO-SkyMed image acquired in 22/01/2011 (Figure 4d) under low tide (i.e., shallow water) and low turbulence conditions we identified a morainic bank.

Supraglacial debris on Wanda Glacier ablation zone are identified by their medium gray tones, while the wet-snow zone appears as dark gray tones in COSMO-SkyMed images. The speckle filtered images were adequate to discriminate these targets (Figure 8). Vertically-copolarized images discriminated better the wet-snow zone from other study area glacier facies (i.e., frozen percolation and bare ice zones) than horizontally-copolarized scenes. In SAR images the wet-snow zone can generally be distinguished from ice-free terrains and this discriminatory ability increases with frequency, so X-band and C-band are commonly used for this purpose (Shi and Dozier, 1993).

Beach ridges have linear and curved forms, aligned parallel to the coast, and they indicated local sea level changes. Raised beaches on SSI coast were formed by the isostatic uplift that accompanied post-LGM (Last Glacial Maximum) deglaciation (John and Sugden, 1971; Sugden and Clapperton, 1977; Del Valle et al., 2002; Bentley et al., 2005). In COSMO-SkyMed images these features were identified on Hennequin Point and have northeastern orientation (Fig. 9). Their eastern faces, towards radar sensor, generated high backscatter values and consequently lighter gray tones then lower areas that had seasonal snow accumulation, meltwater and organic activity, with medium to light gray tones in SAR images. They could be better identified in images at VV polarization, enhanced by a Prewitt filter with southeastern direction and by a vertical edge detection filter, both with 3 x 3 pixels. The 7 x 7 Wallis adaptive filter also improved the contrast of raised beaches.

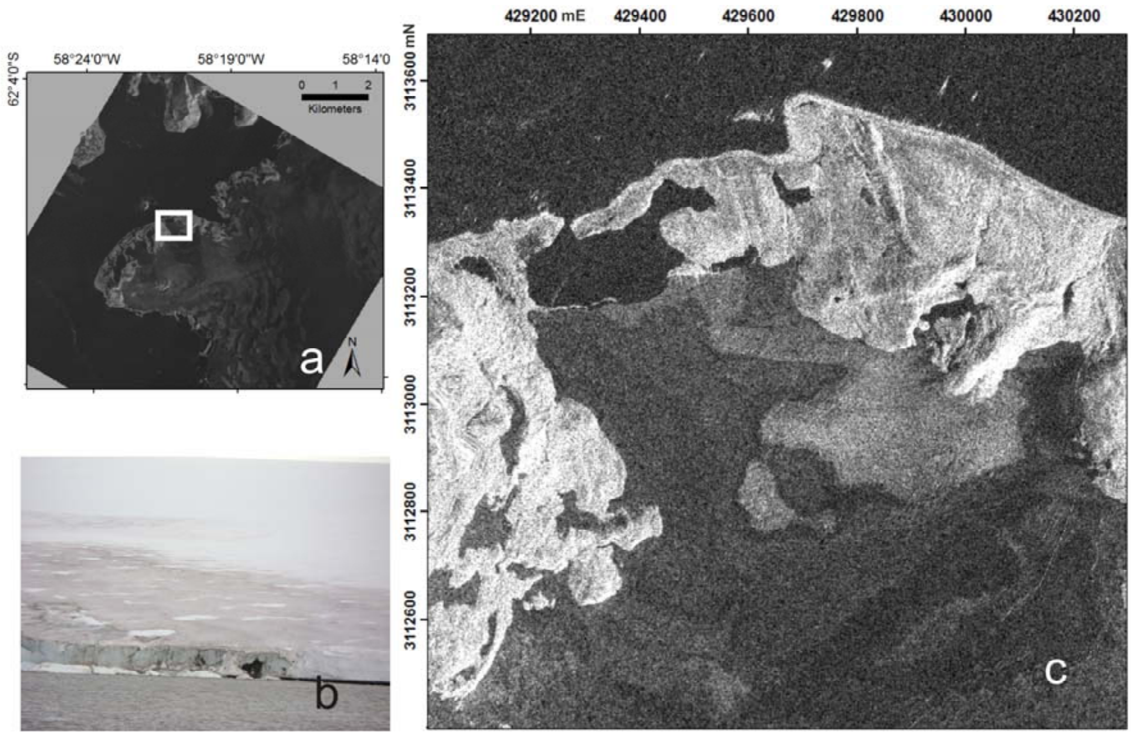

Figure 8 – Supraglacial debris on Wanda Glacier ablation zone; (a) Orthorectified COSMO-SkyMed image; (b) Photography of supraglacial debris, taken on 10/01/2011. (c) at HH polarization (11/02/2011), speckle-reduced by a 5 x 5 median filter. The small square indicates the figure 8c location.

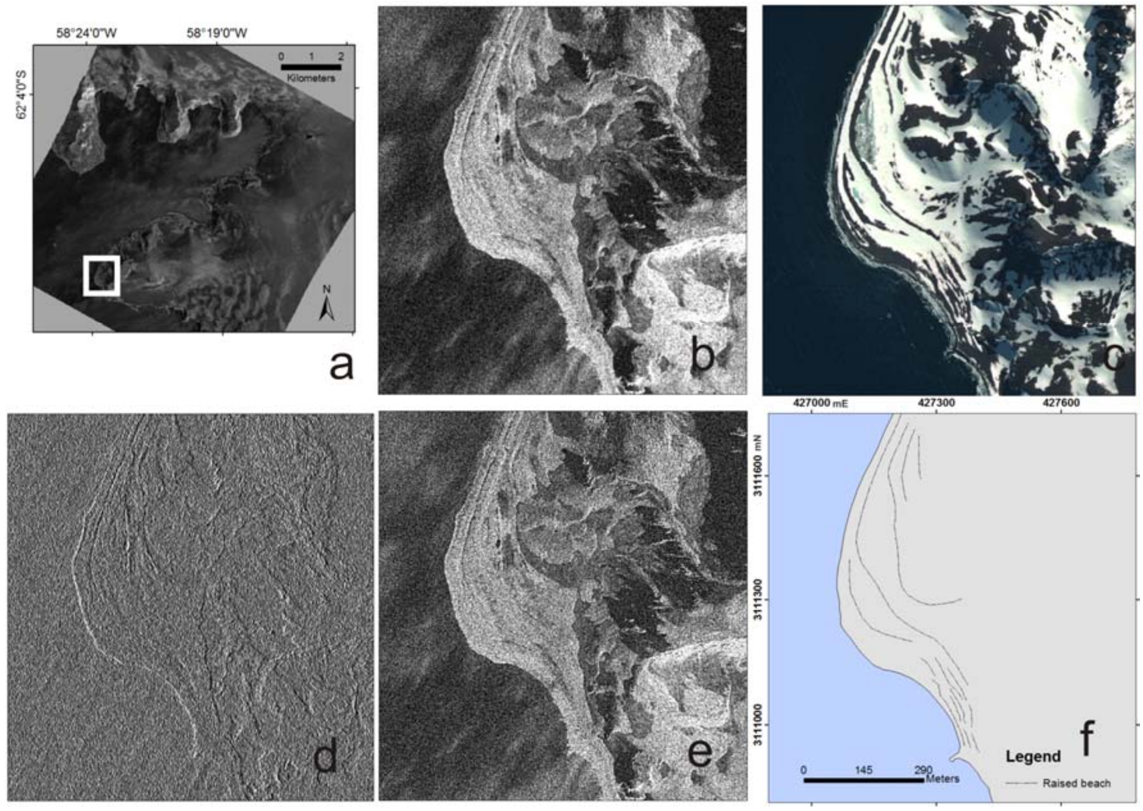

Figure 9 – Beach ridges in Hennequin Point: (a) Orthorectified COSMO-SkyMed image at VV polarization (22/01/2011), speckle-reduced by a 5 x 5 median filter; (b) Subscene of figure 9a; (c) Corresponding subscene of a orthorectified Quickbird image (October, 2006). (d) Enhanced image by a 3 x 3 vertical edge detection; (e) Enhanced image by a 7 x 7 Walis adaptative filter; (h) Geomorphic map of raised beaches, compiled from figures 9d and 9e.

Debris flow deposits were found only on high-elevation parts of the study area with steeper slopes towards radar sensor, which were responsible for foreshortening and layover effects and higher backscatter values, while opposite directions generated shadow effects as described by Lillesand et al. (2008). Furthermore, their very coarse superficial texture resulted in higher backscattering and light gray tones, allowing their identification in COSMO-Skymed images. Shadow effects difficulties of water bodies discrimination in these areas. Thus, we used the orthophotomosaic and high resolution

DEM generated in this study (section 3.2), and a QUICKBIRD fused image (section 3.3), as ancillary information to identify some water bodies.

Arêtes in the Martel Inlet progracial environment are predominantly northward and northeastward oriented (Fig. 10) because of a strong structural geological control in the area. These features are best identified in VV polarized images.

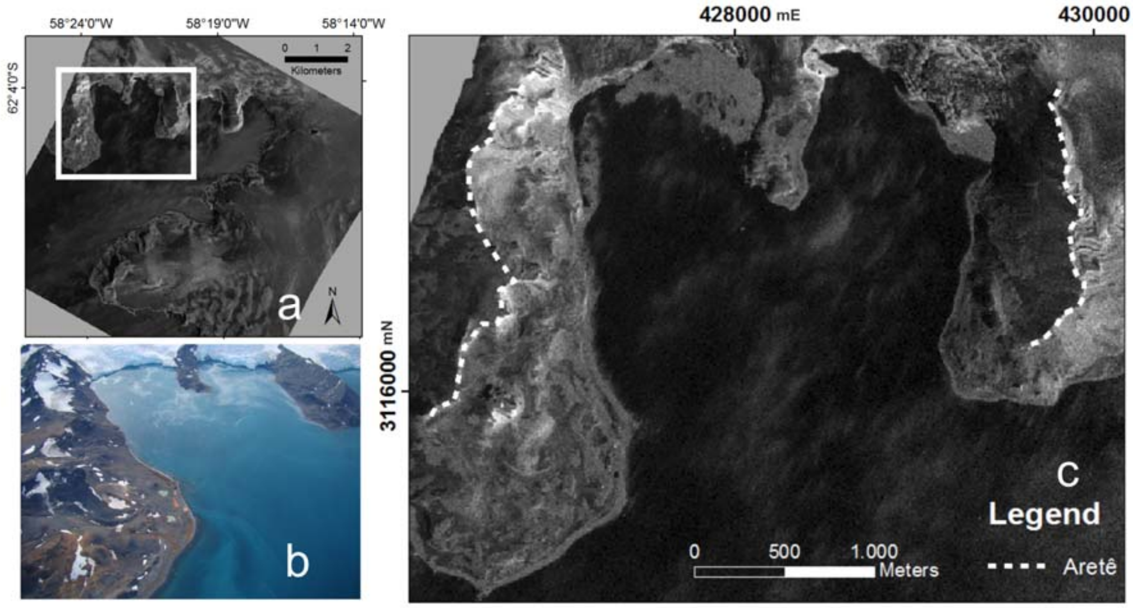

Figure 10 – Arêtes in the Keller Peninsula and Ullman Point are predominantly northward and northeastward oriented. (a) Orthorectified COSMO-SkyMed image at VV polarization (22/01/2011), speckle-reduced by a 5 x 5 median filter; (b) Oblique photography taken in January, 2007, by an aerial detachment onboard Ary Rongel vessel (Brazilian Navy); (c) Subscene with arête delineations, located in the white square represented in figure 10a.

Table 3 summarizes the best filters and polarizations to identify landforms of Antarctic maritime areas in COSMO-SkyMed images.

Table 3 – Martel inlet Ice-free areas land forms identified in the COSMO-SkyMed images used in this study, with the characteristic gray tone and texture used for visual

interpretation, and the best co-polarization mode and filters used to enhance these features.

Landform /feature	Polarization	Gray Tones	Texture	Best filters	Kernel
Arêtes	VV	medium	coarse	Edge enhance filter and texture analysis	3 x 3
Boulders	HH	lighter	coarse	Texture analysis	3 x 3
Coastal sand	HH	medium	Fine	Texture analysis	3 x 3
Coastline	Both	Medium	smooth	Vertical edge detection filter	3 x 3
Debris flow	Both	medium	coarse	Edge enhance filter and texture analysis	3 x 3
Flutings	VV	medium	coarse	Prewitt with northwestern direction	3 x 3
Lacustrine deposits	Both	Dark	Fine	Edge enhance filter and texture analysis	3 x 3
Lagoon and lakes	Both	dark	Fine	Edge enhance filter and texture analysis and	3 x 3
Lateral moraines	VV	Medium	coarse	Morphological Close, Prewitt with northwestern direction and Vertical Edge detection filters	3 x 3
Meltwater channels	Both	dark	Fine	Prewitt filter with northwestern direction	3 x 3
Morainal bank	Both	medium	coarse	Edge enhance filter	3 x 3
Raised beach	VV	medium	coarse	Wallis adaptative filter, Prewitt with southeastern direction and Vertical edge detection filters	7 x 7 3 x 3
Striated pavement	Both	dark	Fine	Edge enhance filter	3 x 3
Supraglacial debris	Both	medium	smooth	Edge enhance filter	3 x 3

5. Conclusions

We presented a preliminary evaluation on the we of COSMO-SkyMed images in spotlight mode for geomorphic analysis of sub-polar Antarctic areas. Images acquired at HH and VV polarization are suitable to identify marine, glaciofluvial, glaciolagunar, glacial and paraglacial landforms. High spatial resolution data and the repeated observation possibilities of COSMO-SkyMed provide a good option for macro or mesorelief classification. However, in complex glacial depositional environments of the Martel Inlet, its difficult to identify mesoscale features because of their heterogeneous composition. Furthermore, the presence of several targets in the instantaneous field of view (IFOV) of this high resolution SAR sensor produces complex return signals and much speckle.

Geomorphological features have different responses in radar signal, depending on the co-polarization mode. In this study, some glacial linear features, like lateral moraines, flutings and arêtes, were better identified in VV polarized images. On the other hand, HH polarization produced stronger return signals from supraglacial debris, debris flow and shorelines than VV one, and, thus, a better discrimination of these glacial features. Meltwater channels, lakes and lagoons were easily distinguished in both co-polarizations.

This paper also evaluated the application of several convolution filters in COSMO-SkyMed images at HH and VV polarizations, to improve visual interpretation of glacial and paraglacial landforms in Antarctic maritime regions. Texture analysis of focal variance and specific kernel size of Wallis adaptative filter, morphological Close filter, some high pass filters and the Prewitt filter with northwestern and southeastern directions yielded the best results for this purpose.

In general, HH and VV polarized COSMO-SkyMed images acquired in spotlight mode, enhanced by focal variance analysis and specific convolution filters, were suitable for recognizing glacial geomorphological features. Images processed with these filters could be used in studies of geomorphic processes and for monitoring periglacial changes in Antarctica.

Acknowledgements

This work was financially supported by the Brazilian National Council for Scientific and Technological Development (CNPq), research project 573720/2008-8. Images used in this study were kindly provided under COSMO-SkyMed AO Project 2294 from the Italian Space Agency (ASI).

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Capítulo 3

Email de recebimento de submissão do artigo pela revista.

Alberto Pio Fiori <fiori@ufpr.br> 21 de outubro de 2011 10:47

Para: Kátia Kellem da Rosa <katiakellem@gmail.com>

Kátia Kellem da Rosa,

Agradecemos a submissão do seu manuscrito "ANÁLISE MORFOMÉTRICA DO SETOR NORTE DA BAÍA DO ALMIRANTADO, ILHA REI GEORGE, SHETLANDS DO SUL, ANTÁRTICA" para Revista Brasileira de Geociências. Através da interface de administração do sistema, utilizado para a submissão, será possível acompanhar o progresso do documento dentro do processo editorial, bastanto logar no sistema localizado em: URL do Manuscrito: http://ojs.c3sl.ufpr.br/ojs2/index.php/rbg/author/submission/24739

Agradecemos mais uma vez considerar nossa revista como meio de transmitir ao público seu trabalho.

Atenciosamente,

Alberto Pio Fiori

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Análise morfométrica do setor norte da Baía do Almirantado, ilha Rei George, Shetlands do Sul, Antártica

Morphometric analysis of the northern Admiralty Bay, King George island, South Shetlands Archipelago, Antarctica

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Resumo

O presente estudo apresenta resultados da análise morfométrica do setor norte da Baía do Almirantado, localizada na ilha Rei George, arquipélago das Shetlands do Sul, Antártica, com a utilização do Sistema de Informações Geográficas (SIG). Fotografias aéreas verticais foram processadas para a geração de um ortofotomosaico e de um Modelo Digital de Elevação (MDE), com resolução espacial de 0,7 m no terreno. Com base no MDE gerado, foram elaborados mapas hipsométrico, de declividade e aspecto (escala 1:10.000), bem como modelos de sombreamento analítico e cenas perspectivas tridimensionais. O setor norte da baía do Almirantado compreende uma área de aproximadamente 103,9 km2 e apresenta uma elevação média de 299,6 m e máxima de 703,4 m. Na área de estudo predominam terrenos com relevo ondulado, seguidos por relevos forte ondulado, suave ondulado e montanhoso, com predominância de vertentes com orientações sul e sudoeste. Feições geomorfológicas glaciais, incluindo *tors*, arêtes, canais fluvioglaciais, circos glaciais, e vales em forma de U, foram identificadas na área de estudo. A presença de áreas de maior declividade nas áreas rochosas recentemente expostas favorece o desenvolvimento de processos de fluxo de detritos. Os mapas morfométricos podem ser usados na reconstrução da evolução deste ambiente, e desta forma contribuir para o estudo da dinâmica glacial e das mudanças ambientais periglaciais observadas na área de estudo.

Palavras chaves: geomorfologia glacial, análise morfométrica, Admiralty Bay, King George Island

Abstract

This paper presents the results of morphometric analysis of the northern Admiralty Bay, located at King George Island, South Shetlands Archipelago, Antarctica, using Geographical Information System techniques. Vertical aerial photographies at scale of 1:50.000 were processed in a Digital Photogrammetric Station, in order to generate an orthophotomosaic and a Digital Elevation Model (DEM) of the study area, with 0.7 m spatial resolution. We used this DEM to derive hypsometric, slope and aspect maps (at scale of 1:10.000), as well as hillshade models and perspective view scenes. The northern Admiralty Bay comprises about 103.9 km^2, while its mean area elevation is 299.6 m and the maximum one is 703.4 m. At study area predominates moderate terrain slopes (36%), followed by steep (23.8%), gentle (22.2%) and very steep areas (7%). Its hillsides are mainly southwestward (22.9%) and southward (22.6%) oriented. Glacial geomorphological features, including tors, aretes, glaciofluvial channels, glacial circles and U-shaped valleys, were identified. The presence of steep terrains in recently exposed rocky areas provides favorable conditions for the development of debris flow processes. The morphometric maps can be used for geomorphological reconstruction of this environment, and thus contribute to the study of glacial dynamics and periglacial environmental changes observed in the study area.
Keywords: glacial geomorphology, morphometric analysis, Baía do Almirantado, Ilha Rei George.

1. INTRODUÇÃO

Dados de Sensoriamento Remoto têm sido utilizados em análises geomorfológicas de ambientes glaciais. Associado à interpretação de imagens e fotografias aéreas, o Sistema de Informação Geográfica (SIG) é outro instrumental usado na análise geomorfológica (Clark, 1997). Com o modelamento numérico do terreno, análises baseadas no SIG têm proporcionado o maior entendimento da evolução da paisagem glacial (Napieralski *et al*., 2007).

Modelos Digitais de Elevação (MDE) e análises automáticas do terreno são amplamente utilizadas na análise geomorfológica (Chandler, 1999; Wilson & Gallant, 2000; Smith & Clark, 2005). Vários parâmetros morfométricos, tais como hipsometria, declividade e aspecto, podem ser calculados a partir de um MDE (Rao, 2002). Além disso, esses modelos fornecem informações para a interpretação dos processos geomorfológicos atuantes em uma paisagem (Etzelmüller & Sulebak, 2000). Classificações automáticas de unidades geomorfológicas são principalmente baseadas nas características morfométricas (Miliaresis, 2001; Adediran *et al*., 2004).

Este estudo tem como objetivo a análise morfométrica do ambiente glacial localizado no setor norte da baía do Almirantado, a partir de um Modelo Digital de Elevação gerado por Fotogrametria e analisado posteriormente em um SIG.

2. ÁREA DE ESTUDO

O ambiente glacial do setor norte da baía do Almirantado localiza-se na ilha Rei George, arquipélago das Shetlands do Sul, a oeste da região setentrional da península Antártica (Figura 1). O setor norte da baía do Almirantado é dividido pelas enseadas Martel (área de 17 km²) e Mackellar

(13 km²). Essas enseadas caracterizam-se por terminações glaciares do tipo geleira de maré, separadas por pontais. As geleiras de maré possuem gradiente superficial acentuado, fluxo relativamente rápido e muitas fraturas. Algumas geleiras possuem frente terrestre, como, por exemplo, a Wanda, Professor e Dragão (Figura 2).

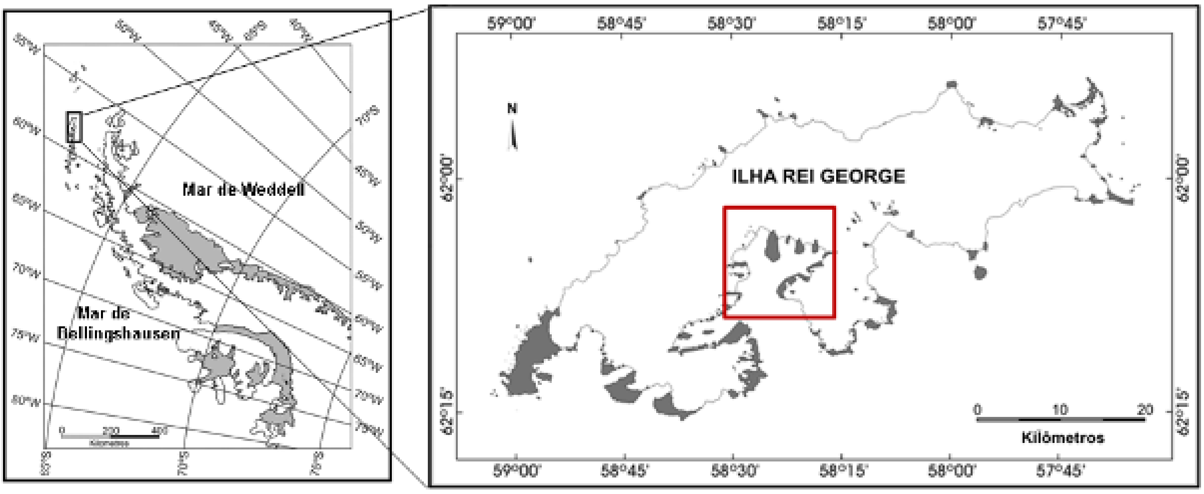


Figura 1 – Localização da área de estudo (retângulo em vermelho) na ilha rei George, nas Shetlands do Sul, a oeste da região setentrional da península Antártica.

As geleiras da área de estudo são sensíveis a variabilidade climática e têm sofrido retração de suas frentes e diminuição de sua espessura (Simões *et al*., 2004, IPCC, 2007). Como resultado do processo de retração dessas geleiras, ambientes de deglaciação formaram-se com a presença de variados depósitos subaéreos e lagunas proglaciais. Ainda observam-se processos paraglaciais nestes ambientes. Nesta ampla área proglacial observaram-se rápidas mudanças morfológicas e a exposição de geoformas (Rosa *et al*., 2010).

Evidências estruturais apóiam a idéia da presença de falhas e zonas de deformação na ilha Rei George (Birkenmajer, 1980). O alinhamento NE-SW das enseadas Martel e Mackelar, associado aos escarpamentos rochosos dos vales esculpidos por ação glacial, evidenciam o condicionamento tectônico dessas feições. Esses vales glaciais, profundamente escavados, possuem profundidades de aproximadamente 200 m (Gruber, 1989). De acordo com esse autor, a presença de falhamentos resultou em uma erosão diferencial por processos glaciais.

A área de estudo localiza-se na Área Antártica Especialmente Gerenciada (AAEG) da baía do Almirantado, delimitada pela Foreign & Commonwealth Office (1997), destinada ao monitoramento ambiental. Desta forma, esta área tem sido o palco de diversos projetos científicos nacionais e internacionais.

Estudos geomorfológicos relacionados com a área de estudo foram realizados por Francelino *et al*. (2004), Schaefer *et al.* (2004) e Rosa *et al*. (2010). Braun *et al.* (2001) elaborou um MDE da ilha Rei George, com 100 m resolução espacial. Mendes Jr *et al*. (2010) gerou um MDE e um mapa topográfico na escala 1:5.000 para a península Keller. Assim, constatou-se que não havia um MDE preciso e com alta resolução espacial que compreendesse todo o setor norte da baía do Almirantado.

3. MATERIAIS E MÉTODOS

O MDE do setor norte da baía do Almirantado foi elaborado a partir de uma estação fotogramétrica digital, com o uso de fotografias aéreas do *Servicio Hidrográfico y Oceanográfico de La Armada del Chile* (SHOA). Foram utilizadas fotografias verticais pancromáticas no formato 23 x 23 cm, na escala 1:50.000 (n° 302714, 302715, 302716 e 302740 e 302741 – linhas de vôo n° 15 e 16), tomadas por câmera fotogramétrica modelo RC10, com distância focal de 88,10 mm, durante uma missão de vôo executada pelo SHOA em janeiro de 2003, sobre a Península Antártica.

As orientações interna e externa das fotografias, bem como a geração automática do MDE, foram realizadas no sistema LPS^{TM} (*Leica Photogrammetry Suite*). Os dados foram georreferenciados ao sistema de projeção cartográfica Universal Transversa de Mercator (UTM), zona 21S, com o elipsóide de referência *World Geodetic System* 1984 (WGS84).

As coordenadas dos pontos de controle planimétricos foram obtidas da ortofotografia da península Keller (Mendes Jr. *et al*., 2010), com resolução espacial de 0,63 m, bem como de uma imagem fusionada e ortorretificada Quickbird, com resolução espacial de 0, 61 m, adquirida por esse satélite em 26/10/2006. Os pontos de controle altimétricos usados na orientação do bloco de fotografias foram locados ao longo da linha de costa da baía do Almirantado e aos mesmos foi atribuída uma cota zero arbitrária. Essa metodologia foi proposta por Mendes Jr. *et al*. (2010), para a geração do MDE da península Keller, na escala 1:5.000, com o objetivo de resolver o problema da falta de pontos de controle altimétricos, que são necessários para a aerotriangulação das fotografias. Segundo esses autores, o MDE da península Keller apresentou resultados compatíveis com dados altimétricos de mapas topográficos locais. Com o uso dos pontos de controle altimétricos obtidos por essa metodologia e de pontos planimétricos obtidos das imagens, foi realizada a aerotriangulação do bloco de fotografias. Os valores dos parâmetros de orientação externa das fotografias aéreas usadas neste estudo estão descritos na Tabela 1.

O MDE foi gerado pela ferramenta *DTM Extraction* do aplicativo LPS^{TM} e interpolado pelo método *Triangular Irregular Network* (TIN), com uma resolução de 0,7 m no terreno, compatível com a resolução espacial e escala das fotografias usadas neste estudo e com a densidade dos pontos cotados. Os pontos cotados da estação fotogramétrica apresentaram baixa concentração nas áreas dos campos de gelo (à montante das geleiras).

Para a geração de um MDE mais preciso nessas áreas, foram utilizados pontos cotados extraídos do MDE do estudo de Braun *et al.* (2001). Esses pontos foram então armazenados no programa ArcGIS^{TM} (ESRI, Inc.), utilizado para a interpolação de um MDE da área de estudo, com resolução de 0,7 m, com o uso do método TIN. Desse modelo foram derivados vários produtos de análise do relevo, tais como mapas hipsométrico, de declividade e aspecto, modelos de sombreamento analítico e perspectivos tridimensionais. Esse MDE foi utilizado no LPS^{TM} para a geração de ortofotos, que foram utilizadas para a elaboração de um ortofotomosaico da área de estudo (Figura 2).

TABELA 1 - PARÂMETROS DE ORIENTAÇÃO EXTERNA CALCULADOS PARA AS FOTOGRAFIAS AÉREAS.

Número da fotografia	Centro perspectivo (UTM 21 S – WGS84)			Ângulos de rotação (graus)		
	x	Y	z	ω	φ	κ
302714	430102,690	3119524,545	4432,145	1,91886	1,27964	-142,38012
302715	277070,647	3117571,914	4433,760	-1,04366	0,67910	-139,77902
302716	423550,640	3115612,317	4448,930	-1,54382	1,59059	-145,51691
302740	432698,372	3111615,921	8195,487	-1,55274	0,45953	-145,41320
302741	428710,218	3108834,396	8239,537	-0,18177	-0,06647	-145,38567

O mapa hipsométrico do setor norte da baía do Almirantado (Figura 3) foi elaborado a partir do fatiamento do MDT em 16 classes, sendo cada classe com amplitude de 50 m. O mapa de declividade (Figura 4) foi elaborado com seis classes temáticas, definidas com os mesmos valores percentuais utilizados em estudo de Francelino *et al.* (2004) e Mendes Jr. *et al*. (2010). No mapa de aspecto (Figura 5) as classes foram definidas pelo ângulo azimutal de orientação das vertentes. As áreas absolutas e relativas de cada classe dos mapas hipsométrico, de declividade e aspecto foram quantificados no programa ArcGIS^{TM}.

4. RESULTADOS

De acordo com dados do ortofotomosaico produzido neste estudo, o setor norte da baía do Almirantado possui uma área continental de aproximadamente 103,9 km². Dados calculados do MDE indicaram que a elevação média do terreno é de 299,6 m e a máxima de 703,4 m (Tabela 2).

O mapa de declividade (Figura 4) indicou que a área de estudo possui um relevo predominantemente ondulado (36%), seguido de áreas com relevo forte ondulado (23,8%), suave ondulado (22,2%) e montanhoso (7%), devido a extensão significativa de áreas cobertas por geleiras (Tabela 3). As zonas frontais de geleiras de maré apresentam as maiores declividades.

Figura 2 – Ortofotomosaico do setor norte da baía do Almirantado, gerado em uma estação fotogramétrica a partir das fotografias aéreas verticais do SHOA (22 de janeiro de 2003). As toponímias foram baseadas em Braun *et al*. (2001).

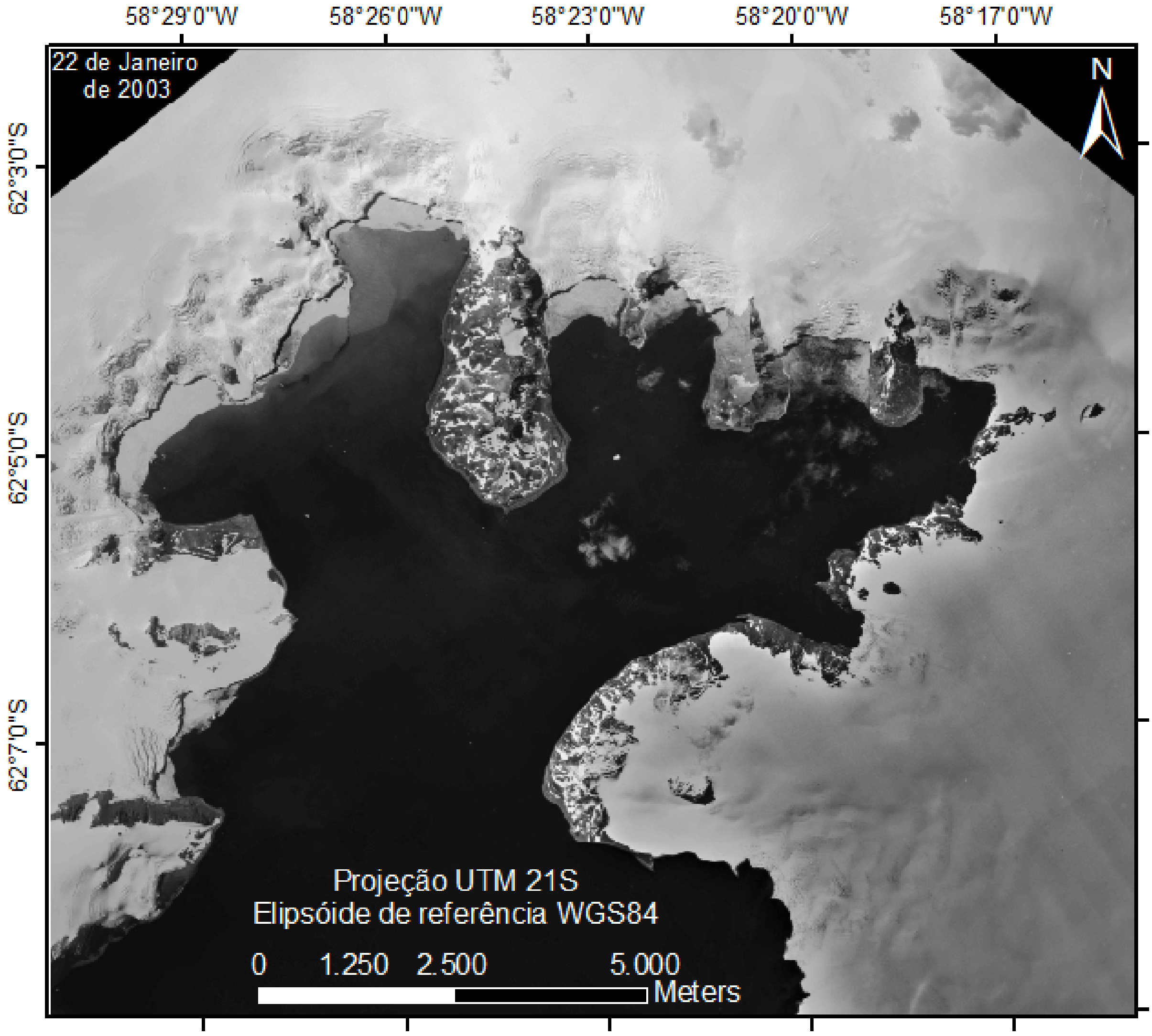


Figura 3 – Mapa hipsométrico do setor norte da baía do Almirantado.

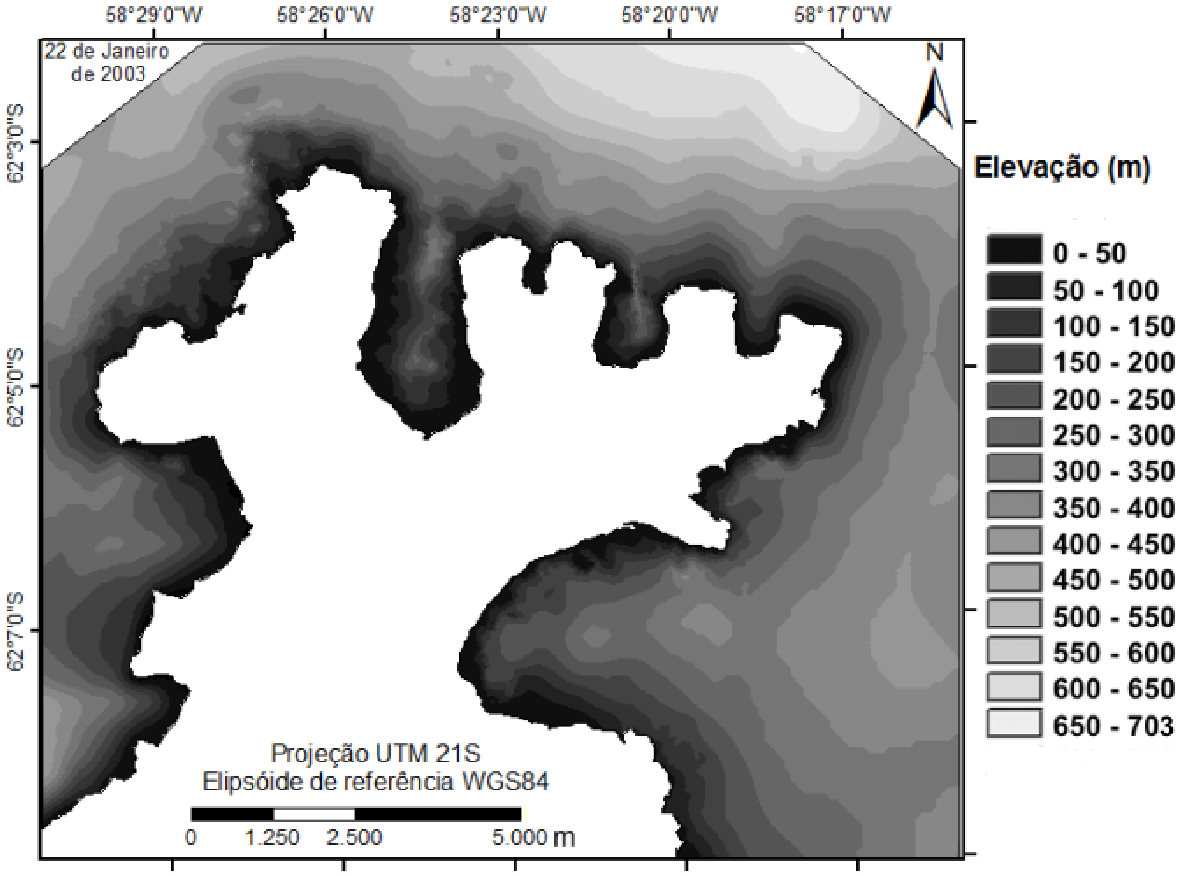


Figura 4 – Mapa de declividade do setor norte da baía do Almirantado.

O relevo do setor norte da baía do Almirantado é caracterizado pela predominância de vertentes com orientações sul (22,6%) e sudoeste (22,9%) conforme dados quantificados do mapa de aspecto (Figura 5). A morfologia de relevo na área de estudo pode ser observada no modelo de sombreamento analítico (Figura 6), onde destacam-se as áreas de pendentes íngremes nas áreas costeiras das bacias de drenagens e áreas rochosas recentemente expostas. O padrão de falhamentos tectônicos e a erosão diferencial resultante exercem um forte controle sobre o sentido de fluxo das bacias de drenagem na área de estudo.

TABELA 2 – ÁREAS ABSOLUTAS E RELATIVAS E ESTATÍSTICAS DAS CLASSES DO MAPA HIPSOMÉTRICO DO SETOR NORTE DA BAÍA DO ALMIRANTADO.

Setor norte da baía do Almirantado		
Elevação (m)	**Área (km²)**	**Área (%)**
0 - 50	7,846	7,6
50 - 100	6,128	5,9
100 - 150	6,454	6,2
150 - 200	7,947	7,6
200 - 250	8,995	8,7
250 - 300	11,874	11,4
300 - 350	14,616	14,1
350 - 400	16,518	15,9
400 - 450	7,612	7,3
450 - 500	5,278	5,1
500 - 550	3,184	3,1
550 - 600	2,101	2,0
600 - 650	3,220	3,1
650 - 703	2,110	2,0
Estatísticas (m)		
Mín. e Máx.	**Média**	**Desvio-padrão**
0 – 703,363	299,593	159,291

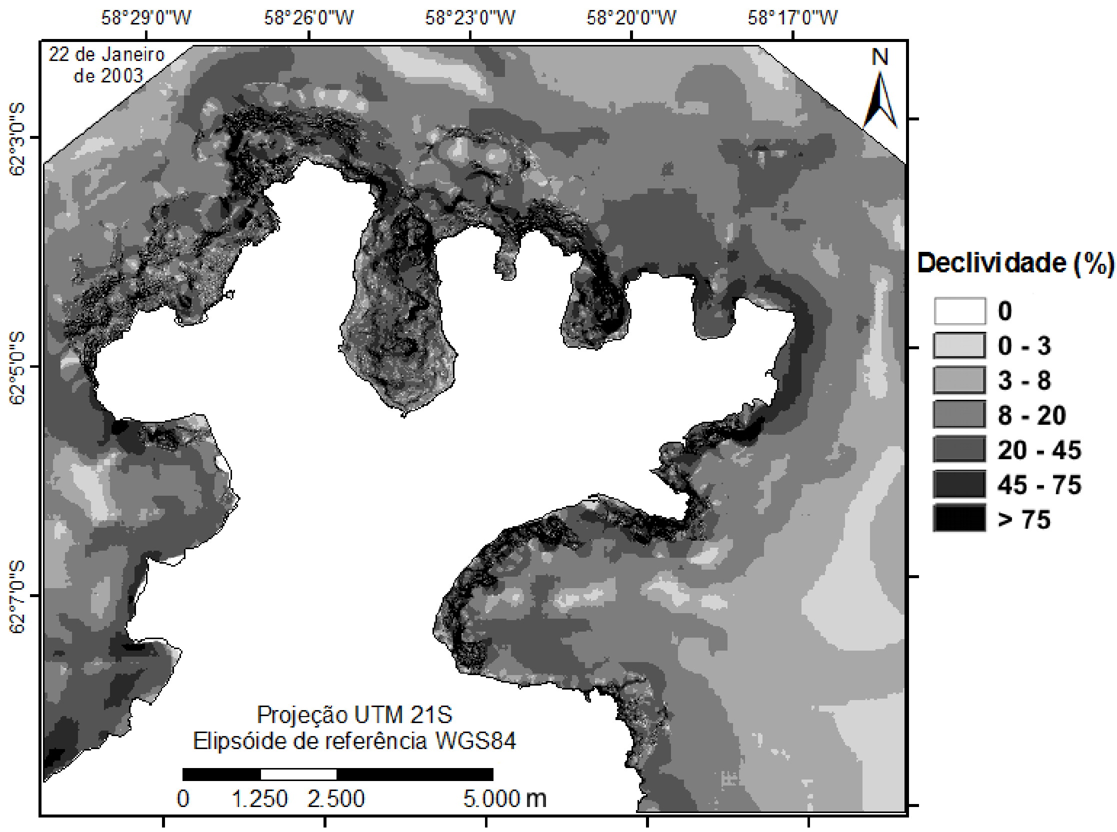


Figura 5 – Mapa de aspecto do setor norte da baía do Almirantado.

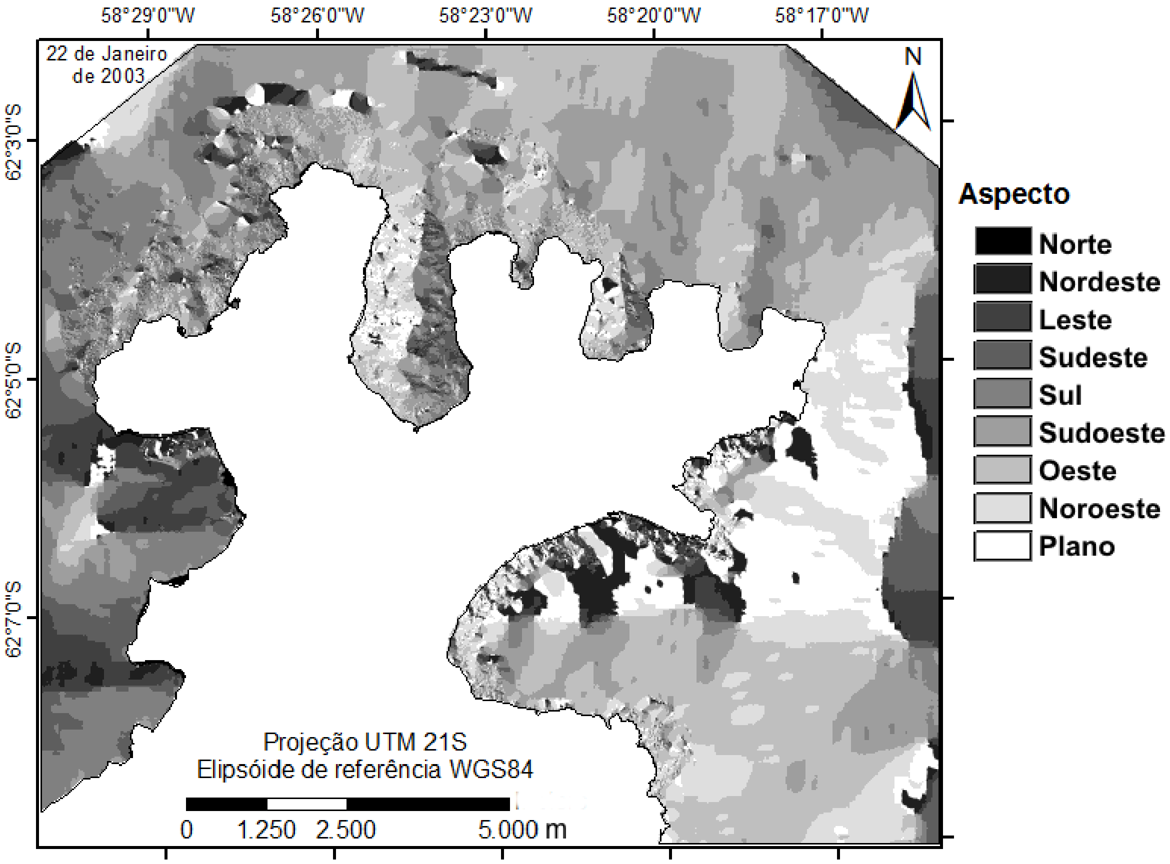
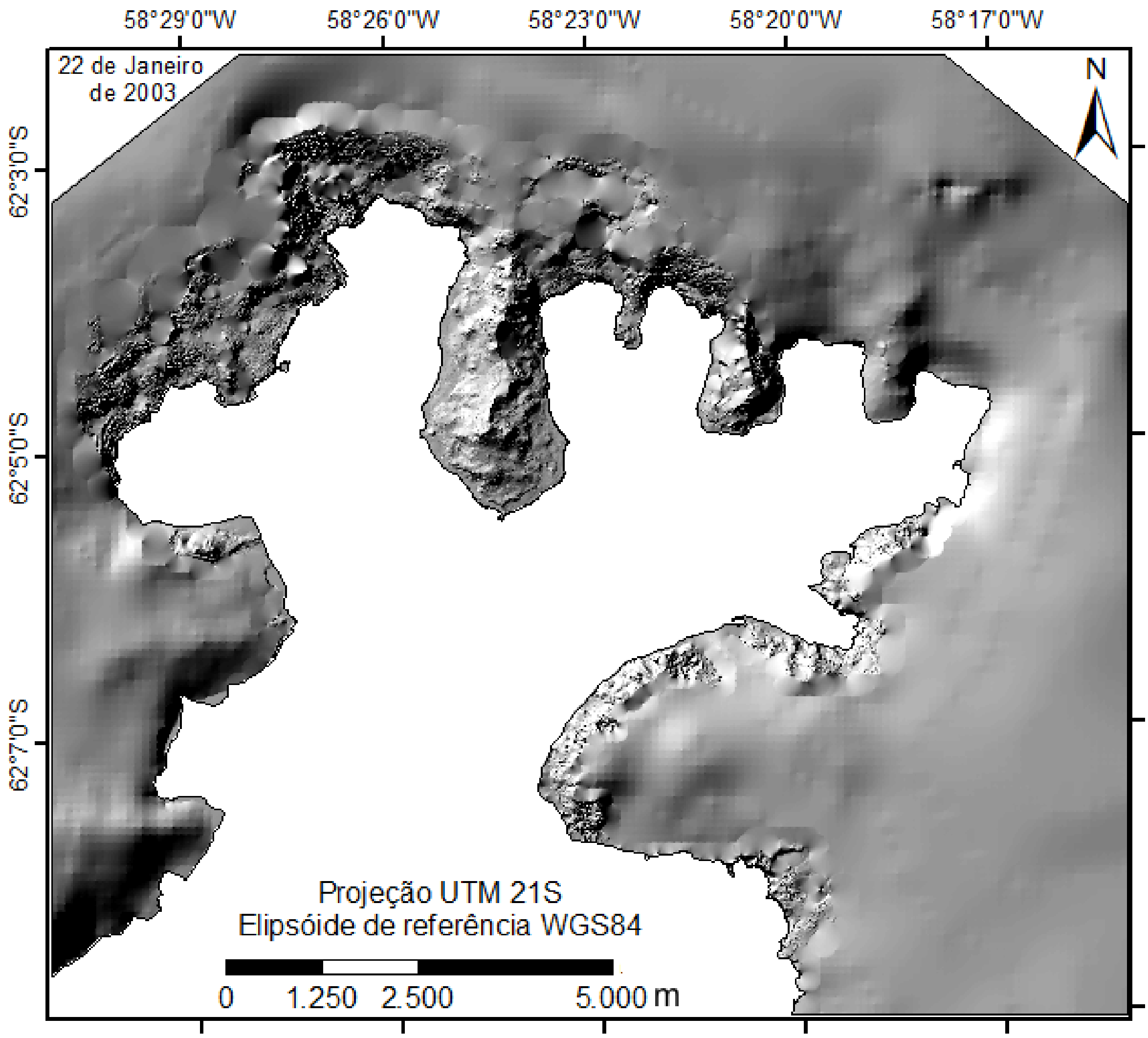


TABELA 3 - ÁREAS ABSOLUTAS E RELATIVAS E ESTATÍSTICAS DAS CLASSES DO MAPA DE DECLIVIDADE DO SETOR NORTE DA BAÍA DO ALMIRANTADO.

Declividade		**Setor norte da Baía do Almirantado**	
Tipo de relevo	**%**	**Área (km²)**	**Área (%)**
Plano	0 - 3	7,071	6,9
Suave Ondulado	3 - 8	23,039	22,2
Ondulado	8 - 20	37,411	36,0
Forte Ondulado	20 - 45	24,711	23,8
Montanhoso	45 - 75	7,244	6,9
Escarpado	> 75	4,407	4,2

Estatísticas (%)		
Mín. e Máx.	**Média**	**Desvio-padrão**
0 - 3664,725	12,001	22,543

Figura 6 - Mapa de sombreamento analítico para o setor norte da baía do Almirantado, iluminado com ângulo solar azimutal de 315° e zenital de 45°.



5. DISCUSSÕES

A presença de áreas de maior declividade nas áreas rochosas recentemente expostas, juntamente com o acentuado intemperismo, favorecem o desenvolvimento de processos de fluxo de detritos nas pendentes de encostas mais íngremes. De acordo com o mapa de declividade, as geleiras de maré da área de estudo apresentaram acentuada declividade em sua porção frontal. As geleiras Stenhouse, Goetel, Dobrowolski e principalmente a Ajax possuíam maior declividade no seu término (Figura 4). Essas acentuadas declividades estão relacionadas com a topografia do embasamento, com forte controle estrutural, as quais podem acarretar no aumento da velocidade de fluxo do gelo. Assim, com uma redução do grau de acumulação dessas pequenas bacias de drenagem, essas geleiras podem ter aumento no processo de perda de massa de gelo.

O ortofotomosaico de alta resolução pode ser utilizado na análise geomorfológica da área de estudo, apoiando atividades de campo e o mapeamento temático. O MDE gerado neste estudo apresentou detalhamento topográfico suficiente para a identificação de geoformas erosivas e deposicionais glaciais e, dessa forma, é uma potencial fonte de informação geomorfológica.

Os produtos de análise do relevo deste estudo podem auxiliar na investigação de mudanças morfométricas na paisagem glacial ao longo do tempo, tais como estimativas de erosão, mudanças morfológicas, balanço de massa glacial e mudanças volumétricas nas geleiras. Assim, podem contribuir no entendimento da dinâmica glacial e no monitoramento dos processos de retração e mudanças ambientais periglaciais observados na área de estudo.

6. CONSIDERAÇÕES FINAIS

As técnicas de Fotogrametria e SIG foram eficientes na geração automática do MDE e na extração dos produtos de análise do relevo. A metodologia proposta possibilitou a caracterização geomorfométrica da área de estudo com a descrição detalhada das condições topográficas. O MDE gerado neste estudo, devido a sua resolução espacial, proporcionou um grande alto detalhamento topográfico do setor norte da baía do Almirantado, o qual foi suficiente para a identificação de geoformas erosivas e deposicionais glaciais. Nesse sentido, destaca-se que diante dos processos de retração glacial contatados na área de estudo, como efeito da variabilidade climática destes ambientes, que os produtos de análise do terreno gerados neste estudo foram uma importante base de dados para a análise geomorfológica glacial. Essa base de dados de análise do terreno possibilitou o mapeamento geomorfológico preciso e a reconstrução da evolução desses ambientes, e desta forma, contribui para o estudo da dinâmica glacial e mudanças ambientais perceptíveis na área de estudo.

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Capítulo 4

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USE OF GIS TECHNIQUES FOR SEDIMENT DYNAMIC ANALYSIS OF THE MARTEL INLET, KING GEORGE ISLAND, SOUTH SHETLANDS

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RESUMO
Este trabalho apresenta resultados da análise da dinâmica sedimentar da Enseada Martel, ilha Rei George, Shetlands do Sul. Como consequência da tendência de aumento da temperatura média do ar superficial nessa região, ocorreu um rápido recuo da frente de geleiras nas últimas décadas, as quais promoveram mudanças ambientais perceptíveis, incluindo impactos na dinâmica sedimentar da Enseada Martel. Técnicas SIG foram aplicadas na análise da variação espacial e temporal da concentração de sedimentos em suspensão (SSC) dessa enseada, com bandas do visível de imagens SPOT HRV obtidas em fevereiro de 1988 e 2000, e março de 1995, além de imagens TERRA ASTER obtidas em novembro de 2005. Além disso, foram correlacionados dados de coletas de Concentração de Sedimentos em Suspensão (SSC) em canais glaciofluviais com dados meteorológicos. Esses dados apresentaram correlação significativa com a retração das geleiras que drenam para o fiorde, podendo assim ser usados como indicadores das consequências da variabilidade climática para a dinâmica sedimentar da área de estudo. A metodologia proposta possibilitou a obtenção de resultados satisfatórios na análise das modificações no padrão espacial e temporal da SSC na Enseada Martel durante os meses analisados. Com o uso de técnicas SIG, pôde-se avaliar a intensidade dos processos de produção de sedimentos pelas geleiras da área de estudo e o seu fluxo de água de derretimento.

Palavras-chave: Martel Inlet, Concentração de sedimentos em suspensão, GIS.

O USO DE TÉCNICAS DE SIG PARA ANALISE DA DINÂMICA SEDIMENTAR DA ENSEADA MARTEL, ILHA REI GEORGE, SHETLANDS DO SUL

ABSTRACT
This paper presents results of the sediment dynamic analysis of the Martel Inlet, King George Island, South Shetlands. As a consequence of the rising trend in study area mean surface air temperature, a rapid glacier front retreat occurred in the last decades, which has caused noticeable environmental changes, including impacts on sediment dynamics on the Martel Inlet. GIS techniques were applied for spatial and temporal changes analysis of suspended sediment concentration (SSC), using: (1) visible bands of SPOT HRV imageries obtained in

February, 1988 and 2000, and in March, 1995; (2) TERRA ASTER imagery obtained in November, 2005. Furthermore, SSC sample data from subglacial frontal zone of the glacier were correlated with meteorological data. SSC data presented significant correlation with glaciers retreat that drain into the fjord, and thus they can be used as indicators of the consequences of climatic variability for the sedimentary dynamic in the study area. This methodology allowed us to obtain satisfactory results for the pattern analysis of SSC spatial and temporal changes in the Martel Inlet, during the months analyzed. By using GIS techniques, we could evaluate the intensity of the glacier sediment production in the study area and its meltwater runoff.
Keywords: Martel Inlet, suspended sediment concentration, GIS.

INTRODUCTION

The suspended sediment concentration (SSC) is one of the most important oceanographic parameters in glacial environments, since its spatial distribution and temporal changes can be used to infer the variability in the glacier ablation processes, due to its sensitive response to the meltwater runoff. The sediment supply indicates the glacier erosion action related with their thermal regimes (Ritchie and Schiebe, 1986). In respect to their thermal regime, glaciers can be classified as cold, temperate or polythermal. The ice temperature has an important control in several processes in the glacial environment, including basal melting and sliding and meltwater runoff, (Benn e Evans, 1998).

This paper aims to identify the SSC spatial and temporal variability in Martel Inlet glaciomarine environment (Figures 1, 2 and 3), King George Island (KGI), South Shetlands. It investigates the relationship between glacier retreat and the SSC contribution of the meltwater runoff in the Martel Inlet, and addresses suspended sediment production and transportation processes integration. The glacial sediment supply changes in Martel Inlet, resulting from the erosion action and from its transport to the glaciomarine environment, depend on several factors, including glacial retreat rate, glacier flow velocity and thermal basal conditions in the fjord.

Martel Inlet is classified as a fjord-like feature with proglacial front (such as Wanda glacier) and it is surrounded by outlet glaciers. Terrigenous sediment rate in South Shetland fjords is higher than those in the Antarctic Peninsula.

The inorganic SSC in Admiralty Bay, measured by Pecherzewski (1980) in the summer, was 44.1m.g.dm³ at 50 m depth; 13.6mg dm³ in 50-100 m depth; and 5.5mg dm³ under 100 m depth. Domack and Ishman (1993) estimated 12mg 1-¹ for SSC in Admiralty Bay in 1993. SSC plumes were observed near the outlet glacier fronts in the Martel Inlet by Pilchemaier *et al.* (2004) and Rosa et al. (2010).

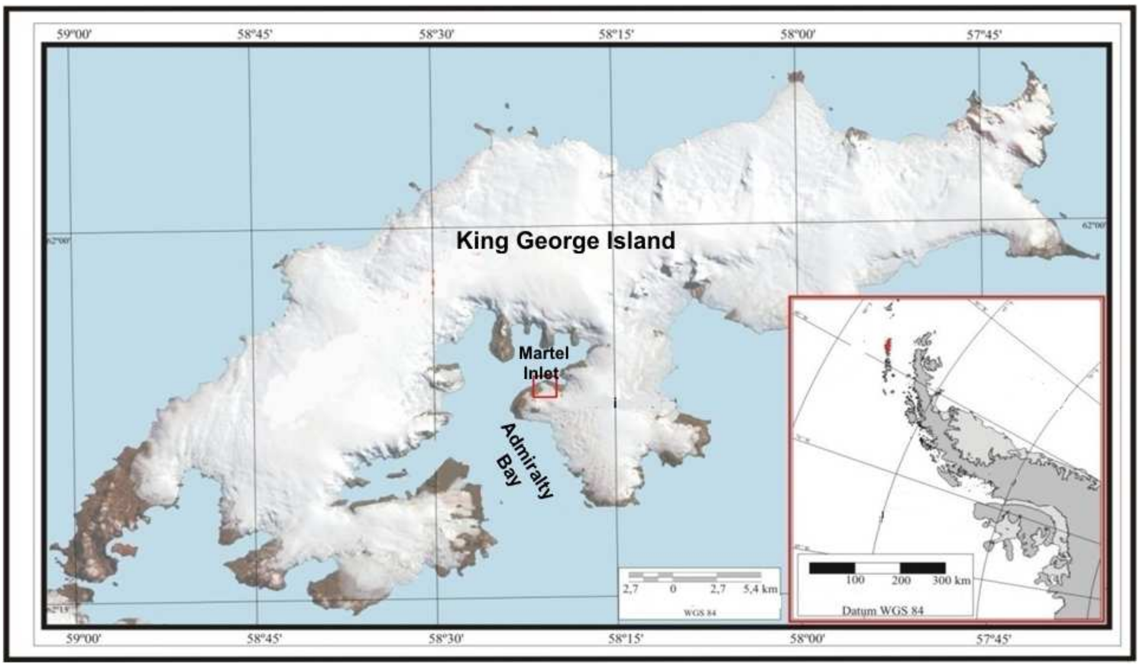

Figure 1 - Martel Inlet location on the King George lsland, and the Wanda Glacier.

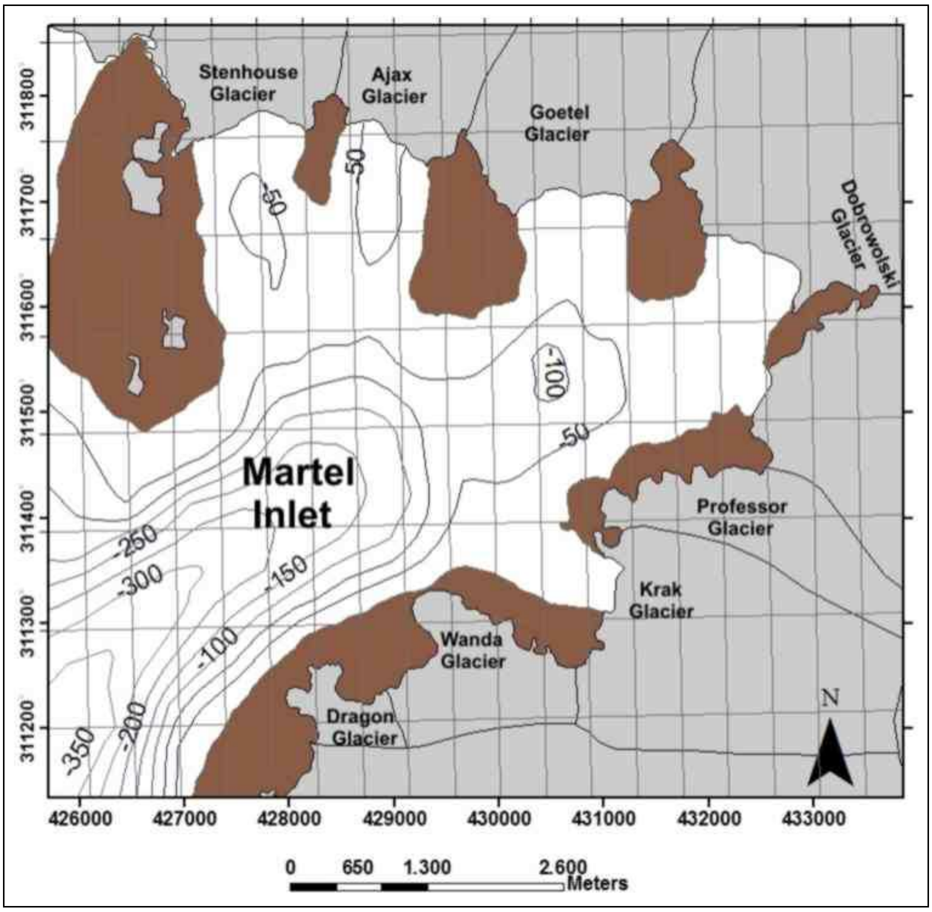

Figure 2 – Glaciers in Martel Inlet. Bathymetric contours and glacier drainage basin limits are also shown. Data provided by the Admiralty Bay Map Server prototype – Polar and Climate Center (2010).

Figure 3 –Sediment plumes in Martel Inlet. (Photography taken by an Aerial Detachment onboard Ary Rongel vessel, during OPERANTAR XXVI – 2007/2008).

The sediment plumes identified on the bay surface are linked mainly to meltwater contribution from subglacial and proglacial channels (Figure 4) (Pecherzewski, 1980; Gruber, 1989; Griffth and Anderson, 1989; Domack et al., 1989; Domack and Ishman, 1993; Yoon et al., 1997; Yoon et al., 1998; Aquino 1999, Pilchemaier et al., 2004). Sediments are also transported by icebergs from tidewater glacier fronts (Pecherzewski, 1980). However, there are not any studies about the rate of sediment supply from icebergs in the study area.

Interflows are formed near the tidewater glacier fronts (Anderson and Molnia, 1989). According to Syvisky (1989), 70% of the sediments total discharge released by glacial action will be deposited up to about 500 m from glacier fronts. The sediments flow within the Martel Inlet form a turbidity plume, with maximal concentrations at about 40 m depth. The mechanisms of the plume generation are attributed to upwelling flows from the subglacial meltwater channels (Gruber, 1989). Domack and Ishman (1993) and Rakfusa-Suszczewski (1993) observed that a surface layer of low saline water can be formed as a consequence of the snowmelt runoff and by liquid precipitation in fjords. Its influence can reach at about 75 m depth.

Aquino (1999) considered the weather as a major factor that control the sedimentation processes in the study area.

Temperature and precipitation changes affect the meltwater generation and influence the terrigenous sediment supply. Additionally, the maritime subpolar climate causes more meltwater runoff, contributing to glacier erosion processes and the erosion product transportation to the glaciomarine environment. The SSC spatial distribution has great variability, in response to the meteorological and oceanographic conditions in the inlet (Vogt e Braun, 2004).

Other studies showed a strong relationship between glacial erosion processes and rapid glacier retreat in fjords. Over the past 60 years, was observed a rising trend in Antarctic Peninsula mean surface air temperature, between 2.5 and 3.0°C (Blindow et al., 2010). Several studies observed a glacier front retreat on the Martel inlet since 1950 (Park et al., 1998; Bremer, 1998; Simões and Bremer, 1995; Simões et al., 1999; Aquino, 1999; Braun and Gossmann, 2002; Vieira et al., 2005; Rosa et al., 2006; Rosa et al., 2009). Over the past 30 years, the number of days with liquid precipitation has increased in the summer. This process accelerated the snowmelt and increased the negative mass balance of the local glaciers (Braun et al., 2001; Ferrando, 2009). As a result of regional warming, the expansion of deglaciarized areas and meltwater runoff were evident. This increased erosion processes and suspended sediment supply to the Martel Inlet. To understand such processes it is important to investigate the influences of the climate variability for sediment dynamic in the study area.

METHODOLOGY

The monitoring of SSC seasonal variability was performed by processing satellite images from different years (1988, 1995, 2000 e 2005) and by using meteorological data. The application of a linear contrast stretch in the SPOT color composite image used in this study enhanced the SSC (Figure 4). Through this operation it was possible to detect the suspended sediment plumes on the water and quantify their spatial distribution and concentration. The remote sensing products can be considered as a potential instrument for mapping the SSC in waterbodies with estuarine circulation. However, applications of remote sensing data in these areas depend on access to time series of images. In subpolar maritime climates, characteristic of the KGI, there is an extensive cloud cover during most of the year and low sunlight conditions in a few months of the year. These conditions can influence significantly the temporal data coverage from optical sensors. Additionally, the differences of the reflectivity in surface water as consequence of cloud cover, presence of shallow water, ice and wind action on surface water can complicate the comparison of satellite data from different years for the SSC quantification in the study area (Vogt and Braun, 2004).

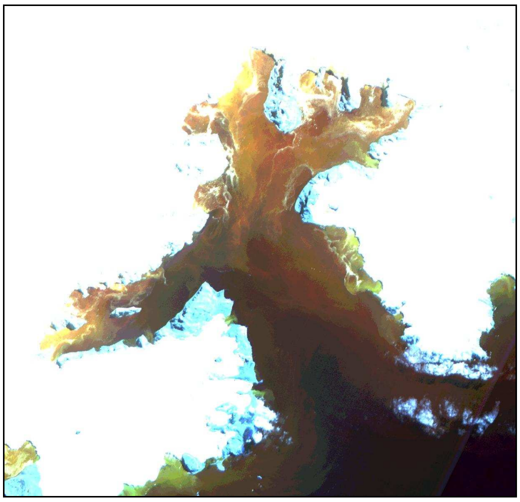

Figure 4 – SPOT color composite (RGB 123), processed by a linear contrast stretch, shows the spatial distribution and concentration of the suspended sediment in Admiralty Bay - February, 2000.

Digital processing was performed in multispectral scenes acquired by SPOT (HRV), on a Quickbird (October, 2006) and TERRA (ASTER) platforms. The SPOT imageries were obtained in February, 1988, March, 2000 and in 1995, with 20 m spatial resolution. The ASTER imagery was obtained in November, 2005, with a 15 m spatial resolution. The methodology proposed in this study was developed in three stages:

(a) Data pre-processing:

Data pre-processing consisted on the ASTER image georeferencing by ENVI software (ITT VIS), using a polynomial model with second order and data resampling by a nearest neighbor interpolation. Control points were collected from the SPOT images geometrically corrected, in UTM projection, with data referenced to WGS-84.

(b) Suspended sediment classification by using an unsupervised method and a knowledge-based algorithm (Figure 5):

The SSC classification was carried out using visible bands of the HRV and ASTER sensors, due to the high SSC reflectivity in the water in these wavelengths (Vogt and Braun, 2004; Lorenzzetti et al., 2007). The image classification was performed by using the Isodata unsupervised method.

The Isodata unsupervised method assigns classes based on statistical parameters of spectral properties and on cluster analysis, considering the image gray levels. Thus, the spectral pattern recognition occurs without the provision of spectral parameters of each class in the scene and this algorithm identifies the classes within the whole data (Crosta, 1992).

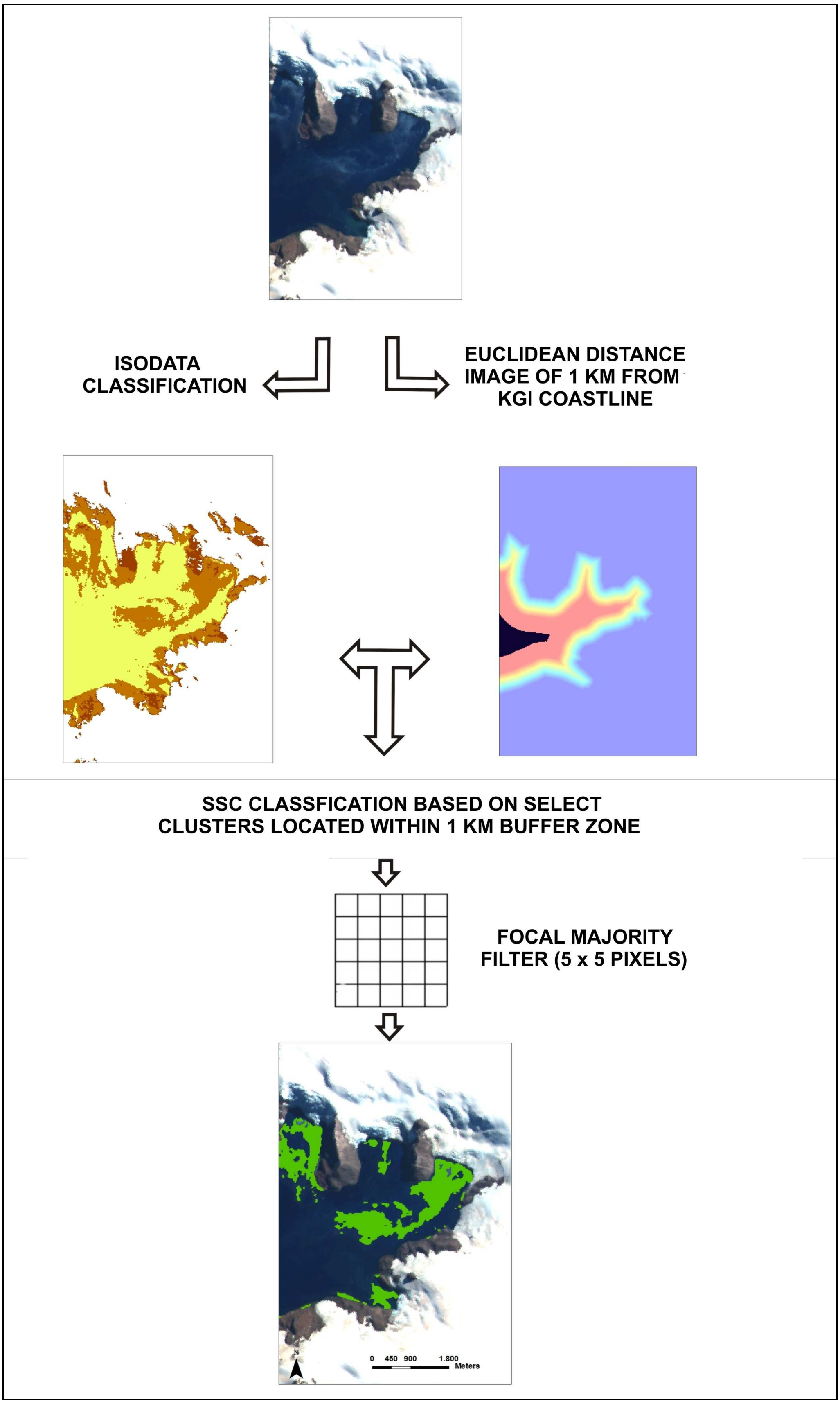

Figure 5 – Data processing chain used for SSC classification.

The SSC classification was carried out by using the selected clusters and it was also based on a buffer zone image derived from Euclidean distance images generated in ArcGIS™ (ESRI, Inc.). The latter consisted on a 1 km buffer zone from KGI coastline in the Martel Inlet (Figure 5), that was considered an area of maximum occurrence of meltwater plume sedimentation. In general, its rates decrease exponentially with distance of 1 km from the tidewater glacier fronts (Syvitski, 1989)..

Classification by decision rules were implemented in ArcGIS™ to detect SSC pixels from the selected clusters located within 1 km from KGI coastline. A focal Majority filter, with 5 x 5 pixels window, was used to data post-classification, to remove pixels and groups of pixels that did not meet the minimum requirement, generating more continuous and consistent classes and thus improving the accuracy of classification.

(c) Analysis and interpretation of the classified maps

The SSC dispersion pattern observed in the classified maps (Figure 7) were correlated to glacier flow velocity data (Figure 6), glacier area, degree of glacier retreat (data provided by the Admiralty Bay Map Server prototype) and even the weather conditions**,** during the acquisition of HRV and ASTER images used in this study (meteorological data obtained by INPE - National Institute for Space Research – Antarctic Station Comandante Ferraz - KGI, 62 ° 05 '07"S, 58 ° 23' 33"W).

The monitoring of the SSC dispersion pattern by *in situ* collection is inaccessible for most of the year. SSC samples in the ablation channels of the Wanda Glacier (which drains into the Admiralty Bay, through a proglacial lagoon) (Figure 2) were made daily during January and February, 2010 and 2011 (ablation season), to estimate the sediment supply and the variability of its contribution to the bay. These fieldwork activities were conducted during the Brazilian Antarctic Operations XVIII and XXIX.

RESULTS AND DISCUSSION

The SSC classification, resulted from the application of the knowledge-based algorithm elaborated in this study, allowed us to identify satisfactorily the pattern of the SSC spatial and temporal distribution in the Martel Inlet, during the months analyzed (Figure 7).

However, the presence of clouds in the study area affected the application of classification methods. In this methodology, there were difficulties to estipulate digital number thresholds for

SSC detection in visible bands, due to its spectral characteristic changes, as well as the type and areas of clouds in the study area.

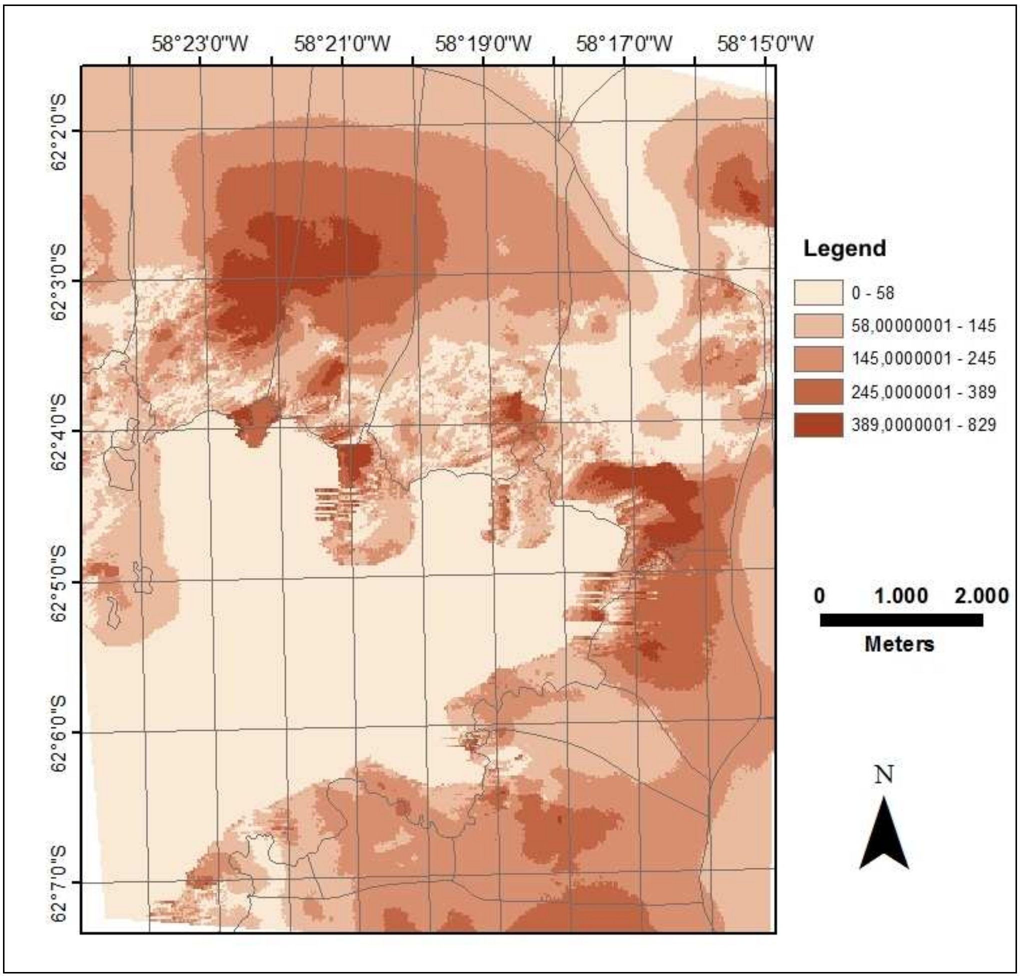

Figure 6 – Flow velocity map of glaciers located at the Martel Inlet. Data provided by Mathias Braun (Moll et al, 2006).

According to Mendes and Cirilo (2001), classification problems may occur due to changes in reflected energy in relation to time of day and season. Therefore, the SSC spectral signature can change from one image to another and there can also be differences among classes within the pixel, generating uncertainties in the classifications.

We observed in the classified images that sediment plumes are well distributed in proximal zone of the tidewater glaciers in the Martel Inlet. The high SSC agreed with data obtained by Vogt and Braun (2004). The absence of sediment plumes near the exposed areas indicated that there was little SSC contribution. The SSC data can be correlated with meltwater runoff from tidewater glacier fronts. These sediments were product of the glacial erosion action and were transported by a possible developed subglacial drainage system.

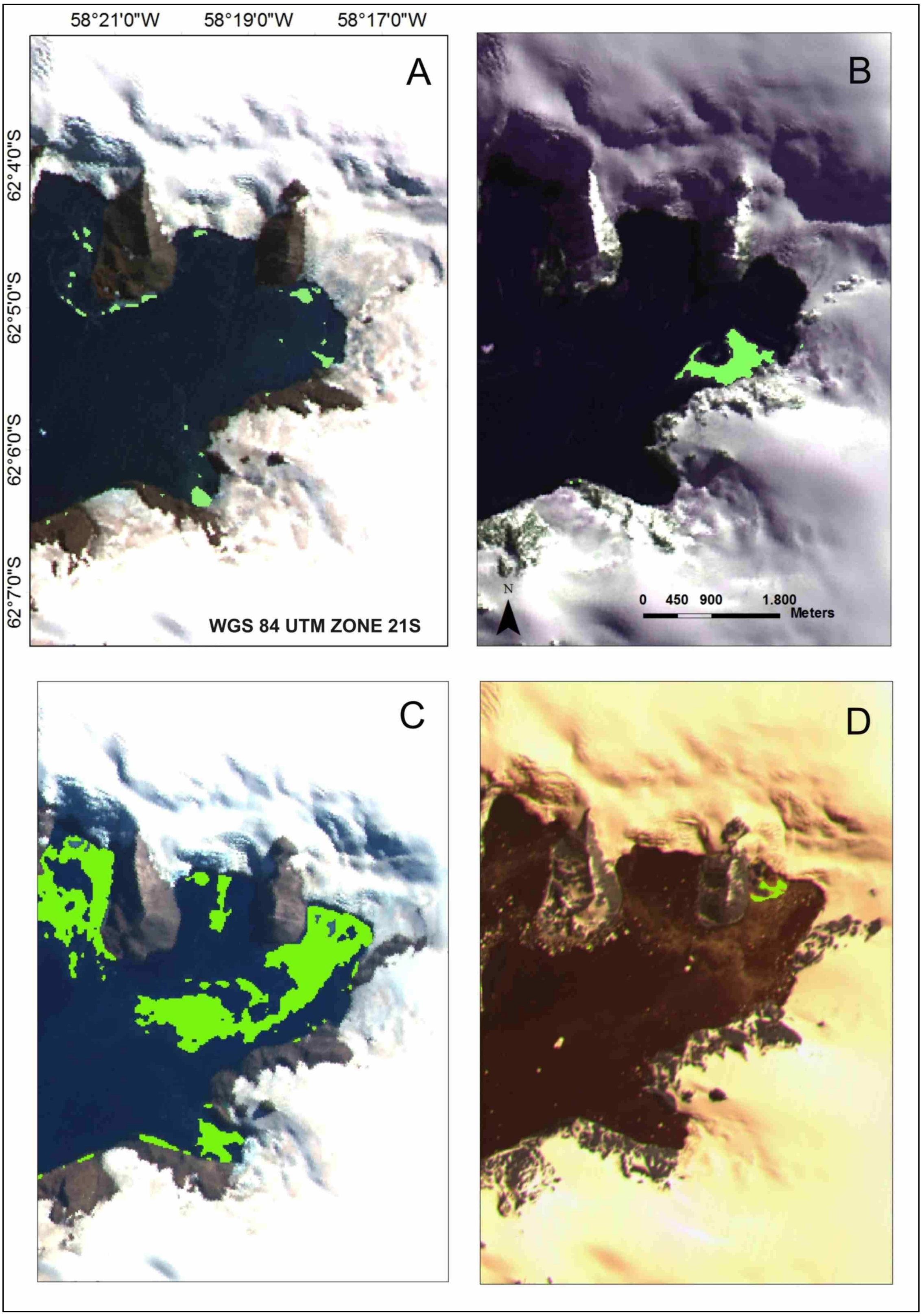

Figure 7 – SSC spatial distribution on images obtained in (A) 1988, (B) 1995, (C) 2000 e (D) 2005.

Besides, they can evidence warm thermal basal conditions for these glaciers. According to Vogt and Braun (2004), the strong fresh water and sediment inputs to the Martel Inlet have relevant impact on marine ecosystem. Rakusa-Suszczewski et al. (1993) observed that the nutrients availability and seasonal variations are more controlled by the dynamics of hydrological processes than biological processes in the study area.

There was a contribution to SSC supply from some glaciers, which have recorded the most rapid retreat process (e.g., Krak, Dobrowolski, Stenhouse and Ajax glaciers - Figures 8 and 9). Additionally, it was observed that the highest concentration of SSC occurred at the proximal zone of the glaciers that have greater extension (Figure 2) and ice flow speed (Figure 7), and therefore a higher sediment transport capacity.

Meteorological and satellite image acquisition data presented strong correlation. Images of February, 1988 and 2000 were obtained during days with positive air temperatures and high solar radiation conditions, and showed higher SSC than images of March, 1995 and November, 2005, which were obtained during days with greater snowfall, more negative air temperatures and low solar radiation conditions.

There was a considerable SSC temporal fluctuation due to weather conditions. The highest concentrations were associated with days of liquid precipitation. According to Pilchmaier et al. (2004), the SSC temporal changes in the Martel Inlet can also be attributed to storm and rainfall events. These changes were associated with increased freshwater discharge and erosion processes. Furthermore, resuspension by wind of material previously deposited on the fjord bottom is also linked to high SSC found in the Martel Inlet. Processes involved in SSC spatial and temporal distribution in fjord environments may also be influenced by tidewater changes and hydrodynamic characteristics of the bay (Drewry, 1986).

The proglacial discharge and SSC time series monitored during the two periods analyzed from the Wanda glacier meltwater channel, during January, 2010 and 2011, indicated that the subglacial meltwater discharge with suspended sediment had great alteration during the melt season and it represented a fraction of total sediment discharge to the Martel Inlet. SSC measurements in subglacial meltwater channels, presented in the Glacier Wanda proglacial area, demonstrated the prevalence of probable subglacial origin of suspended sediment in the bay, thus indicating great influx of basal meltwater from these glaciers, with accelerated and continuous retreat process.

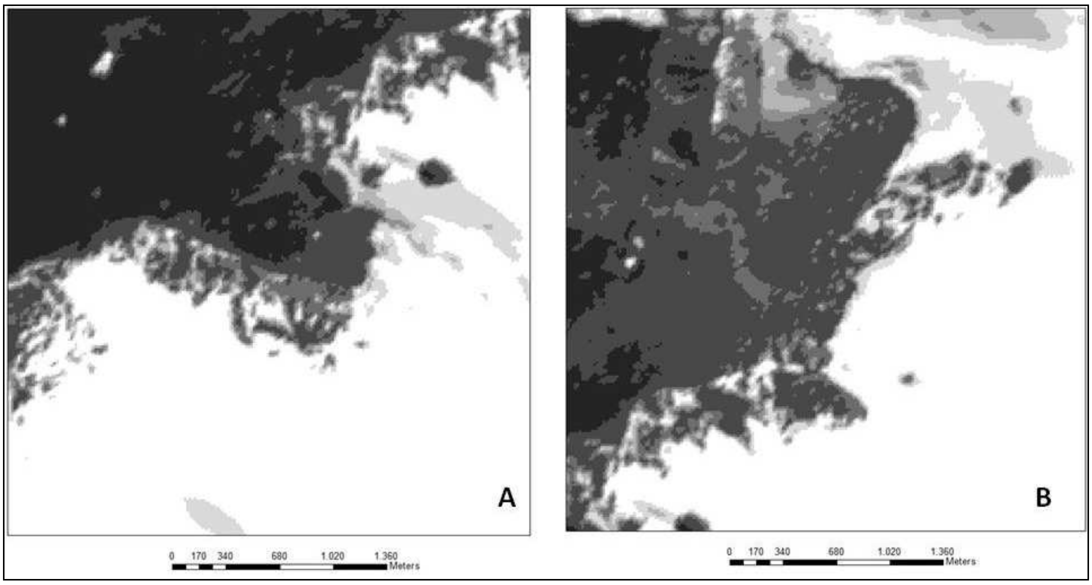

Figure 8 – SSC spatial distribution from Krak (A) and Dobrowolski glaciers (B) (February, 2000).

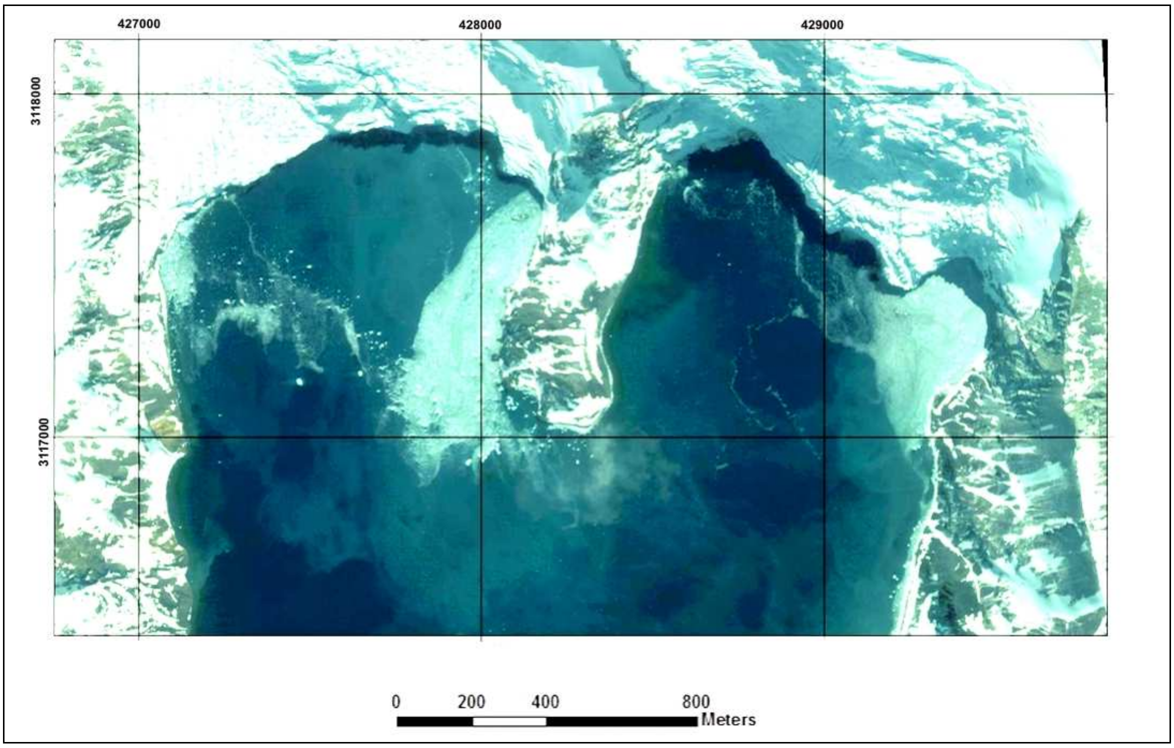

Figure 9 – SSC spatial distribution from Stenhouse and Ajax glaciers, as seen on a Quickbird image color composite (RGB 321) processed by a linear contrast stretch, obtained in October, 2006.

The SSC from subglacial origin may be related to an effective rate of sediment removal due to intense glacier meltwater runoff, thus providing indicators to quantify the rate of sediment production, which is related to the degree of glacier basal sliding (i.e., represents the proportion of subglacial meltwater and is also linked to local precipitation). Additionally, the concentration of sediment plumes in the proglacial area can indicate a sediment production and indicates a warm basal thermal regime for local glaciers.

CONCLUSION

The proposed knowledge-based classification algorithm could be applied successfully for monitoring the SSC spatial and temporal variability and the glacial erosion processes. These processes could be associated with climate variability and glacier retreat, evidenced in the study area in the latest six decades.

The use of GIS techniques allowed us to evaluate the spatial distribution of glacier sediment production processes in the Martel Inlet, related to glacier retreat and increased meltwater runoff. It could be used for the development of conceptual and numerical models of the processes involved in glacial dynamics and estuarine circulation related to the climate changes evidenced in the study area.

Differences in SSC spatial changes related to the month in which the image were obtained and measurements of meltwater discharge data showed strong seasonal and weather condition control in these processes.

We highlighted some difficulties in obtaining optical images without cloud cover in the study area, which could affect the analysis of temporal processes associated with glacier retreat. In addition, it was difficult to quantify more accurately the SSC, because the sensor signal was integrated with the entire water column. Thus, the samples collected in fieldworks became essential to check the classification accuracy and to estimate quantitatively the SSC in the fjord.

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Capítulo 5

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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 of the digitized over a orthophotomosaic (2003), SPOT (February, 1988; March, 1995 and 2000), Quickbird (October, 2006) and Cosmo-Skymed (February, 2011) images. This mapping was supported by fieldworks carried out in the summers of 2007, 2010 and 2011, and by topographic surveys and geomorphic map in the 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 moutonnés, 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 0.71 km² of their ice masses (13.2% of the 50.3 km² total area), without any advances during 1979-2011. Since those years these glaciers receded by an average of 25.9 m a^{-1}. These ice-free areas were susceptible to rapid post-depositional changes.

Keywords: retreat glacier, glacial landforms, landscape evolution of ice-free areas.

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 *moutonnés* 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 0,71 km² de suas áreas (13,2% de uma área total de 50,3 km²), sem reavanços durante o período entre 1979-2011. Estas geleiras têm retraído em uma média de 25,9 metros por ano. Estas áreas recentemente deglaciarizadas são susceptíveis a rápidas mudanças pós deposicionais.

Palavras chaves: retração glacial, geoformas glaciais, evolução da paisagem de áreas sem cobertura de gelo.

1. 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 glaciers 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 high accurate Digital Elevation Models (DEM) (DIXON *et al*., 1998; CHANDLER, 1999; 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.

2. Study area

Martel 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, which results in high rates of local precipitation. The mean summer air temperature can reach 2.8ºC, which results 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, which resulted in glacier advances (HALL, 2007). About 9 k BP, this glacier ice retreated to the heads of the smaller tributary fjords and the terrestrial portions of KGI started to become ice-free (MAUSBACHER *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*. (2000), glacial deposition records (subglacial till) indicated that Martel Inlet was covered by glaciers, about 2.3 ka BP. Glacimarine sediment 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).

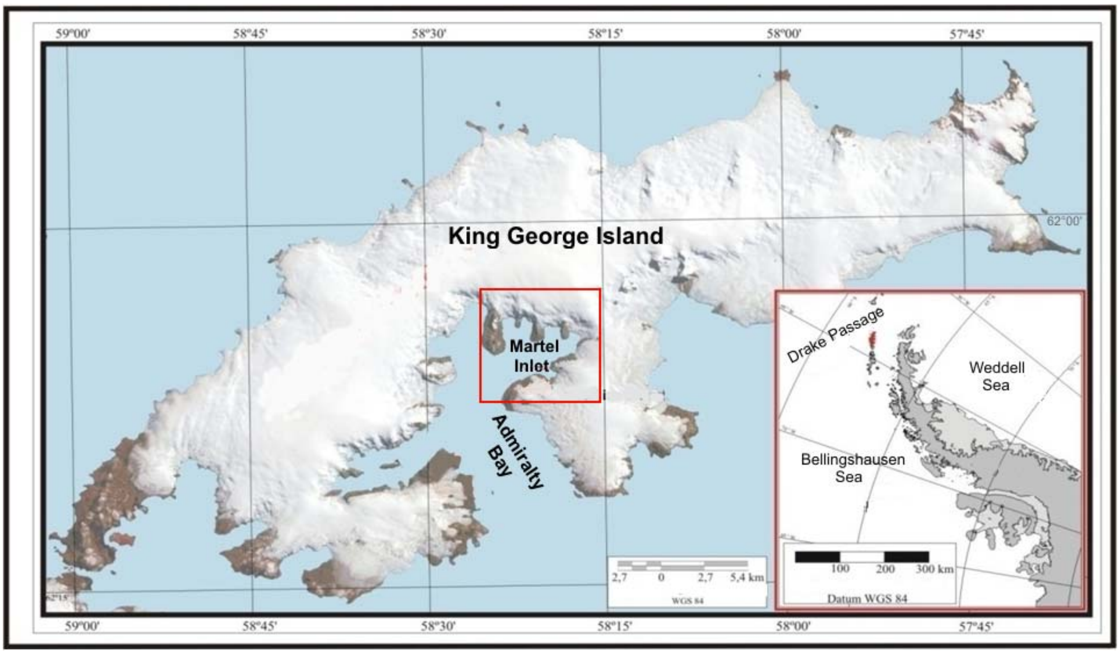


Figure 1 - Martel Inlet location in King George Island.

3. Methods

A geomorphological map of ice-free areas in the Martel Inlet was compiled with multitemporal remote sensing data processed in a GIS environment, supported by recognize the glacial landforms and landscapes during fieldworks, 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, covering different microenvironments and geomorphical 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 del 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 identification of geographical distribution of glacial marginal landforms was based on fieldworks, 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 remotely sensed 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). The area of glaciers in 1979 was based in study of Arigony-Neto (2001) (orthophotomosaic-1979). Striations, subglacial melttwater channels and fluting deposits indicated the pattern of ice discharge in glaciers.

4. 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 moutonnés, stoss and lee, striated pavements, arêtes and glacial cirques (Figure 2).

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.

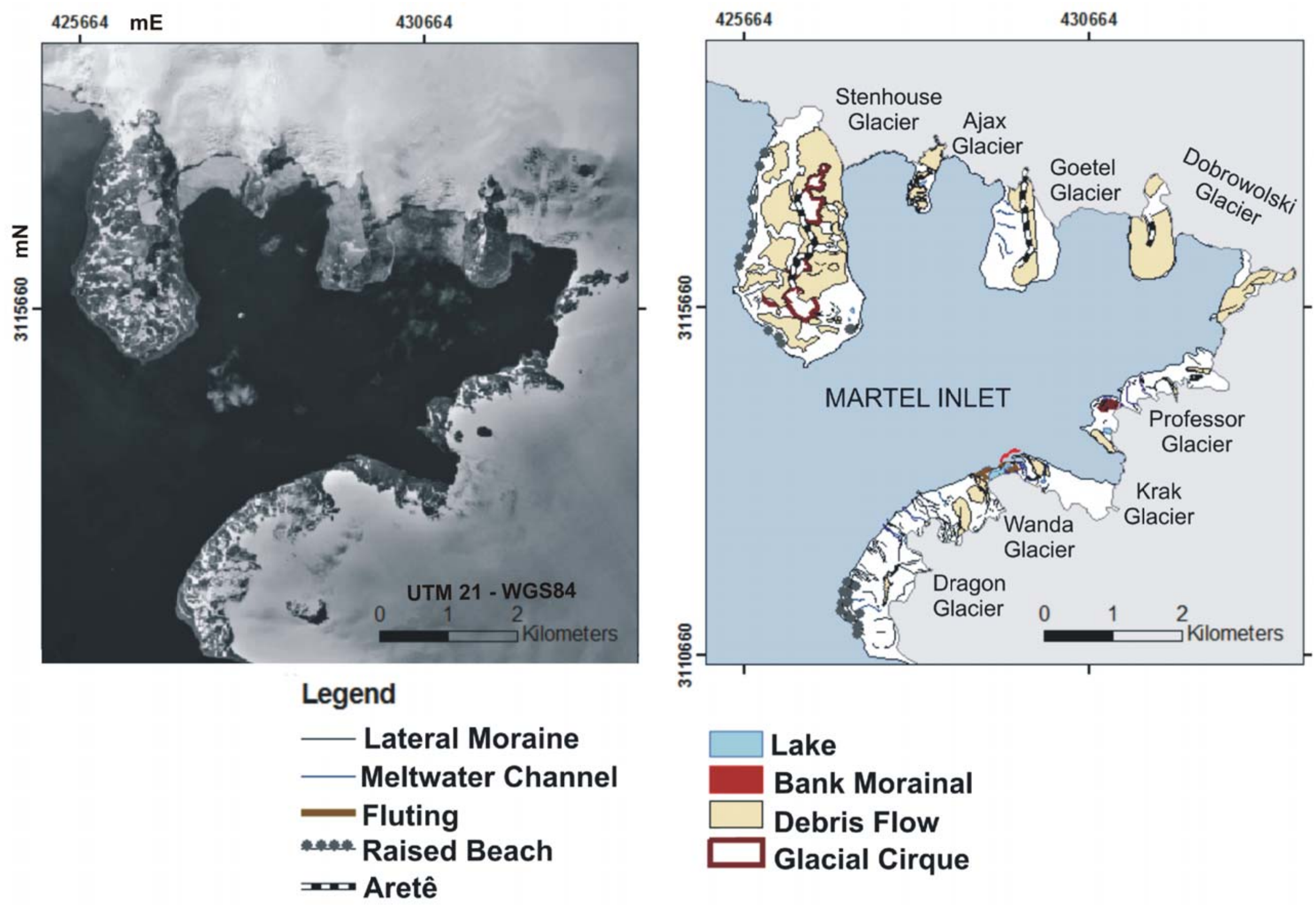
Figure 2 – Striated pavement in Wanda proglacial area and glacial cirques in the Keller Peninsula.

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) are resulted from meltwater channels near front glaciers with land terminus. Flutings 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-LGM deglaciation (JOHN and SUGDEN, 1971).

A transverse topographical profile indicated the presence of an U-shaped valley (Figure 5) valley 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 moraines deposits



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Debris Flow
Glacial Cirque

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

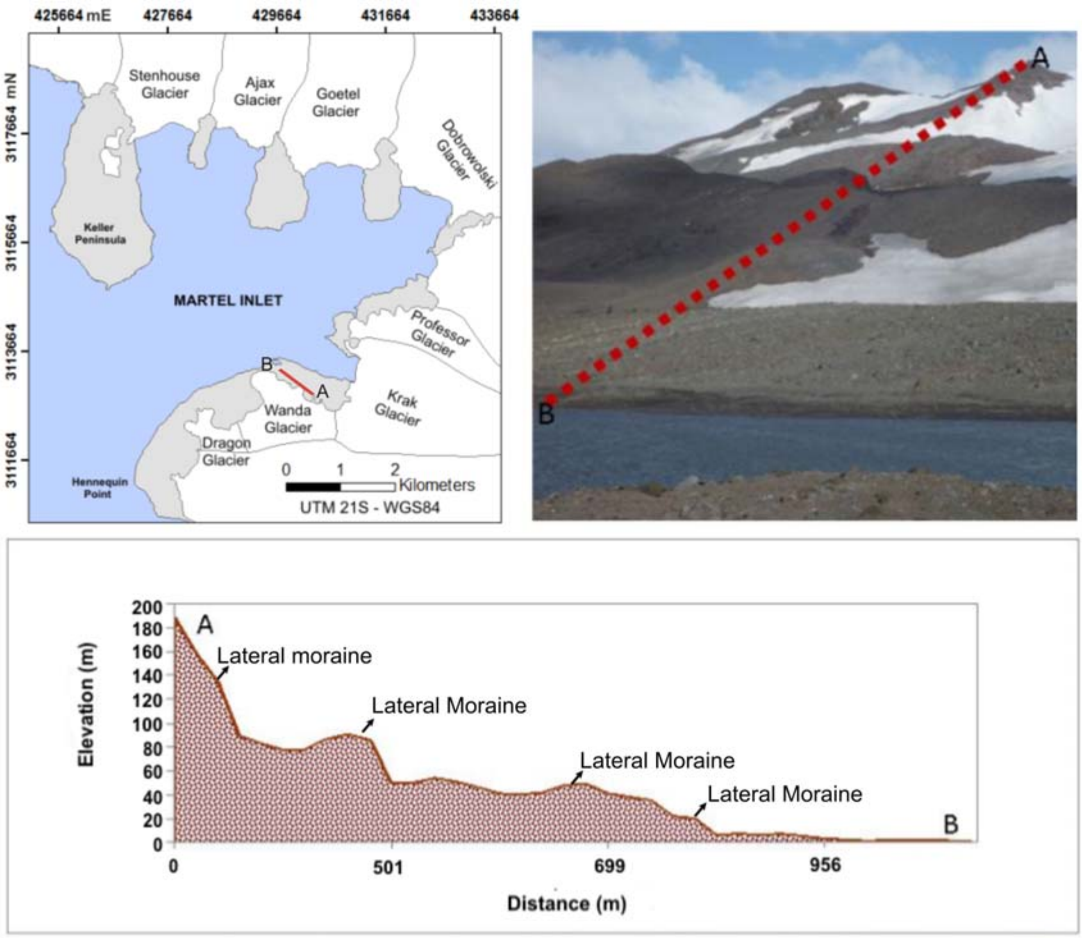

Figure 4 – Topographical profile A-B (dashed line) shows morainic ridges in Wanda Glacier marginal area.

Ferguson, Noble and Flagstaff glaciers, located in the Keller Peninsula, are already masses of stagnant or quasi-stagnant ice, and fastly disappearing. Thus, in those years glaciers in study area have retreated by an average of 25.9 m a^{-1}. There were relatively minor volume changes over the period 2000-2011, while in 1979-2000 we observed a higher loss of glacial area (0,64 km²).

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% (Table 1) of the 50.3 km² total area, accounting for an area loss of 0.71 km². Tidewater glaciers (e.g., Dobrowolski and Krak) and land terminus glaciers (e.g., Dragon and Professor) presented the highest annual retreat rates.

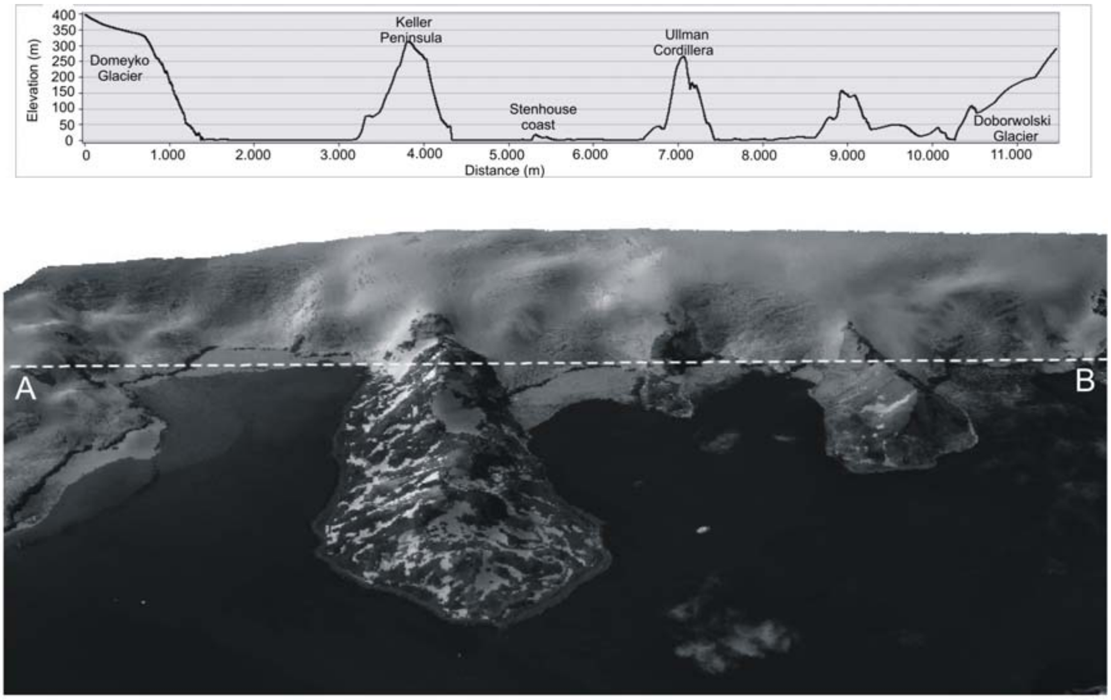

Figure 5 – Transverse topographical profile (white dashed line in the perspective view scene) indicated the presence of an U-shaped valley in the northern sector of the Martel Inlet.

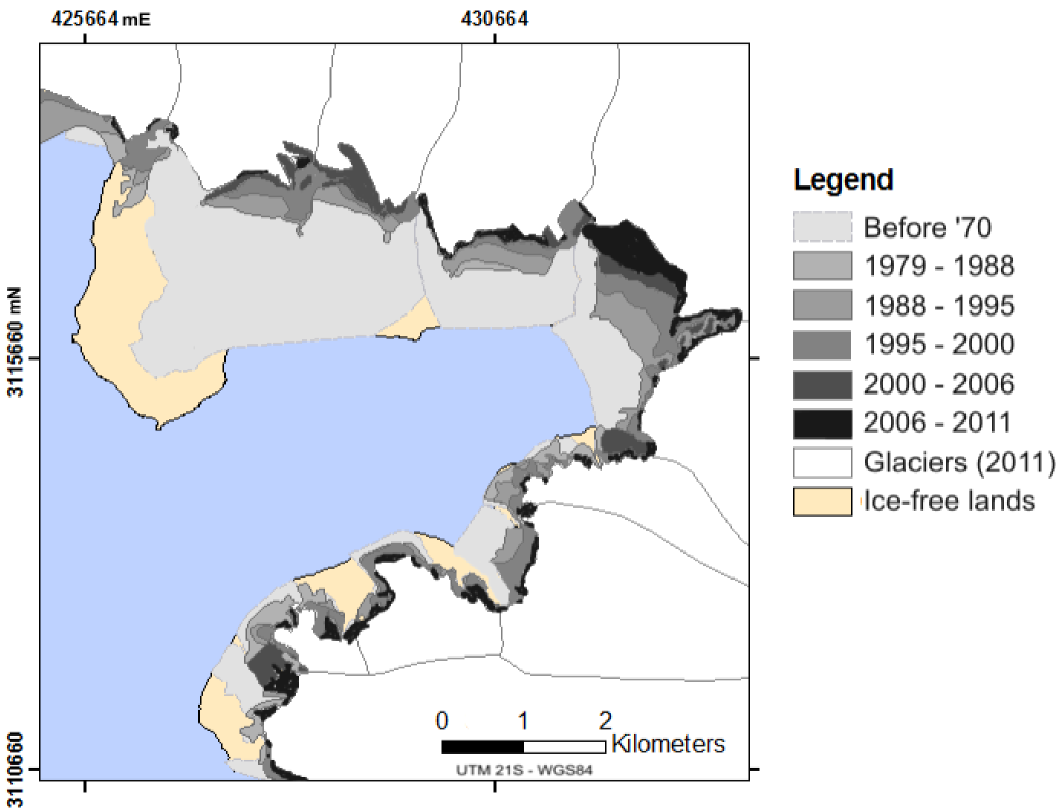

Figure 6 – Glacial retreat in the Martel Inlet. Glacier extend data were derived from lateral and bank morainal positions and orthophotomosaic (1979) and SPOT (February,

1988; March, 1995 and 2000), Quickbird (October, 2006), Cosmo-Skymed (February, 2011) orthorectified images.

Table 1 – Glacier from 1979 to 2011.

Glacier	Area in 1979 (km²)	Area loss (km²) 1979 -88	Area loss (km²) 1988 -95	Area Lost (km²) 1995 -00	Area loss km²) 2000 -06	Area loss km²) 2006 -11	Area loss (km²) 2011	Total area loss %	Retreat rate m^2a^{-1}
Wanda	2.27	0.25	0.09	0.30	0.05	0.02	1.56	31.30	22
Krak	5.73	0.29	0.11	0.21	0	0.06	5.06	11.70	20
Ajax	6.94	0.01	0.16	0.12	0.23	0.01	6.41	7.70	16
Stenhouse	9.70	0	0.20	0.2	0.18	0.02	9.10	6.20	18
Dobrowolski	14.07	0.54	0.57	0.56	0.22	0.54	11.64	17.30	75
Dragão	0.91	0.28	0.08	0.06	0.05	0.02	0.41	54.90	15
Professor	1.41	0.23	0.08	0.13	0.06	0.06	0.85	39.80	17
Goetel	9.30	0.06	0.26	0.18	0.06	0.09	8.65	7.00	20

6. Discussion

The distribution of distal moraine systems and patterns of glacial lineations, identified in satellite images, fieldworks 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.

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

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

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 have the highest retreat rate. It’s stepped topography and lost of the anchorage can cause influences the velocity ice flow and calving process. Last stability position of this terminus was determined by the morainical bank (Figure 6) 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 determine lower front retreat in the last decades.

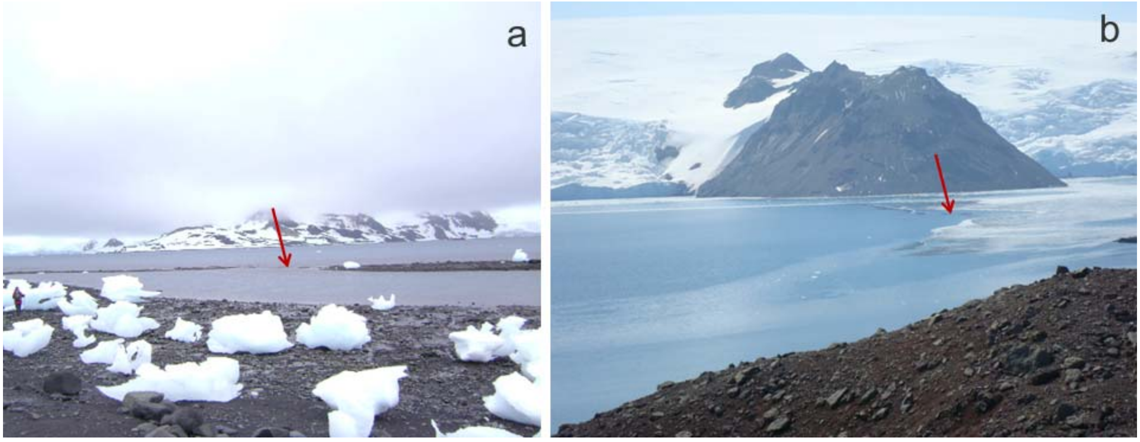

Figure 6 – Morainal banks in latest stability positions of the Wanda (a) and Dobrowolki (b) glaciers.

Multitemporal satellite images, topographic surveys and geomorphical 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. Biological activity was also recorded in the proglacial area near the Wanda proglacial lagoon. Debris flows are characterized for abundant clasts with accelerated mecanical mechanisms of the weathering. These deposits have different characteristics of the till deposits. Quimical weathering processes are observed in proglacial area related with high air temperature and liquid precipitation the summers 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. The abundance of fine granulometric deposits in the proglacial zones indicates an efficient action of subglacial abrasion and less subglacial quarrying processes.

7. Conclusions

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

This work showed the reduction degree of glaciarized area in Martel Inlet over the last three decades (1979-2011), the glacier total area loss was about 0.71 km² (13.2% from the total area of 50.3 km²), without any advances during this period. Thus, since those years the glaciers in study area has receded by an average of 25.9 m a^{-1}. Martel Inlet glaciers has a small drainage basins and a 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 dynamic information. Glacier type and its proglacial area are sensitive to climatic conditions and may be greatly impacted by recent patterns of climate variability. Furthermore, geomorphical mapping may be used for monitoring paraglacial and glacial changes observed in study area.

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Capítulo 6

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RECENT CHANGES IN THE WANDA GLACIER, KING GEORGE ISLAND, ANTARCTICA

MUDANÇAS RECENTES NA GELEIRA WANDA, ILHA REI GEORGE, ANTARTICA

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ABSTRACT

Recent glaciological changes in Wanda Glacier, King George Island, South Shetland Island (61°54’ and 62°16’S, 57°35’ and 59°02’W) off the Antarctic Peninsula, were quantified by ice flow velocity, direction and fluctuation of glacier termini measurements. In order to monitor its changes topographic and DGPS surveys were carried out to generate a Digital Surface Model, as well as transverse and longitudinal profiles. Results show that Wanda Glacier has a small drainage basin, a high retreat rate through fusion processes and reduced ice thickness if compared to others ice masses in KGI. Surface-area changes are assessed using historical satellite imagery from 1979 to 2011. Wanda glacier lost a about 31% of its original 1979 area (1.5 km²). The current continuous and fast retreat phase is attributed to the recent regional warming. Maximum ice surface velocity, measured using a stake network, reached 2.2 cm d^{-1} during the period 2007–2011. Transverse profiles show the influence of the topography on the ice flow. Due to its small size and thermal conditions, Wanda Glacier responds rapidly to climatic variations and is relevant for environmental studies.

Keywords: glacier monitoring, climatic changes, glaciology, remote sensing.

RESUMO

Mudanças glaciológicas recentes na geleira Wanda, ilha Rei George, Shetlands do Sul (61°54’ and 62°16’S, 57°35’ and 59°02’W), península Antartica, foram quantificadas através de medidas da direção e velocidade do fluxo de gelo e da flutuação de sua posição frontal. Visando monitorar estas flutuações foram coletados dados topográficos e medidas de DGPS para a geração de um Modelo Digital de Superfície e perfis transversais e longitudinais da geleira. Resultados demonstraram que a geleira Wanda possui uma pequena bacia de drenagem, um alto grau de retração através de processos de fusão, e reduzida espessura se comparada com outras massas de gelo da ilha Rei George. Mudanças em sua área foram obtidas pela utilização de imagens de satellite multitemporais do periodo de 1979 a 2011. A geleira Wanda perdeu aproximadamente 31% de sua area original desde 1979 (1,5 km² de area em 1979). Atualmente, apresenta uma continua fase de rápida retração, e esta é atribuída ao recente aquecimento regional. A velocidade superficial maxima do fluxo de gelo, medida através de uma rede de estacas implantadas na geleira, foi estimada em $2{,}2^{-1}$ cm ao dia durante o period de 2007 a 2011. Perfis transversais mostraram a influência da topografia na direção do fluxo de gelo. Devido sua pequena area apresentada e sua condição termal, a geleira Wanda responde rapidamente as variações climáticas, sendo assim, relevante para estudos ambientais.

Keywords: glacier monitoring, climatic changes, glaciology, remote sensing.

1. INTRODUCTION

Glaciers are sensitive indicators of climatic changes and play an important role in regional climates (Hope *et al*., 1998). Glaciers are components in albedo feedback mechanisms of the climate system and their low temperature contribute to the global temperature gradient (Pellikka and Rees, 2010).

Glacier velocities and their surface topography are very important parameters to monitor there are keys to glacier volume and glacier mass balance studies (Pellikka and Rees, 2010).Therefore, monitoring data of glacier area changes, ice flow velocity and glacier frontal position could be used to model accurately the response of glaciers to regional climate variability.

This paper investigates recent glacial changes in Wanda glacier, King George Island, Antarctica. This work provides quantitative datasets that can be used to measure rates at which such changes are taking place. Multitemporal satellite image data were used to monitor the glacier. Topographical and DGPS surveys were carried out during two fieldworks, in order to generate a Digital Elevation Model (DEM) and transverse and longitudinal profiles, and to estimate superficial ice flow directions and velocities of the Wanda glacier.

2. MATERIALS AND METHODS

2.1 STUDY AREA

Wanda glacier is located in King George Island (61°54’ and 62°16’S, 57°35’ and 59°02’W), South Shetland Islands off the Antarctic Peninsula (Figure 1). This glacier has a proglacial front characterized by several landforms and proglacial deposits, as a consequence of its recent retreat.

Figure 1 - Wanda glacier location in King George Island, South Shetlands archipelago.

The Antarctic Peninsula region (AP) had one of the most intense climatic warming trends over the last decades (IPCC, 2007). According to Turner *et al*. (2005), there was an increase in air temperature of approximately 0.56°C per decade in the western AP (Faraday/Vernadsky weather station; 65°15'S and 64°16'W). The AP annual surface air temperature has increased about 3ºC since 1950 (Monaghan *et al*., 2008).

Several studies have provided evidences of glacier retreats in the Martel Inlet (Figure 1) since 1956 (Simões and Bremer, 1995; Park *et al*., 1998; Bremer, 1998; Simões *et al*., 1999; Aquino, 1999; Braun and Goβmann, 2002; Vieira *et al*., 2005; Rosa, 2008; Rosa *et al*., 2009).

Over the past 30 years, the number of days with liquid precipitation and positive air temperatures has been rising in summer. These processes accelerated the snowmelt and increased the negative mass balance of local glaciers (Braun *et al*., 2001; Ferrando *et al*., 2009). The South Shetlands ice masses are highly sensitive to environmental changes due their geographical position (between 61°04' and 63°20'S, 54°00' and 62°25'W), the their small area, and because de glacier ice is near or at the pressure melting point (Macheret *et al*., 1997; Pfender, 1999; Arigony-Neto *et al*., 2001; Simões, 2004). Their retreat processes are linked to the regional atmospheric warming observed over the last decades (Park *et al*., 1998; Simões *et al*, 2004; Cook *et al*., 2005; Blindow *et al*., 2010).

We used SPOT imageries (acquired on February, 1988 and on March, 1995 and 2000), QUICKBIRD (2006) and COSMO-SKYMED (February, 2011) imageries to quantify recent area changes in the Wanda Glacier. All data were projected in Universal Transverse Mercator (UTM) zone 21) World Geodetic System 1984 - WGS84).

Flutings deposits were identified in the proglacial area to determine the recent glacier ice flow directions. These deposits have an elongated form aligned parallel to the ice flow direction and also indicate basal melt rates (Bennett and Glasser, 1996).

The glacier montion was surveyed by putting stakes on the glacier during fieldwork activities on December, 2007 (Figure 2 and 3), according to techniques of Anderson *et al*. (2004) and MacGregor *et al*. (2005).

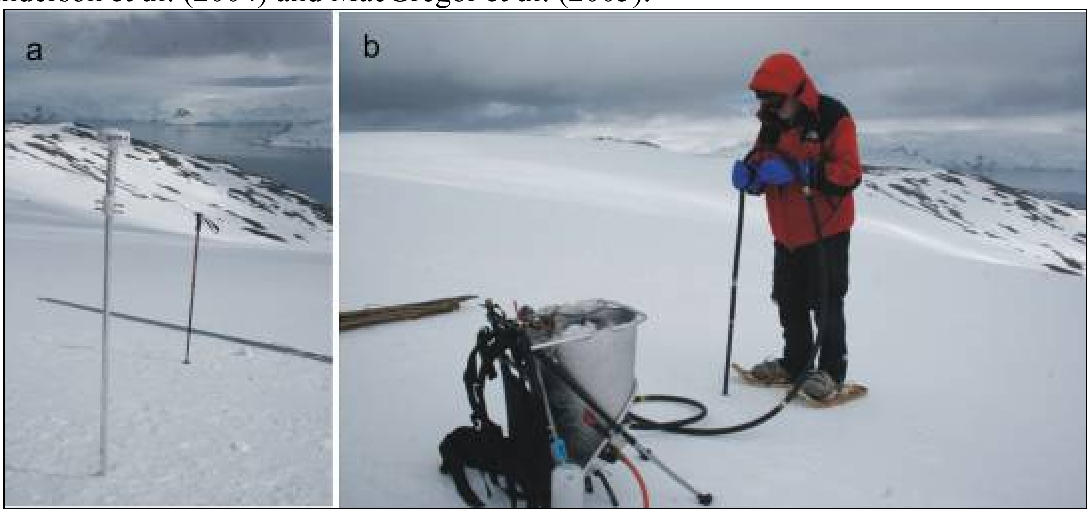

Figure 2 - GPS antenna coupled to one stake (a) fixed into the Wanda glacier centerline. Each 3 m aluminum stake was fixed in a hole of 2 m depth, dug by an thermal ice drill (b).

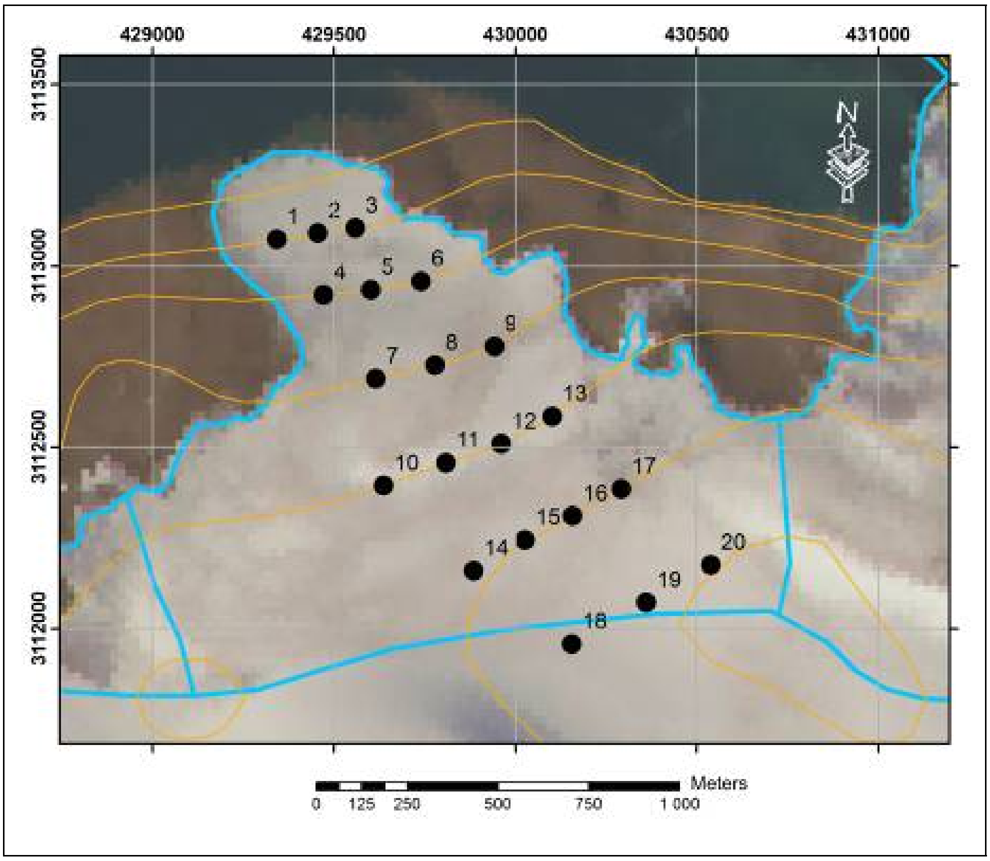

Figure 3 - Stakes location along the Wanda Glacier surface. The blue line indicates the glacier drainage basin boundaries delimited by Bremer (1998), overlapping a SPOT subcene (2000) used in this work.

The measuring x, y stakes coordinates over a period of years was performed using of accurate differential global positioning systems (DGPS). These data were post-processed for differential correction in EZSurv software (VIASAT Geotechnologies, Inc.). The coordinates points were corrected in relation to a base station, which consisted of a GPS antenna (62°04'58"S and 58°23'39"W; altitude of 57.53 m) installed near the Brazilian Comandante Ferraz Antarctic Station (EACF). This antenna is part of the Brazilian Network of Continuous Monitoring (RBMC) GPS System, managed by the Brazilian Institute of Geography and Statistics (IBGE). We carried out another DGPS survey of the same stakes on January, 2011. Ice flow direction and velocity were determined based on the stakes position in these two years.

Glacier orthometric altitudes were obtained by a trigonometric survey carried out on January, 2001, with a total station model Topcon (Leica Geosystems). We determinated other planialtimetric points by DGPS surveys, using a topographic receiver (model GTRA). Corseuil and Robaina (2003) demonstrated the possibility of using GPS for altimetric surveys, if these data are corrected by a geoid undulation model. The points planialtimetric coordinates were determined by rapid static and kinematic surveys, using reference data from the EACF GPS antenna. GPS points ellipsoidal altimetric coordinates were transformed to orthometric altitudes, referenced to World Geodetic System (WGS 84), by using the geoid undulation model EGM86 (Earth Gravity Model 1996), based on the procedure described by Hofmannw-Ellenhof *et al.* (1997). These orthometric data were then interpolated using the SURFER software (Golden Software, Inc.) to generate a glacier DEM. The Ordinary Kriging interpolation method was applied for better representation of the glacier smooth surface morphology.

3. RESULTS

4.1 Wanda glacier retreat rate

The glacier drainage basin area, estimated using the orthorectified COSMO-SKYMED imagery acquired on February (2011) is about 1.56 km². Figure 4 shows the changes in Wanda Glacier terminus position from 1979 to 2011, with details provided in Table 1. In 1979, the glacier was characterized by tidewater terminus (Figure 4 and 5). Since that years the glacier has receded by an average of 22 m a^{-1}.

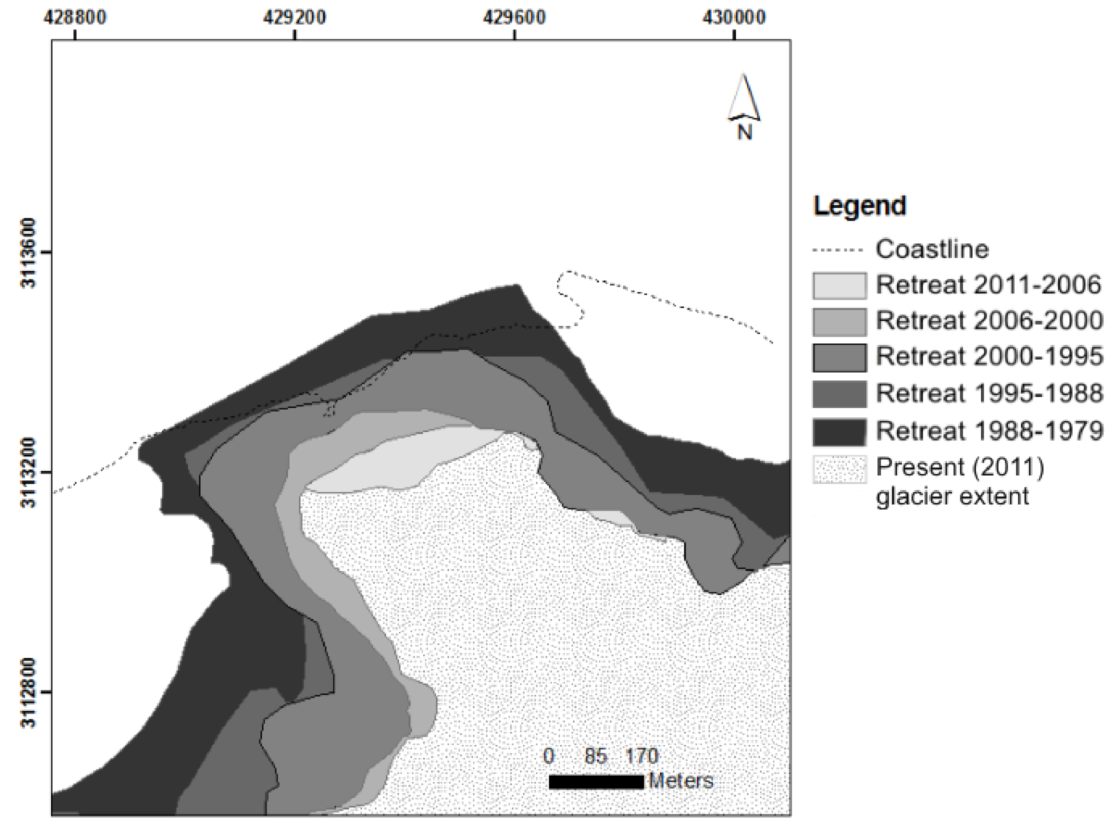

Figure 4 - Wanda glacier map showing different glacial retreat phases.

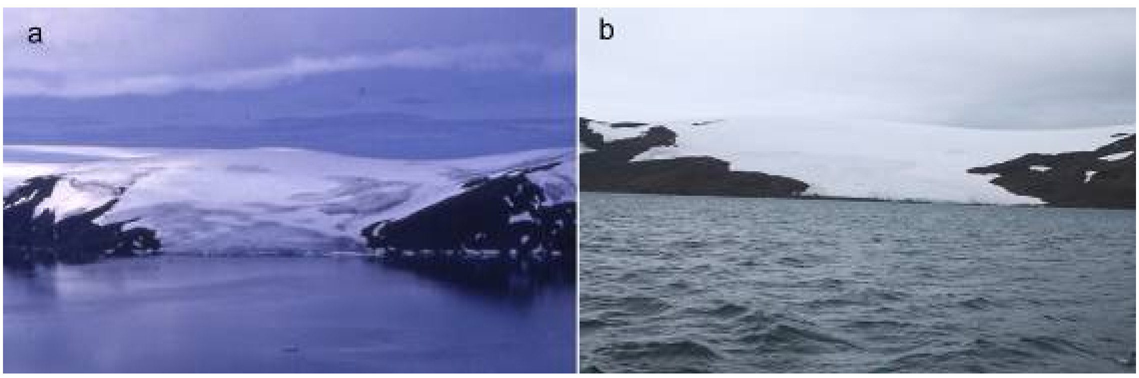

Figure 5 - Wanda glacier in 1988 (a) and 2011 (b). Photography (a) was provided by Nelson Sambaqui Gruber.

Table 1 - Wanda Glacier total area and retreat rates since 1979, was derived from multitemporal satellite imageries.

Area in 2011 (km²)	Lost ice area (km²)				
	2011 - 2006	2006 – 2000	2000 - 1995	1995 - 1988	1988 - 1979
1.56	0.02	0.05	0.30	0.09	0.25

Over the period 1979 to 2011, glacier retreat amounted to 31% of the 1.5 km² total, accounting for an area loss of 0.71 km². The current continuous and fast retreat phase is attributed to the recent regional warming. There was relatively minor volume change over the period 2000 – 2011, while over the period 1979 – 2000 recorded a higher glacier area loss (0,64 km²). In its current phase, Wanda Glacier has presented continuous retreat processes and a thickness reduction, as response to the rapid changing climate in the study area.

Supraglacial ablation and glaciofluvial processes are observed in the Wanda Glacier. As a consequence of these processes and the ice retreat, a large proglacial lagoon was formed (Figure 6).

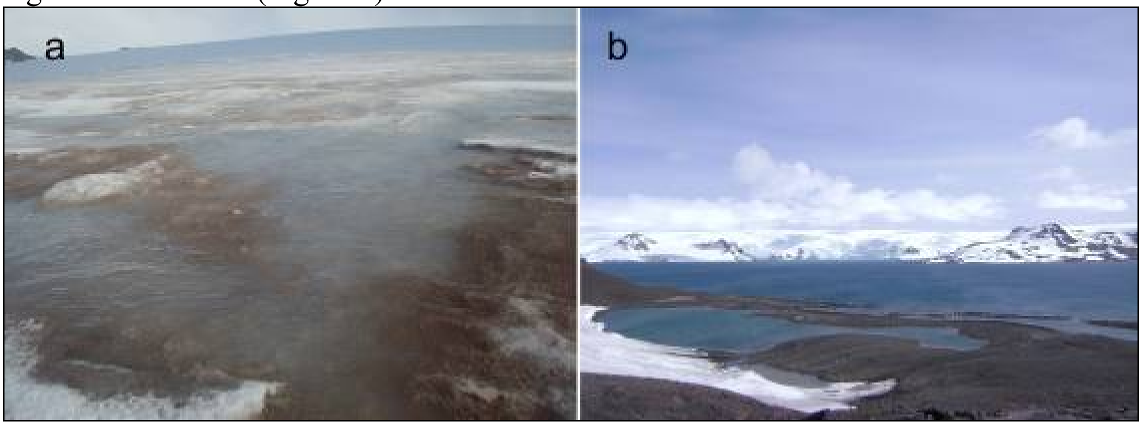

Figure 6 - Supraglacial ablation processes (a) and proglacial lagoon (b).

Flutings deposits (Figure 7 and 8), located on the Wanda Glacier proglacial area, on a recently exposed environment, were mapped by high spatial resolution imagery of QUICKBIRD satellite, which indicates that the latest ice flow glacier direction occurred toward northwestern.

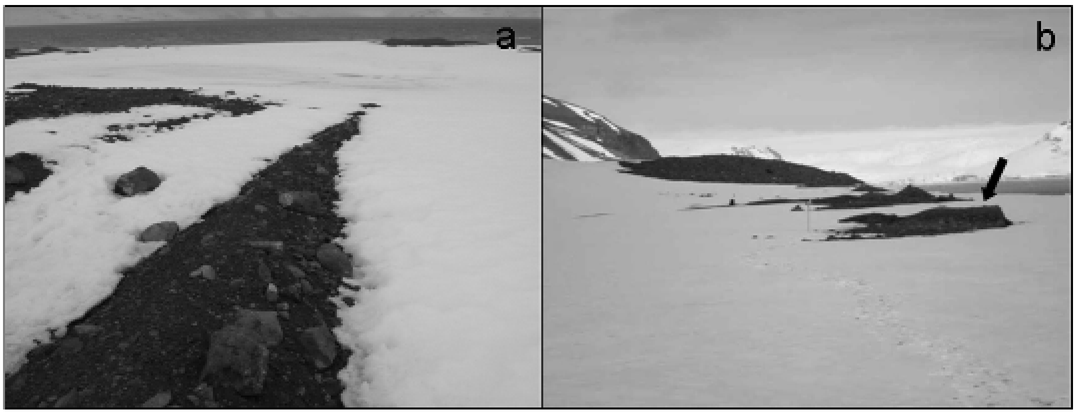

Figure 7 - Flutings on the Wanda Glacier proglacial area.

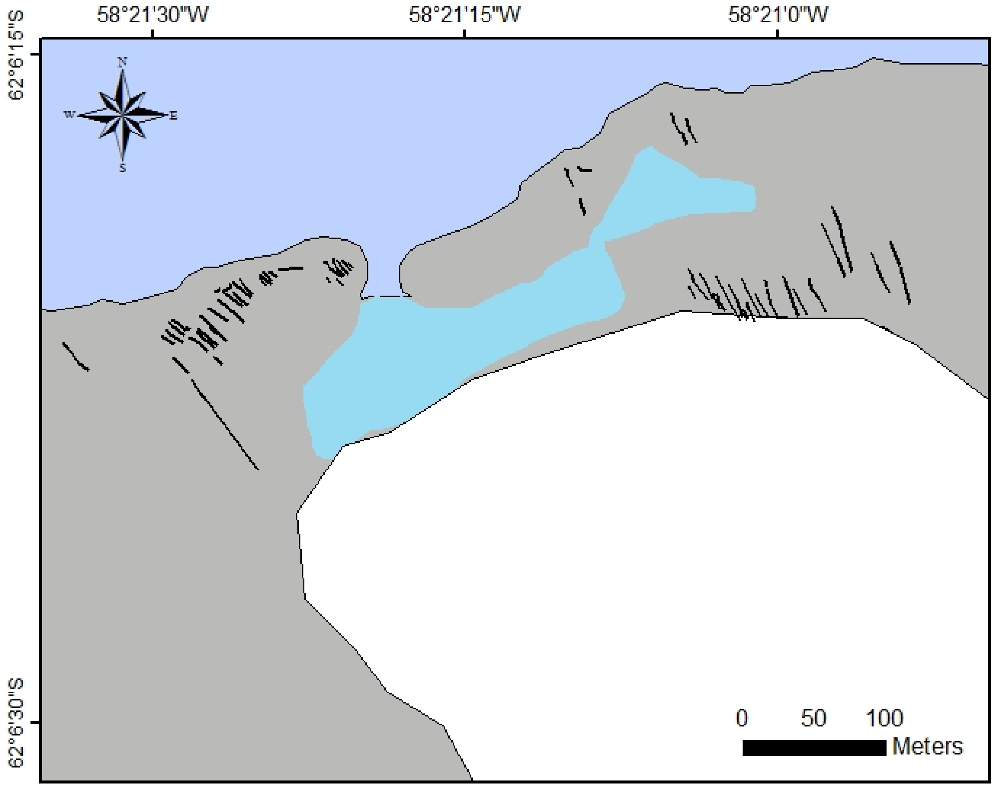

Figure 8 - Flutings deposits location on the Wanda Glacier proglacial area, indicating a former northwestern ice flow direction.

4.2 Superficial ice flow velocity of the Wanda Glacier

Maximum ice surface velocity, measured with a stake network, reached 2.2 cm d^{-1} during the period 2007–2011. Considered the velocity data measured by Moll *et al.* (2006), who estimated a mean of 10 cm d^{-1} for glacier during 1995 through Differential Radar Interferometry (DInSAR), the Wanda velocity data indicated a decrease ice flow velocity due to reduction in glacier area and thickness. However, higher velocity observed in a sector of this glacier can be explained by ice sliding due to increased topographic gradient (Figure 9).

4.3 Digital Elevation Model generation

Transverse and longitudinal topographic profiles (Figure 10 a and b) and a DEM are used to describe the Wanda glacier surface morphology (Figure 11). This elevation model indicated the predominant ice flow direction (Figure 12) and glacier morphology configuration. The transverse profile (Figure 10a) showed that subglacial and surface topography has a great influence in the ice flow. The higher altitudes of the glacier are located at its eastern margin. The longitudinal profile showed a steep slope toward the glacier front (Figure 9 and 10b).

5. DISCUSSIONS

Results cleary indicate that Wanda Glacier has lost mass over the period 1979-2011. These findings are similar to those recently observed at other glaciers in KGI Island by Arigony-Neto (2001) and Bremer *et al.* (2004).

Figure 9 - Topographic slope observed on the Wanda glacier accumulation area.

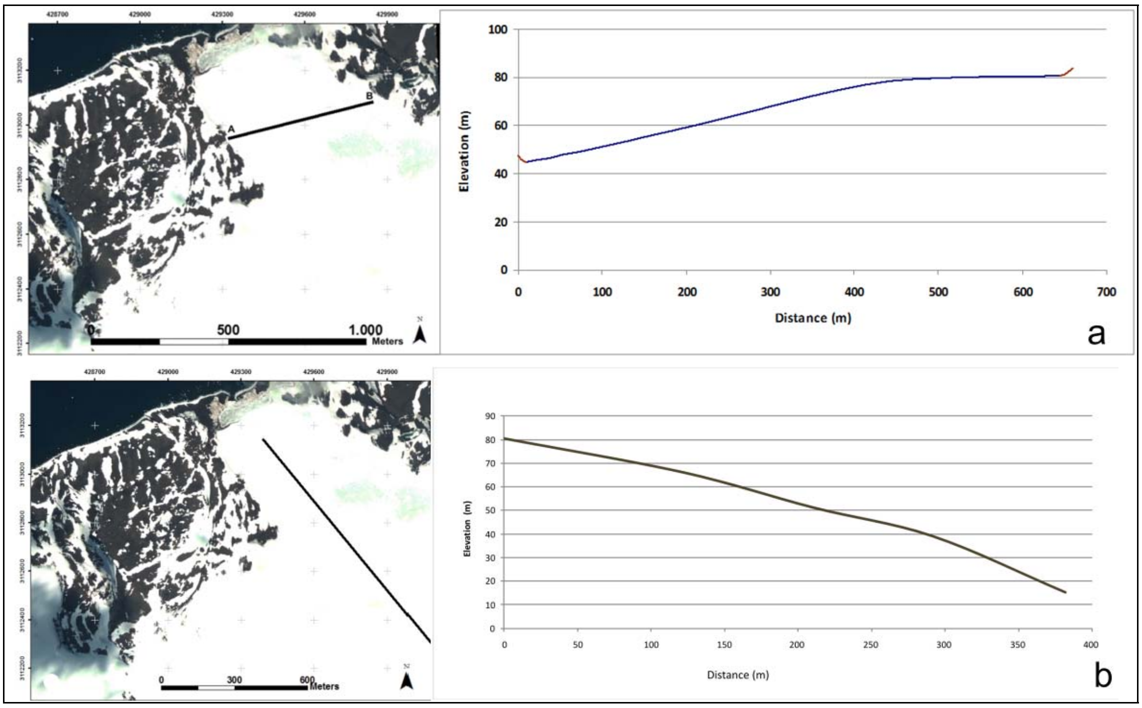

Figure 10 – (a) Transverse and (b) longitudinal topographical profile location on Wanda glacier.

The present study reveals that the Wanda Glacier is a small drainage basin and shows higher retreat rate through fusion processes if compared to others ice masses in Martel Inlet. The superficial ablation and the presence of merging subglacial channels evidenced a temperate basal thermal condition. Topographical data indicate that current glacial dynamics conditions and glacier ice flow patterns are highly influenced by morphometric characteristics of the study area.

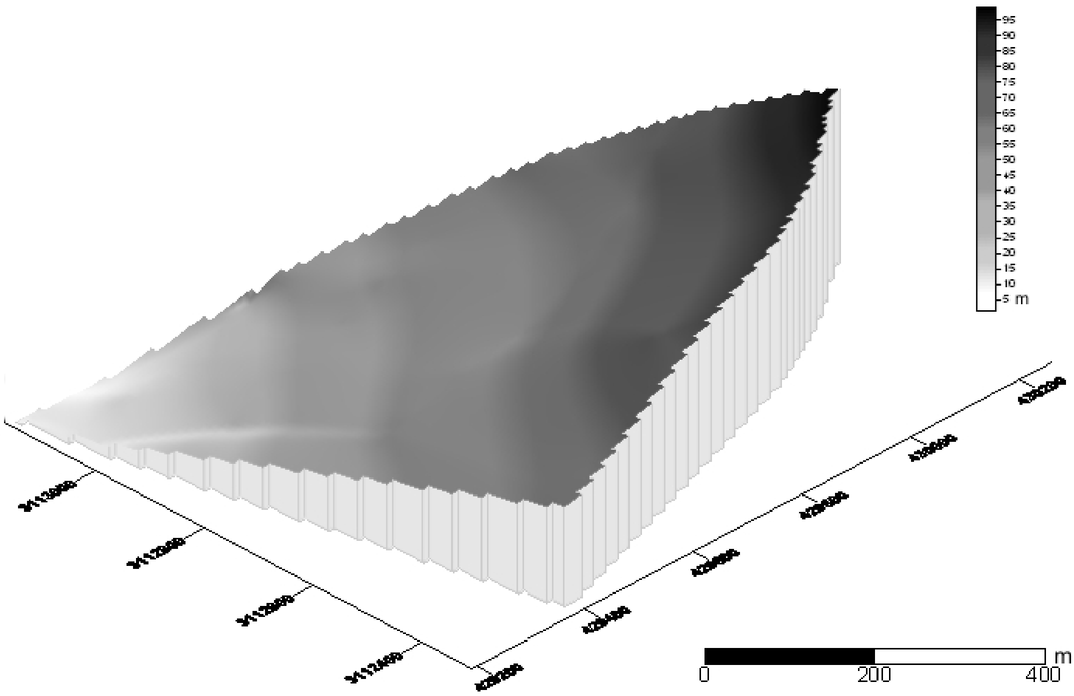

Figure 11 - Eastern perspective view of a DEM, showing the Wanda glacier surface morphology.

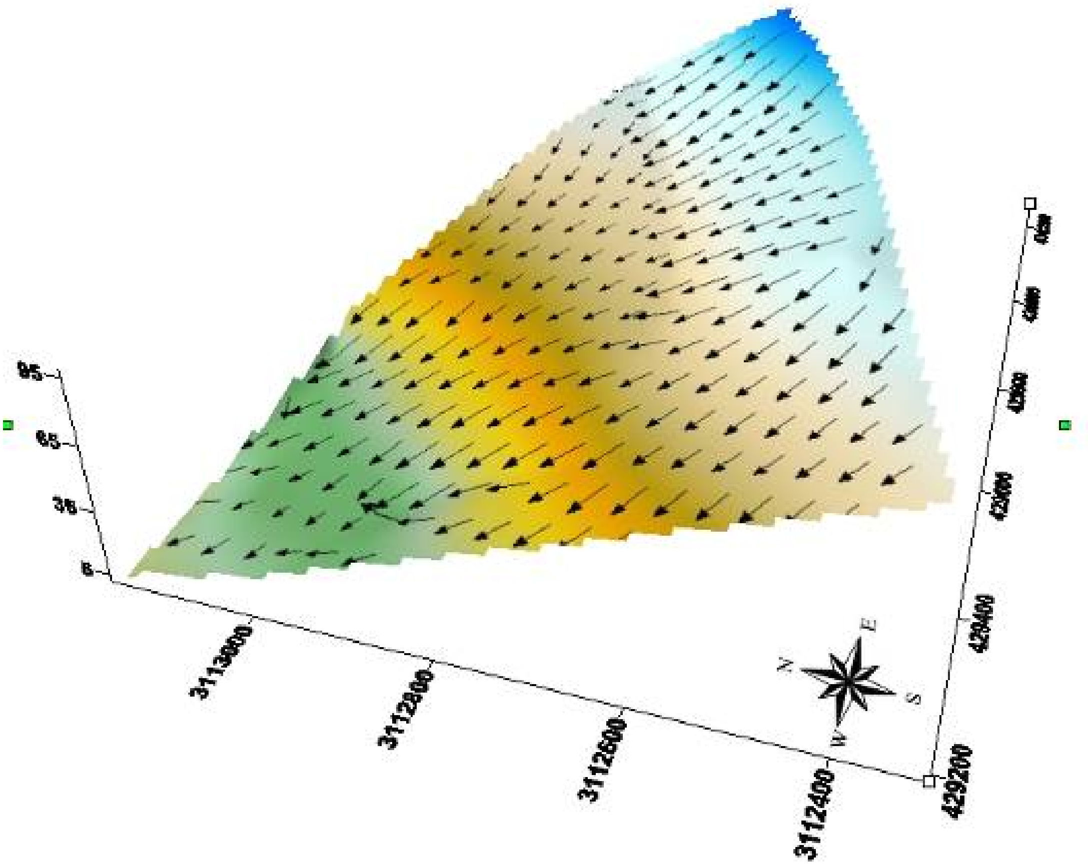

Figure 12 - Wanda glacier ice flow direction. Black arrows indicate the ice flow predominant direction, derived from the DEM.

The estimated rate of surface movement can be associated with probable basal sliding, which can be caused by significative subglacial melting processes. According to Hallet (1979), Riihimaki *et al*. (2005), and Anderson *et al*, (2006), there is a link between ice flow velocity processes and the glacial basal sliding. The small ice thickness and drainage basin area can be related with the relative slow ice flow of the glacier.

The glacier retreat rate was pronounced when Wanda glacier was a tidewater glacier and lost their anchorage point due to the retreat processes and fast front calving, as evidenced by the reconstruction of former glacier front positions during 1979 – 1988 period (Figure 4).

Volumetric data derived from the glacier DEM provided inferences of the ice flow direction and also changes in glacial dynamics. The thinning at the glacier terminus increased the slope on glacier interior portion, as seen in the Figures 9, 10 and 12. Such morphological changes were observed in some Greenland outlet glaciers by Jouguin and Moon (2008) which could produce a positive feedback, destabilizing the glacier ice front.

6. CONCLUSIONS

This study provides a comprehensive multitemporal glacier fluctuation record from 1979 to 2011. Wanda glacier underwent a decrease in area of 0.71 km² (about 31% of the 1.5 km² total surface area) over this period. This glacier inventories showed the glacier retreat pattern and provided the basis to compare rates of glacier recession with others glaciers in study area.

Maximum ice surface velocity, measured using a stake network, reached 2.2 cm d^{-1} during the period 2007–2011 and transverse profiles show the influence of the subglacial topography on the ice flow. Due to its thermal conditions, small size, a relative slow ice flow and a high retreat rate compared to the other KGI glaciers, Wanda Glacier responds rapidly to climatic variations and is relevant for environmental studies.

Multitemporal satellite imageries, topographic and GPS surveys proved to be useful techniques to monitor glacier changes. Regular continuous monitoring of the Wanda glacier is important for improving our knowledge of glacier response to climate change.

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Capítulo 7

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[RBGf] Agradecimento pela Submissão

Cleverson Guizan Silva <editor@sbgf.org.br> 2 de julho de 2012 16:30

Para: Sr Kátia Kellem da Rosa katiakellem@gmail.com

Sr Kátia Kellem da Rosa,

Agradecemos a submissão do seu manuscrito "STRATIGRAPHY OF WANDA GLACIER, KING GEORGE ISLAND, ANTARCTICA, USING GROUND-PENETRATION RADAR PROFILE" para Revista Brasileira de Geofísica. Através da interface de administração do sistema, utilizado para a submissão, será possível acompanhar o progresso do documento dentro do processo editorial.

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STRATIGRAPHY OF WANDA GLACIER, KING GEORGE ISLAND, ANTARCTICA, USING GROUND-PENETRATION RADAR PROFILE

ESTRATIGRAFIA DA GELEIRA WANDA, ILHA REI GEORGE, ANTÁRTICA, USANDO PERFIS DE RADAR DE PENETRAÇÃO NO SOLO

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Abstract

We present the results of high-frequency (100 MHz) Ground-penetrating radar (GPR) surveys carried out during the ablation season of 2011, in Wanda Glacier, King George Island, Antarctica, aimed to determine its geometry, internal structure and thermal regime. GPR data were collected along 17 longitudinal and transversal profiles in the ablation area in late January 2011. Migrated and topographically corrected radar profiles show strong internal reflectors in firn layer. Similar internal structure is observed in other glaciers in KGI. Strong scattering of radio waves are attributed to supraglacial, englacial and subglacial meltwater channels and constitutes further evidence that the ice in the ablation area of this glacier is temperate. Because of its small size (1.5 km²) and thermal conditions, Wanda Glacier responds rapidly to climatic changes and its relevant for environmental studies.
Keywords: glaciology; thermal regime, glacial dynamic.

Resumo

O trabalho apresenta resultados de dados de GPR de alta frequência (100 MHz) obtidos durante a estação de ablação de 2001, na geleira Wanda, Ilha Rei George, Antártica, com o objetivo de determinar a geometria, a estrutura interna e o regime termal. Dados de GPR foram coletados em 17 perfis longitudinais e transversais na área de ablação em janeiro de 2011. Perfis de radar topograficamente corrigidos e migrados mostram fortes refletores internos na camada de firn. Estruturas similares foram observados em outras geleiras da KGI. Fortes espalhamentos das ondas de radio são atribuídas a canais de água de degelo nas zonas subglaciais, supraglaciais, e englaciais e constituem evidências para que o gelo na zona de ablação seja temperado. Devido a sua pequena dimensão (1,5 km²) e condições termais, a geleira Wanda responde rapidamente as mudanças climáticas e isto é relevante para estudos ambientais.
Keywords: glaciologia, regime termal, dinâmica glacial.

1. INTRODUCTION

Wanda Glacier is a small (total area of about 1.56 km²), temperate land terminus glacier located in Kraków ice field, King George Island (KGI). This island is the largest of the South Shetland Islands at the northern tip of the Antarctic Peninsula (Fig. 1).

Since 2007, systematic field activities have been carried out in Wanda Glacier. More recently, the main emphasis has been on extensive investigations of glacier hydrology and dynamics. The glacier is 1.4 km long, 0.4 to 1.0 km wide and has a mean surface slope of approximately 20% to 30%. Crevasses are observed in the ablation area and subglacial conduits emerge at the glacier front.

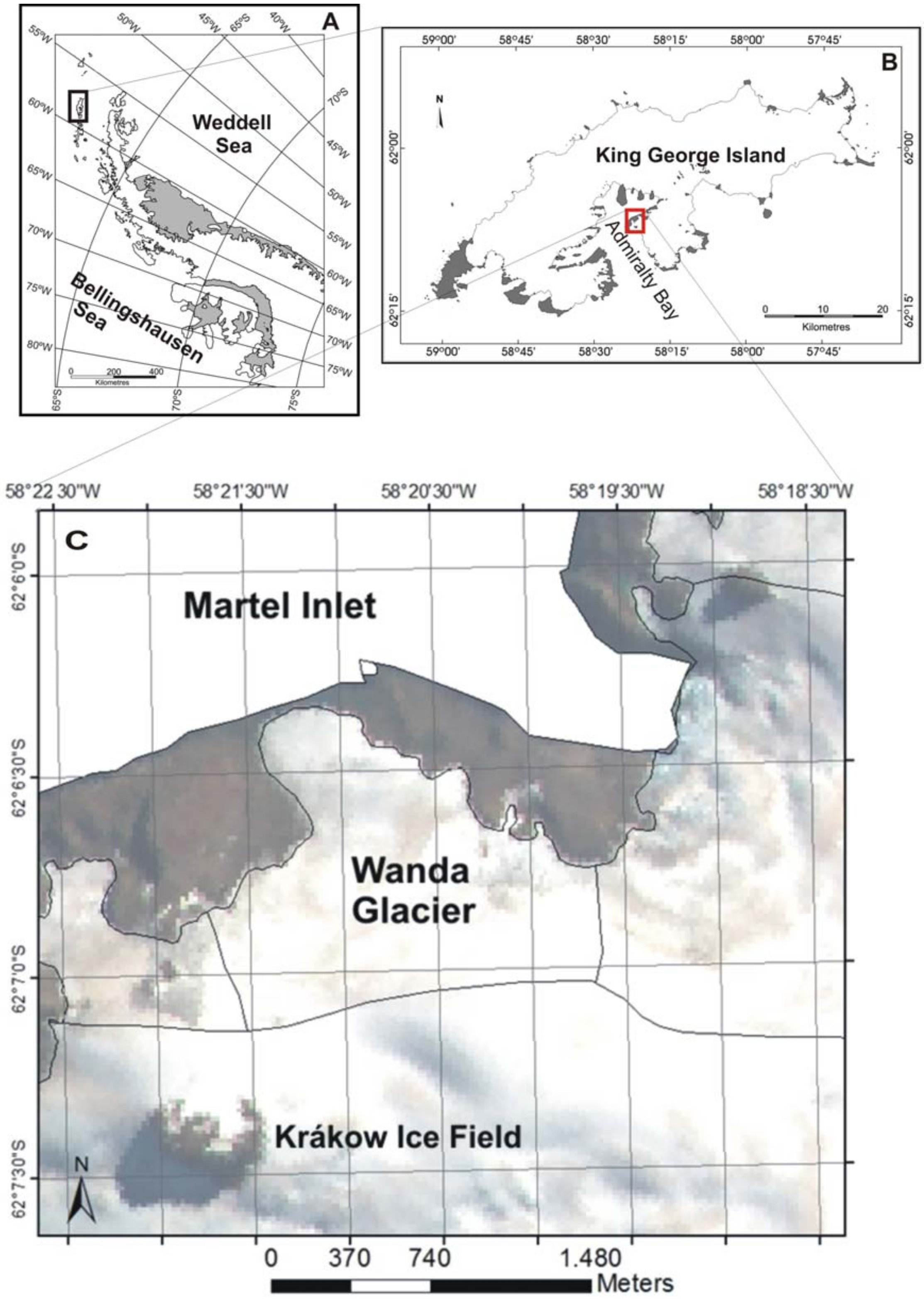

Figure 1 - Location map of Wanda Glacier: (A) Antarctica Peninsula, small square area is detailed in (B) that shows the King George Island; (C) Wanda Glacier is in the Martel Inlet, Admiralty Bay.

Several recent studies have indicated that Wanda glacier has lost 0.71 km² since 1979 (Simões and Bremer, 1995; Rosa *et al*., 2009). During the last 40 years, ice caps in King George have lost 6.6% of their area (Simões and Bremer, 1995; Simões *et al.*, 1999; Blindow *et al*., 2010). Furthermore, over the past 30 years, the number of summer days with liquid precipitation has increased and the mean annual temperature increase 3°C. These changes have accelerated the snowmelt and increased the negative mass balance of local glaciers (Braun *et al*., 2001; Ferrando *et al*., 2009).

Equilibrium line altitude (ELA) in King George Island is estimated to be between 300 and 350 m (Simões *et al*., 1999). According to Braun and Rau (2000), the firn line elevations ranged between 160 and 270 m on KGI. Over the last three decades GPR systems have been utilized to study a variety of large-scale glaciological applications as internal structure investigation (Forster *et al.*, 1991; Arcone *et al.*, 1995; Murray *et al*., 1997; Arcone et al., 2004), hydraulic pattern, crevasses detection, channels water, cavities and bedrock identification, ice mass balance and thermal conditions investigation (Kohler *et al.*, 1997; Travassos *et al*., 2004). The knowledge of internal structure and ice content is crucial for the understanding of the glacial dynamic (Patterson, 1994).

This study proposes the use of GPR data to determine the internal structure and thermal regime of the Wanda Glacier. The glaciological characterization and monitoring of glaciers in this region is important for understanding the effects of climate regional variability.

2. METHODS

The Ground-Penetrating Radar (GPR) sounding is an established technique for glaciological investigations. Because of the glacier ice low conductivity and hence its low dielectric loses, this is an ideal material for the propagation of electromagnetic waves (Plewes and Hubbard, 2001; Travassos *et al.*, 2004). The fundamental principles of GPR are described by Daniels *et al.* (1988) and Davis and Annan (1989) and detailed summaries of GPR glaciological data acquisition techniques and post-processing approaches by Daniels (1996), Plewes and Hubbard (2001), Woodward *et al*. (2003), Neal (2004), Hubbard and Glasser (2005).

Ground-penetrating radar (GPR) data were collected along 17 longitudinal and transverse profiles in the ablation area in late January 2011. Sampling was based on the continuous mode and common-off set data acquisition. We used a Geophysical Survey Systems Inc. (GSSI) SIR System control unit and a 100 MHz transceiver single (‘monostatic’) antenna. The antenna was polarized orthogonally to the transect and longitudinal directions (following the central flowline), and data were collected with a time window of 600 and 800 ns.

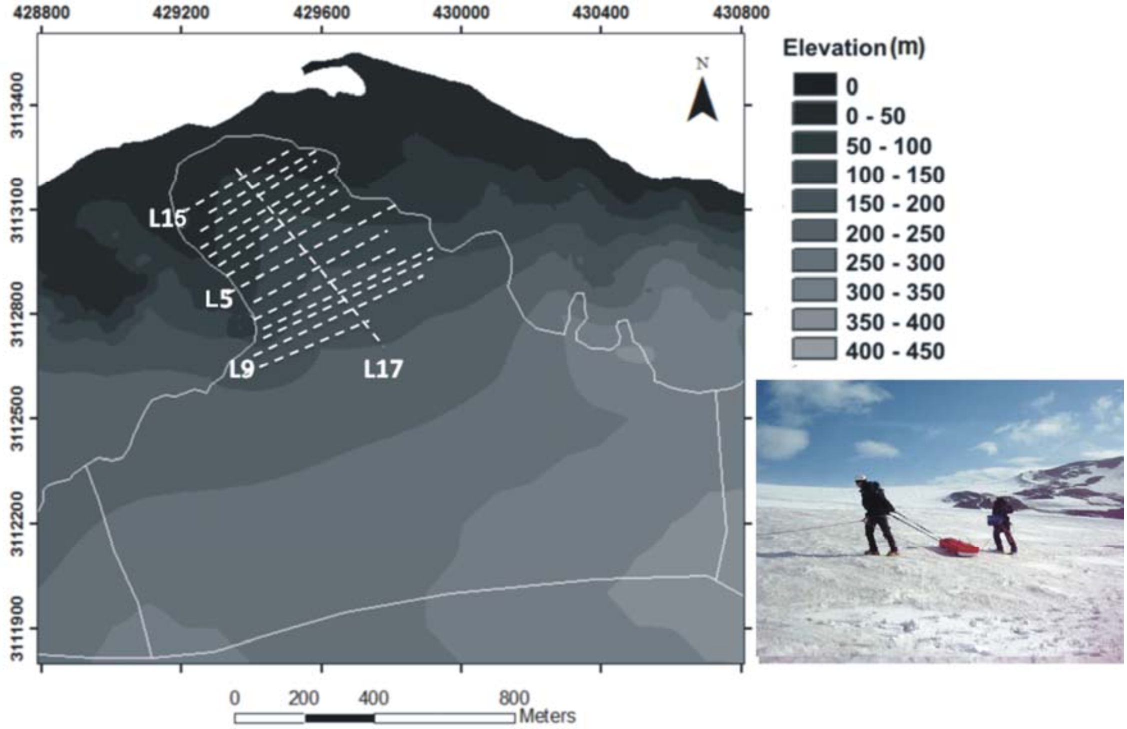

Figure 2 – Location of seventeen GPR common-off set profiles and one longitudinal profile superimposed on the study area topographic map. Profiles appear series of white equally spaced line. The four profiles L5, L9, L15, and L17 referred in this paper are highlighted in the figure. Photograph shows a GPR survey at Wanda Glacier.

GPR data were corrected with topography data and were processed using the RADANTM 6.5 software from GSSI (Geophysical Survey Systems, Inc.). Range gain was used to compensate for progressive radar-signal strength attenuation, and a filtered to remove noise.

Position correction was applied to remove depth distortions of the reflection profiles upper parts and to create zero-offset traces. According to Fisher et al. (1996) time-zero must be move up the trace to the point at which the initial pulse is generated at the transmitting antenna. Distance and surface normalization for time was performed using topographic profiles from total station and differential GPS data. Glacier profiles were migrated to collapse diffraction hyperbolas and to correct the orientation of steep dipping layers.

One radar section (15) was processed using a gain function exponential and filter band pass and migrated, using the REFLEX software, with several parameters of the scattering hyperbolae migration velocity for analysis of the vertical velocity distribution. Radar wave velocity propagation in glaciers is highly sensitive to the presence of liquid water because of the large velocity contrast between ice (0.168 mn s^{-1}) and water (0.032 mn s^{-1}). According to Bradford and Harper (2005), this strong sensitivity allows us to estimate the relative water proportions along a cross-section of the glacier. The thermal conditions of the glacier were inferred based on this analysis. The possibility of detecting thermal regimes within glaciers by means of radar surveys has been established by several studies (Watts and England, 1976; Jacobel and Anderson, 1987; Bamber, 1988).

3. RESULTS

We concentrate our discussion on 4 profiles that illustrate the most important features of our data set. The longitudinal and transverse GPR data present strong continuous horizontal upper reflectors (HR), these indicate direct air waves and direct groundwaves, and a water table from supraglacial melting processes (Fig 3-6). There are strong localized (point) reflectors (Fig. 3-6) in the terminus area, possibly representing water filled crevasses. Surface crevasses were observed during field activities.

Characteristics of the internal reflections found in the profiles (Fig. 3-6) reveals information about englacial ice. Below the HR there are several isochronous ice layers (Fig. 3). Stronger reflections associated to water in the bed interface correspond to a low velocity zone in the Fig. 7. Scattering noise zones in the ice body (Fig. 3 to 7) are attributed to water inclusions, such as water lenses or water channels crossed by the radar profiles. A strong reflection marks a water table at an average depth of 35 m, which indicates the firn-ice boundary (Fig. 6). But a strong reflection due to a supraglacial stream obscures the firn-ice transition in parts of the profile (Fig. 5).

Continuous sub horizontal and steep dipping reflectors in the profiles lower zone (Fig. 3-6) are evidences for a film at the ice-bed interface. Semi continuous dowlappping reflections at the bottom of the radargram can be caused by (Fig. 3) ice-bedrock interface with unfrozen sediments content. Bedrock reflections are interrupted by strongly diffractive parts, masking the bedrock in the profiles, and showing an U-shaped valley form.

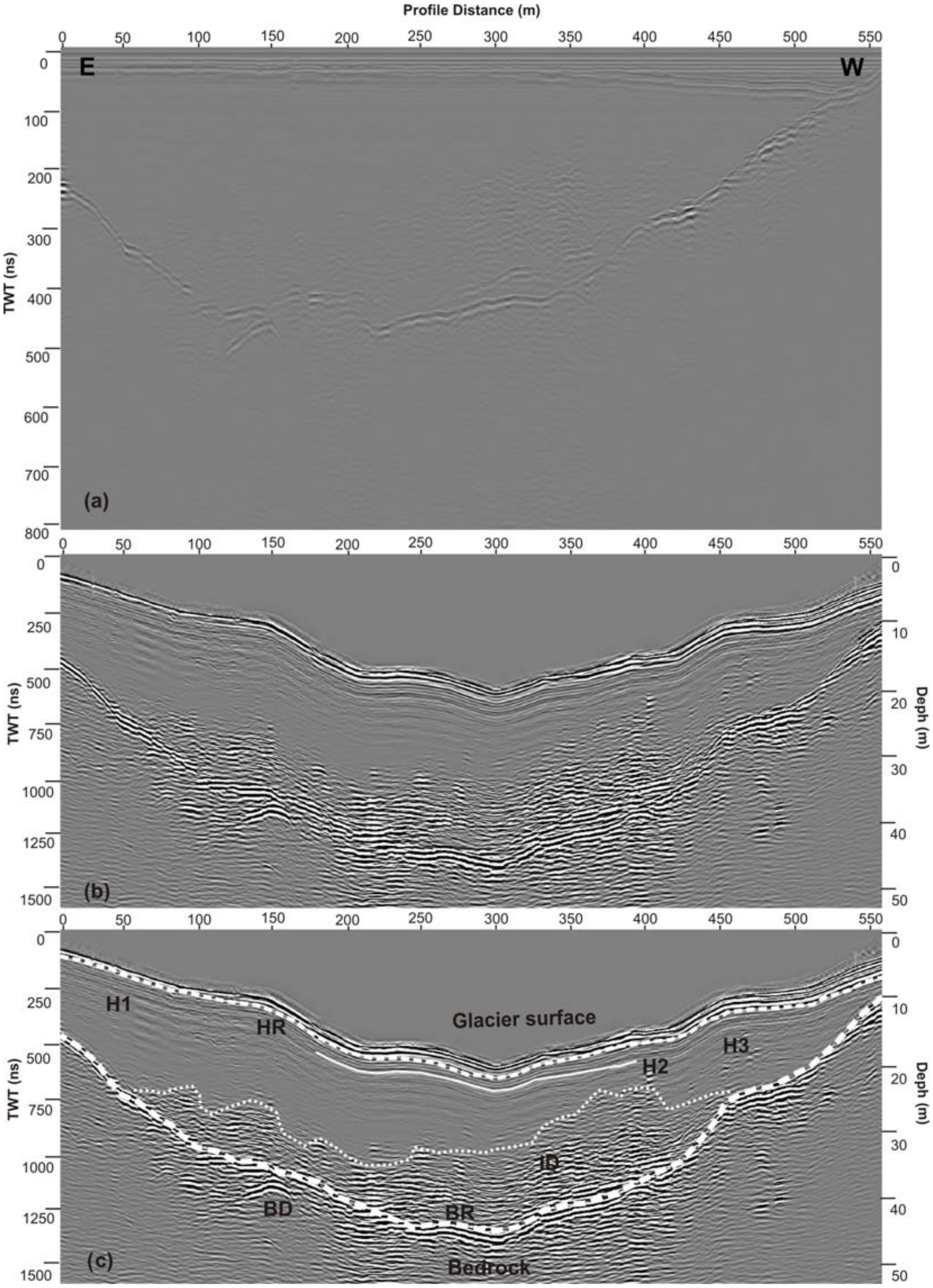

Figure 3 – Profile line 15. (a) No processed profile. (b) Topography-corrected and migrated radargram. (c) Interpreted radargram. This transverse GPR profile crossed the Wanda Glacier from E to W and is located near the glacier terminus. Location of the profile line is showed in Figure 2. The upper strong continuous horizontal reflectors (HR) are indicators of two air waves and one groundwave, and a water table. The high supraglacial water content, indicated by horizontal reflectors near surface, increases towards the thinner margins. Below HR there is a distinct reflector interpreted as interbedded ice with strong localized point reflectors (englacial water voids). There is a zone of chaotic returns above a cleary defined bed reflection. High water content in the englacial zone is indicated by abundant diffractions (ID). Semi continuous steep dipping reflectors and point difractions a bed zone are present and reveal water table and debris rich layer in the ice-bed interface. The profile provides a cross-sectional view of the strong, quasi-continuous dipping reflection that appears concave-upward, with maximum depths of 25 m. Interpretation classes: HR = horizontal reflections, H = diffraction hyperbolae, BR = bed reflections, ID =diffraction within the Ice and BD = bed diffractions.

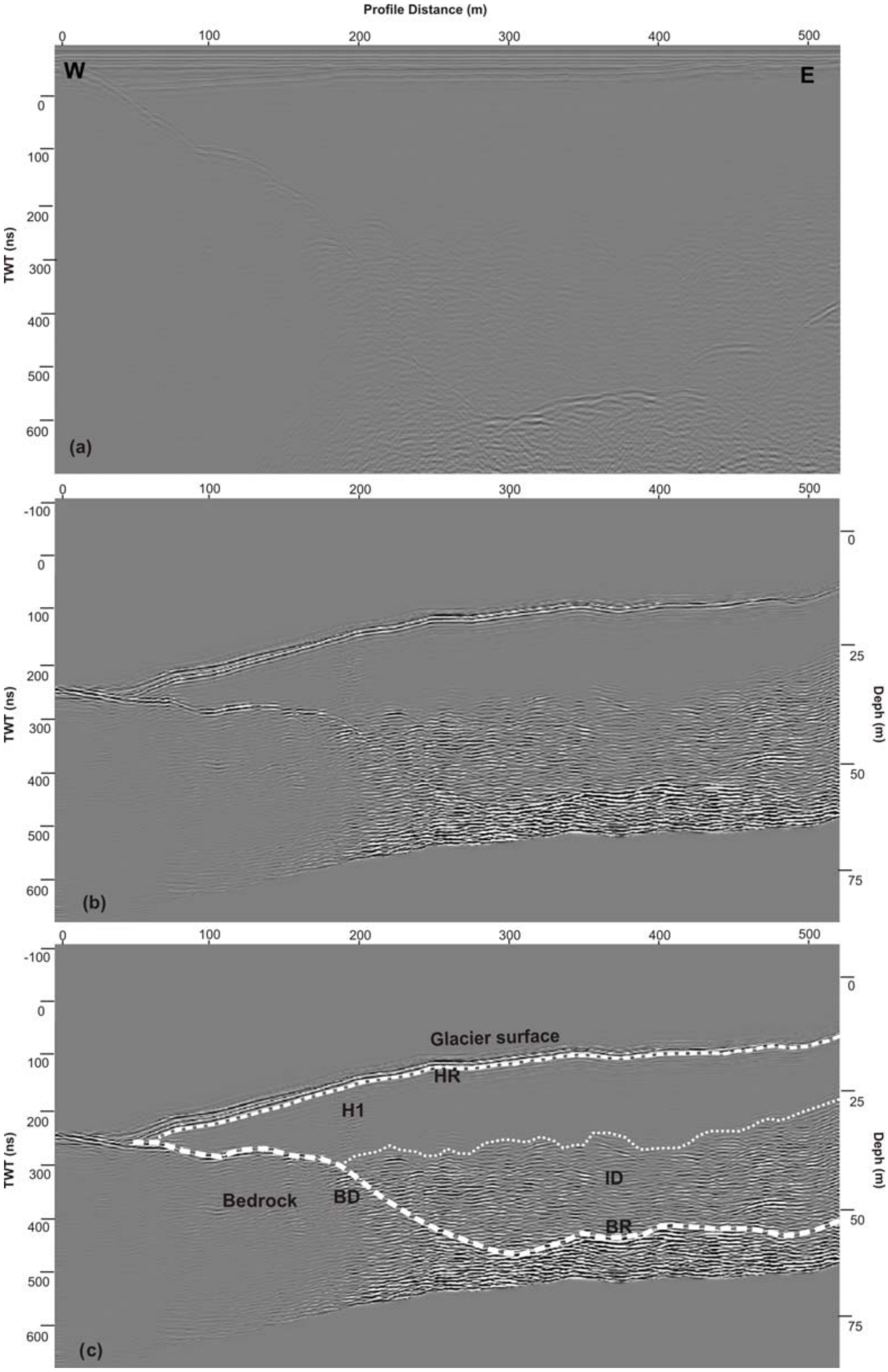

Figure 4 – Profile line 5. (a) No processed profile. (b) Topography-corrected and migrated radargram. (c) Interpreted radargram. This transversal GPR profile crossed the Wanda Glacier from W to E along 500 meters. Profile line location is showed in Fig. 2. Noise near the surface is a strong evidence for water storage from supraglacial streams. A low reflectivity zone (below noise near the surface) can be related with a macroscopic change in permitivity. Abundant diffractions within ice (ID) denote liquid-water in subglacial environment. Dielectrically dissimilar interfaces within heterogeneous basal ice thereby generate chaotic, noisy returns. Below this layer there are sub-horizontal dowlappping reflectors with continuity that provided evidence for water table in the bed-ice interface. A cluster of bed diffractions can be observed in the central part of the radar profile and is an indicator of water and no-frozen sediments filled channels. The average ice thickness is 40 meters.

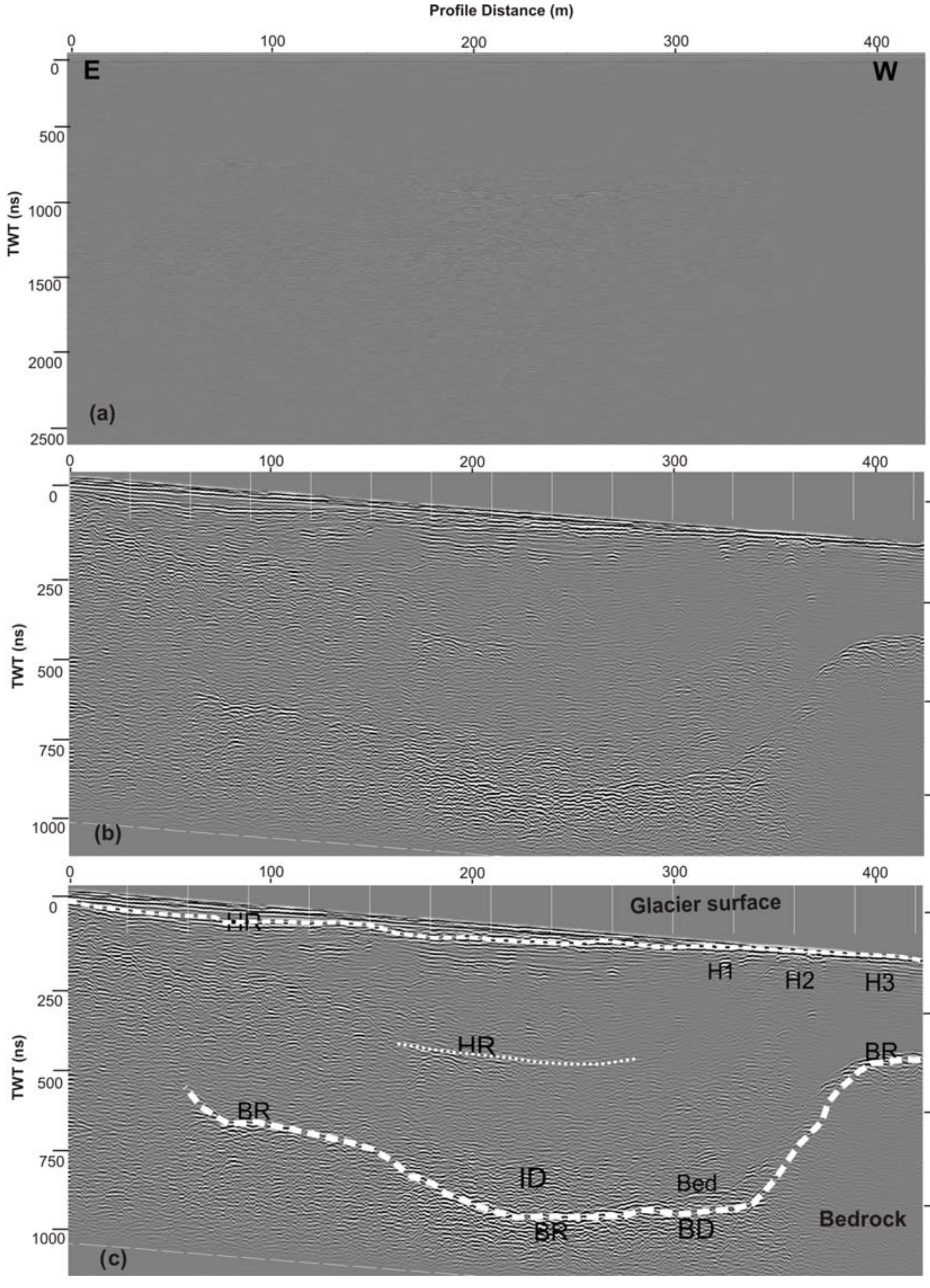

Figure 5 – Profile line 9. (a) No processed profile. (b) Topography-corrected and migrated radargram. (c) Interpreted radargram. This GPR profile transverse crossed the Wanda Glacier from E to W. Strong surface and bed semi-continuous reflections are evidences for supraglacial and liquid-water percolation. Localized point-source reflector (ID) point to water filled channels in the englacial zone. No continuous bed reflectors can be an evidence for a firn-ice boundary at 35 m depth in the central section. However, this interface is obscured in many sectors due strong scattering noise in the ice body. Liquid water inclusions also partly obscure bed set horizons reflectors. Dipping slopes of the glacier bed reveal the U-shaped valley topography.

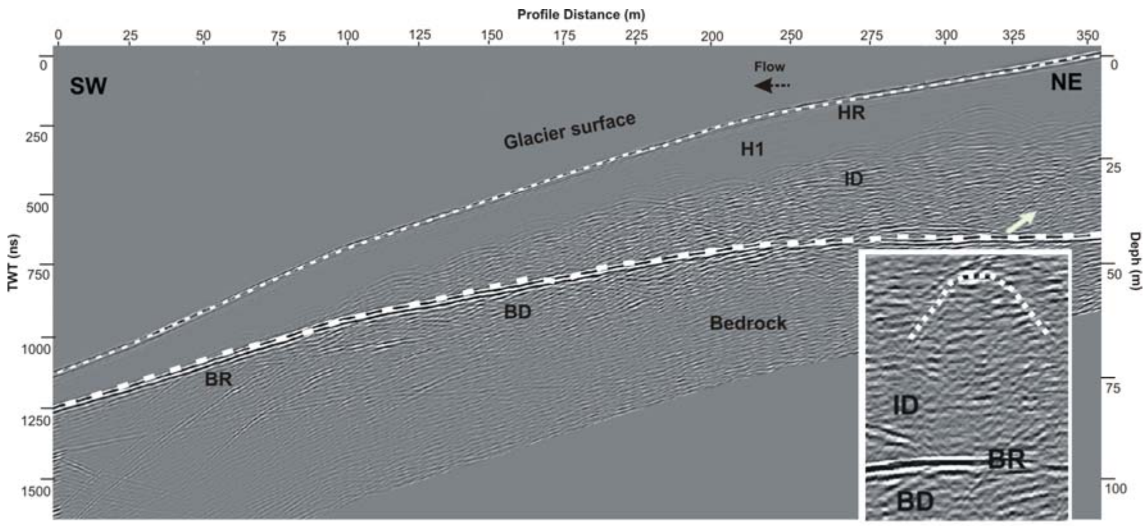

Figure 6 – Profile line 17. (a) This interpreted topography-corrected longitudinal radargram is 360 meters long and is located in the central flowline (SW-NE) (Fig. 2). The minimum and maximum ice thickness are about 5 and 35 meters, respectively. Water contact with basal ice is evidenced by strong continuous reflections. The inset shows part of the unmigrated cross-section and presents a hyperbole that is a indicator of the glacial drainage. Stronger sub-horizontal reflector showed in the first part of this profile may indicate a liquid water percolating the ice-bed interface towards the glacier terminus. There are dense chaotic returns within the ice body. Excessive diffractions near subglacial zone, toward the end of this profile, show more no-frozen sediments and water filled channels interconnected with crevasses. The longitudinal profile shows an up-valley dipping reflection at the ice-bed interface as evidence from bedrock topography. Similar reflections are observed in the transverse profile at this site. This no-migrated profile can portray a distorted image of subsurface stratigraphy.

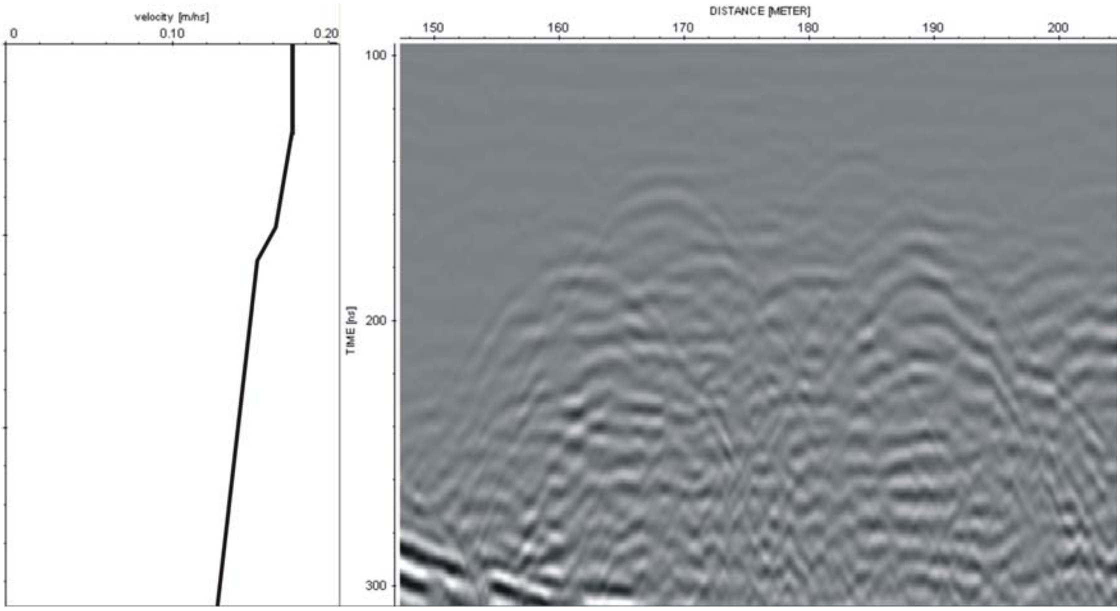

Figure 7 – Part of an unmigrated cross-section (profile 15) shows hyperbolic returns created by point-source reflector at the apex of the curve, and a vertically variable velocity structure with high water content above the bed.

4. DISCUSSION

The surveyed profiles strongly suggest the presence of englacial conduits in Wanda Glacier. Water inclusions are seen in the nonmigrated GPR profiles as small hyperbolic diffraction features. The migration to aligned the traces with surface location and collapse any possible interfering diffractions. According to Moorman and Michel (2000), the relative transparency of ice improves the detection of englacial tunnels.

Strong horizon reflections due the presence of a water table are found in the near-surface GPR data. Blindow and Thyssen (1986) also credited a similar boundary between radar scattering/non-scattering layers in a temperate Austrian glacier to a water table. According to McGee *et al*. (2003), a water table may be present within macro scale voids that have some hydraulic connection to the bed. There are numerous crevasses in Wanda Glacier, and these are probably important pathways for the surface melting water.

Continuous internal reflectors and diffractions (high backscatter) in englacial and subglacial environments constitute further evidence for temperate ice. The glacier water content shows a vertically variable velocity structure (Fig. 7), with a lower layer with relatively high water content. We used the water content to provide information about the thermal structure of the glacier. Point scattering within the body of a temperate glacier, typically from macro-scale water bodies, is common (Watts and England, 1976; Jacobel and Anderson, 1987). According to Jacobel and Raymond (1984), water bodies in temperate ice are regions with the strongest dielectric contrast because of the large relative permittivity difference between ice and water at radar frequencies. Based on the diffraction hyperbolas polarity, hyperboles near the profiles bed is interpreted as water-filled conduits, high water content toward the lower part of the profile points to wet ice conditions.

Deeper profile firn-ice interface reflections with sub-horizontal layering. The firn-ice transition is also consistent with GPR data from other KGI surveys by Travassos and Simões (2004); Rückamp *et al*. (2010) and Blindow *et al*. (2010).

According to Navarroa *et al.* (2005), high frequency radars offer a resolution that allows a detailed analysis of the upper glacier surface, allowing a better identification of the firn-ice transition, but this depends on the ice thermal characteristics. Snow and firn layering within the ice we obscured in profiles because the strong surface scattering resulting from the highly inhomogeneous Wanda Glacier ice. According to Arcone (2002), in temperate glaciers the profiles shows much scattering due to englacial water bodies.

Profiles bed reflections point out to a subglacial topography with smooth slopes. Ice thickness estimation is provided by migrated and topographically corrected profiles, assuming a relative dielectric constant for ice of 3±4 (Moorman and Michel 2000), corresponding to a 0.168 m ns^{-1} average velocity as proposed by studies of Blindow *et al*. (2010). However, the heavy electromagnetic waves scattering, due to temperate ice inhomogeneities can cause errors in this estimative. The up-turned asymptotes and loss of coherent reflections, found in the profiles (Fig. 7), are typical of a low velocity (water) surface, Arcone *et al*. (1995) identified similar patterns.

High-frequency (100 MHz) GPR used in this work is considered an appropriate tool for the study of temperate glaciers. However, strong scattering caused by water inclusion at this frequency can obscure firn-ice transition and the detection of bedrock reflections.

5. CONCLUSIONS

We used GPR reflections to determine the internal structure and thermal regime of the Wanda Glacier. Migrated and topographically corrected transverse radar profiles show strong internal reflectors typical of firn layers. Similar internal structures are observed in other glaciers in KGI. Strong radio waves scattering is attributed to supraglacial, englacial and subglacial meltwater channels. The bed and englacial wet condition were evidenced by radio waves and reveal continuous internal reflectors and diffractions, further evidences for temperate ice in the Wanda Glacier ablation area. Because of its small size (1.5 km²) and thermal conditions, Wanda Glacier responds rapidly to climatic changes and it's relevant for environmental studies.

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Capítulo 8

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MELTWATER DRAINAGE AND SEDIMENT TRANSPORT IN A SMALL GLACIARIZED BASIN, WANDA GLACIER, KING GEORGE ISLAND, ANTARCTICA

DRENAGEM DA ÁGUA DE DEGELO E TRANSPORTE SEDIMENTAR EM UMA PEQUENA BACIA GLACIARIZADA, GELEIRA WANDA, ILHA REI GEORGE, ANTÁRTICA

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Abstract. Basal sediment transport by efficient subglacial drainage system is widely assumed to dominate the sediment budget of most temperate glaciers in glacimarine environments. Hydrological characteristics of the drainage system and mechanisms of basal sediment transport in Wanda Glacier, King George Island, were examined by the analyses of temporal variations of discharge and sediment load in the proglacial channels. In the investigation about the variability of sediment load transfer to Admiralty Bay we analyzed the control of the drainage system, thermal conditions, ice flow velocity, topography and meteorological conditions in the period. Data collected in January 2010 and 2011 show the control of the subglacial drainage configuration on rates of basal sediment evacuation and delivery by subglacial meltwater to glacimarine environment. Thus, data show strong relation between suspended sediment load, water discharge and air temperature, radiation and precipitation rate. High sediment concentrations recorded in proglacial channels are related to efficient rates of basal sediment transport, thus, indicate sediment yield availability to Martel Inlet glacimarine environment. Direct measurements of sediment in proglacial channels allowed estimating of the actual sedimentary contribution of 19.4x 10^{-3} kg s^{-1} to the glacimarine environment. Sediment load is an indicator of erosion and sediment yield processes beneath the glacier. These processes are interconnected with high summer temperature presented, responsible for the relatively high rates of meltwater production and sediment supply to glacimarine environment and with consequences for the sediment dynamics of the study area.

Keywords: subglacial hydrology; sediment evacuation; suspended sediment; climate variability.

Resumo. O transporte de sedimentos subglaciais por uma eficiente rede de drenagem subglacial é amplamente considerado como a forma dominante de descarga sedimentar na maioria das geleiras temperadas em ambientes glacimarinhos. Características hidrológicas do sistema de drenagem e mecanismos de transporte de sedimentos basais na geleira Wanda, ilha Rei George, foram examinados por meio de análises das flutuações temporais da descarga de água de degelo e sedimentos em canais proglaciais. Foram realizados inter-relações entre o sistema de drenagem, as condições termais, a velocidade de fluxo de gelo, a topografia e as condições meteorológicas no período observado. Dados coletado em janeiro de 2010 e 2011 demonstram o forte controle da configuração dos sistemas de drenagem no grau de remoção sedimentar e transferência para o ambiente glacimarinho. Desta forma, resultados indicaram uma forte relação entre a carga de sedimentos em suspensão, descarga de água d e degelo, temperatura do ar, radiação solar e precipitação. Altas concentrações sedimentares registradas em canais proglaciais estão relacionadas ao eficiente grau de transporte sedimentar, e indica, assim, a produção sedimentar disponibilizada ao ambiente glacimarinho da enseada Martel. Medidas da concentração de sedimentos em suspensão em canais proglaciais permitiram estimar a atual produção sedimentar de 19,4x 10^{-3} kg s^{-1} pela geleira Wanda. A carga de sedimentos em suspensão é um indicador de processos de erosão e produção sedimentar na zona subglacial da geleira Wanda. Estes processos estão conectados com as altas temperaturas no verão apresentadas, responsáveis por relativos altos graus de produção de água de degelo e suprimento sedimentar para o ambiente glacimarinho e com consequências para a dinâmica sedimentar na área de estudo.

Palavras chaves: hidrologia sublgacial; remoção sedimentar; sedimento em suspensão; variabilidade climática.

1- Introduction

Meltwater is an important component of subglacial erosion and yield sediment in wet bed glaciers (Sugden & John 1976, Swift et al. 2005, Eyles 2006). These glaciers produce efficient debris transport by abrasion, quarrying and fragmentation processes (Drewry 1986, Swift et al. 2005). Subglacial meltwater runoff in temperate glaciers results from geothermal and friction heat, rainfall and flush-out of storage water (Boulton 1974). Meltwater runoff may also enter glacial drainage systems by supraglacial meltwater, ice and snow, acessing the glacier bed through crevasses and moulins (Benn & Evans 2010).

Hydraulic erosion enhances sediment transport, and is related to the balance between the water flow capacity and competence (according to basal sliding, subglacial drainage configuration and development) and nature of sediment and its availability (Alley et al. 2003). Topographic gradients may influence this process (Shreve 1972, Paterson 1994, Swift 2006).

The pattern of a subglacial hydraulic system is controlled, in part, by runoff meltwater. Drainage system development is controlled by: (a) ice mass type, morphology and topography, (b) thermal conditions, (c) ice mass balance, (d) ice flow velocity, (e) basal conditions and (f) amount of debris transported (Menzies 1995).

Seasonal changes and canalized drainage variations may increase erosion capacity and contribute to glacial sediment yield variability. Subglacial conduits tend to form or enlarge near the terminus in the spring and early summer and extend further upglacier as the melting season proceeds (Nienow et al. 1998, Anderson et al. 2004). Abrupt discharge increases during summer, along short time-periods such as days or hours are important for erosion and sediment discharge (Drewry 1986). The evacuation efficiency is greater in the ablation area where the streams reach their maximum extension (Swift 2006). Runoff tends to be minimum in winter due to the collapse of channels formed in previous ablation (Hubbard & Glasser 2005). Thus, seasonal changes in the glacier sediment transport system are strongly controlled by the evolution of this subglacial drainage system (Nienow et al. 1998).

Several researches have focused on Alpine and Arctic glaciers, but subpolar glaciers hydrology in the Antarctic Peninsula region have received little attention. These glaciers represent a powerful source for hydrological studies due to their temperate influence on the hydrological processes.

This work presents an investigation on the mechanisms of basal sediment evacuation in Wanda glacier King George Island, South Shetland Islands, Antarctica (Figures 1 and 2), and specifically determines its suspended sediment contribution to the Martel Inlet glacimarine environment. This study integrates geomorphological, hydrological, glaciological and meteorological aspects that affect suspended sediment transport and yield. The interpretation of the transport processes may contribute to our understanding about temperate glaciers in maritime and sub-Antarctica region.

In the investigation about the variability of sediment load transfer to Admiralty Bay, were also analyzed the drainage system control, thermal conditions, ice flow velocity, topography and meteorological conditions.

2. Study area

Wanda glacier (Figure 1) is characterized by its proglacial front and a proglacial lagoon. The glacier comprises 1.56 km² (based in a QUICKBIRD image obtained in 2006), has a thin glacier front (4 meters thick maximum). In the ablation areas, crevasses observed on glacier surface are connected to subglacial conduits where meltwater flow penetrates downward to the subglacial zone. Subglacial conduits emerge at the front of the glacier (Figure 5) and fine sediments are transported towards Martel Inlet through a proglacial lagoon (Rosa et al. 2009).

Several studies have provided evidence for a general glacial retreat in the Martel Inlet since 1950 (Simões & Bremer 1995, Park et al. 1998, Bremer 1998, Simões et al. 1999, Aquino 1999, Braun & Gossmann 2002, Vieira et al. 2005, Rosa et al. 2009). The retreat processes of those glaciers can be related to the present regional atmospheric warming recorded (Blindow et al. 2010). For the past 30 years, the number of days with liquid precipitation has increased in the summer. These processes accelerated the snowmelt and increased the negative mass balance of local glaciers (Braun et al. 2001; Ferrando et al. 2009).

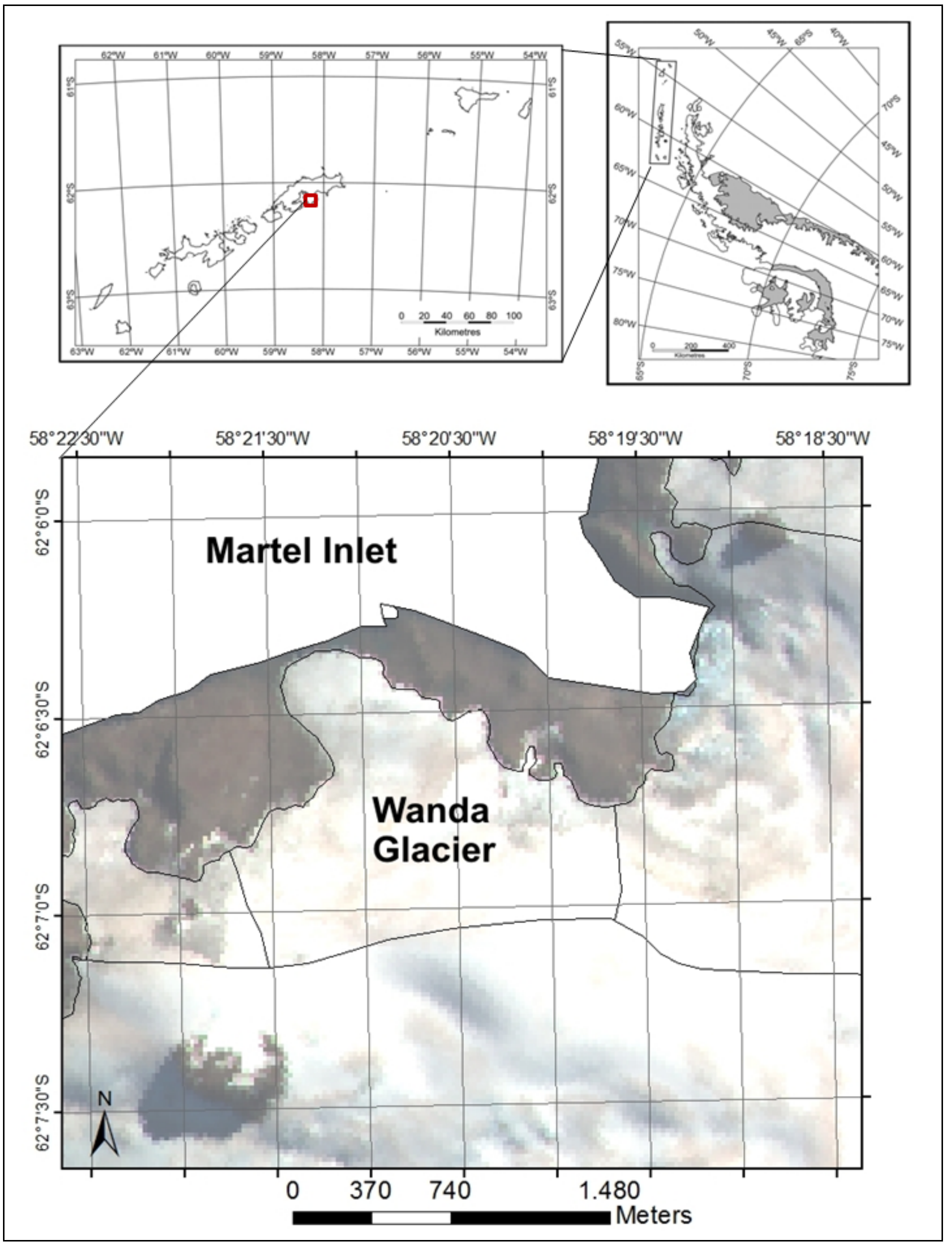

Figure 1 - Location map of Wanda glacier, Admiralty Bay, King George Island, South Shetland Islands (based on SPOT image obtained in 2000).

Wanda glacier retreat may increase sediment supply and also result in a high runoff by developing proglacial streams. Proglacial meltwater streams transport significant amounts of sediments, mainly during the summer season which may contribute for sedimentation processes in Admiralty Bay.

3. Data sources and methods

Monitoring of sediment transport from subglacial drainage system of Wanda glacier was carried out in January 2010 and February 2011 to characterize the efficiency of sediment evacuation and to investigate the subglacial drainage configurations. Time-series of daily discharge and sediment load in proglacial streams were used to explore the relationship between discharge, sediment load, and glacial drainage systems within the glacier. The observed variability was related to meteorological conditions (radiation, precipitation and air temperature) in the period (the database was updated using the continuous meteorological record from the Brazilian Antarctic Station - *Estação*

Antártica Comandante Ferraz, EACF, 62°05'S, 58°23.5'W.
Meteorological stations maintained by the Brazilian *Instituto Nacional de Pesquisas Espaciais* (INPE), and their data are available at the following Internet address: ''http://www.met.inpe.brhtmldoc/antarctica).

Figure 2 - Wanda Glacier, viewed from Admiralty Bay, KGI in the summer of 2011.

Hydrological characteristics of englacial and subglacial drainage systems in Wanda Glacier were examined by analyzing temporal variations of discharge and sediment load in the proglacial streams.

Proglacial streams daily discharge (Q) was estimated by multiplying the cross-sectional area (A) with water flow velocity (Vm) (Q= A.Vm) according to Santos et al. (2001), Collischon (2005) and Correa (2006). In order to estimate the partial discharge value of each section (Figure 3), the area of influence was calculated accordingly to Formula 1.

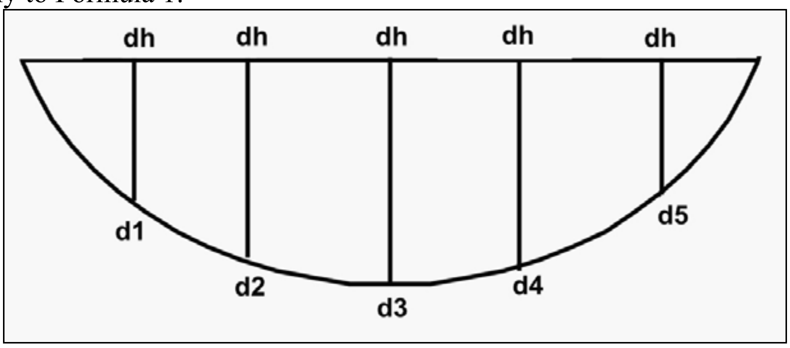

Figure 3 – Cross sections channel measurements for partial discharge estimative.
Fórmule (1)

$$A_i = \left(\frac{d_1 + d_2}{2}\right).dh + \left(\frac{d_2 + d_3}{2}\right).dh$$

The partial discharge of each section was estimated by multiplying the water flow velocity by its influence area. The water sample is collected in the field and filtered to extract suspended matter. The filtered material is then dried, weighed and divided by the sample volume to obtain SSC concentration (mg/L). The total sediment load transported in proglacial streams was quantified by multiplying total discharge by the sediment load in January - February in 2010 and 2011. This methodology aims to investigate runoff processes in the proglacial streams and suspended sediment supply variability for Martel Inlet. According to Rubin and Topping (2001) and Morehead et al. (2003), the sediment load in proglacial streams will predict correctly the sediment bulk transported by glaciers if the sediment transport is regulated only by meltwater discharge.

The SSC temporal variability was used to infer glacial ablation processes, considering that the meltwater is sensitive to those processes. Sediment supply is an important proxy for erosion action related to subglacial thermal conditions (Ritchie & Schiebe, 1986). According to Benn & Evans (2010), ice temperature controls several glacial processes, including glacier motion, meltwater flow, and subglacial erosion and deposition.

4. Results

Hydrological characteristics examined by analyzing temporal variations of suspended sediment and discharge in the proglacial meltwater channels (Figure 4) of Wanda Glacier in January 2011, are related by fluctuations of air temperature, radiation and precipitation rates (Figure 5).

Each curve gradient reflects the relationship with sediment transport capacities, which are related linearly with discharge, mainly during early ablation season, as there are more sediments avaliable to evacuation processes.

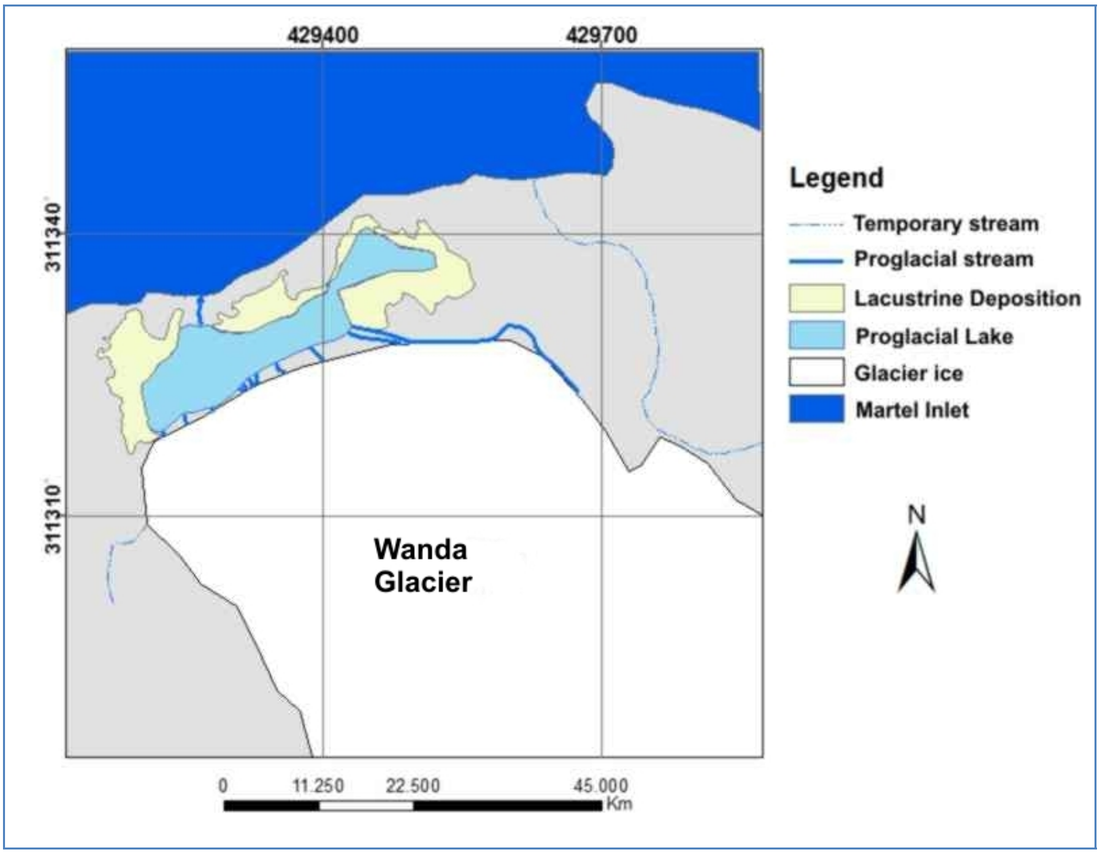

Figura 4 - Localization map of the Wanda glacier proglacial channels.

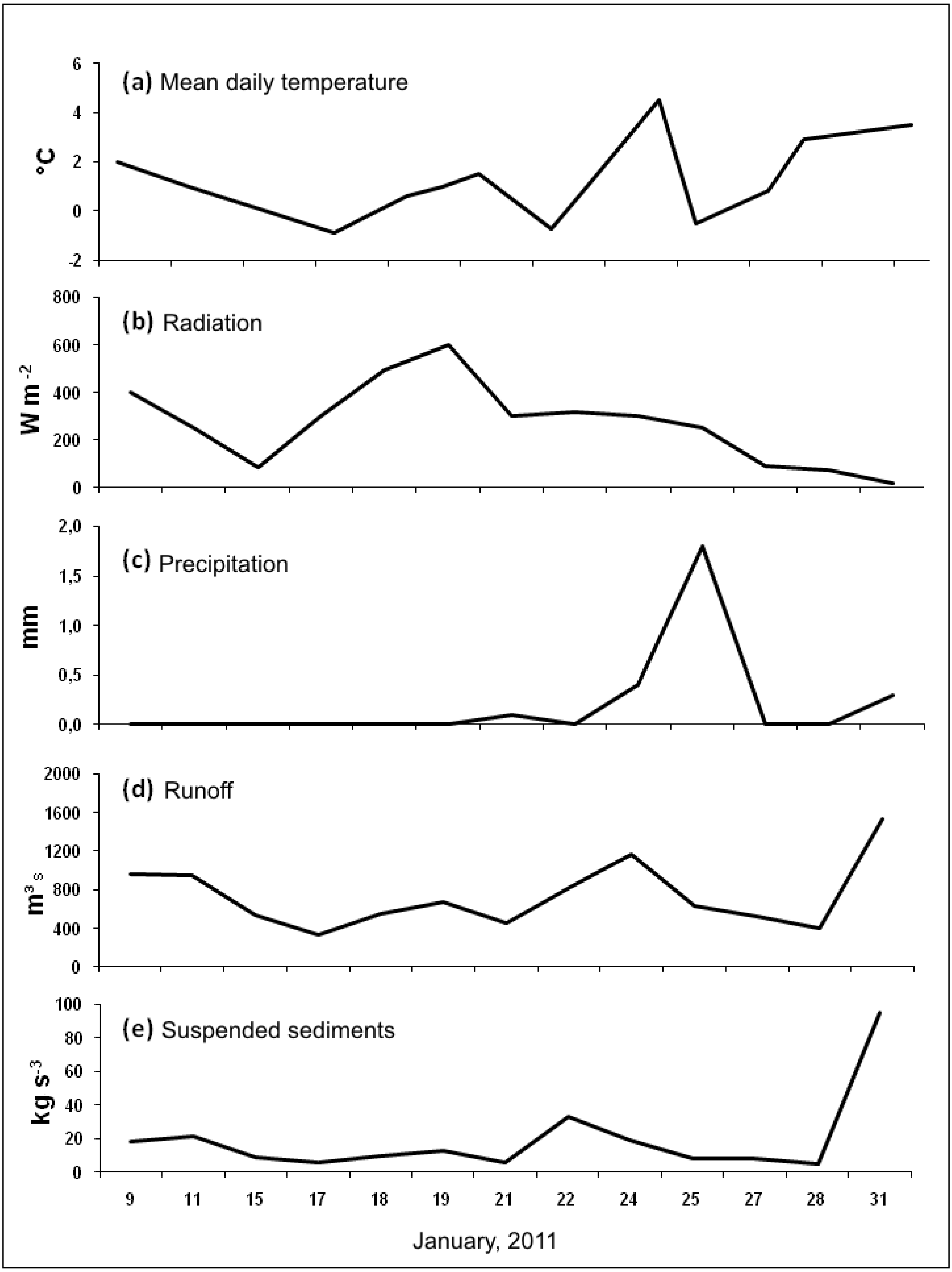

Figure 5 – Relationship between temporal variations of air temperature (a), radiation (b) and precipitation rate (c), runoff (d) and suspended sediment loads (e) at site in January, 2011.

There are considerable temporal changes in proglacial suspended sediments due to high variability of the local meteorological conditions in the studied period. Low discharges are associated with low temperatures, lower snowfall, and little radiation in early morning, when the channels can still be occluded. Higher values of surface air temperature and solar radiation induce a high meltwater and sediments supply to the glacimarine environment. Days with high SSC are related to consecutive periods of rainfall and positive air temperatures. Rainfall induces occasional runoff peaks. According to Benn & Evans (2010), the highest weather-related discharges tend to be associated to high rainfall during summer storms and runoff in the basin, and therefore contributes to snow and ice melting.

The increase in the correlation between runoff and incident radiation, probably reflects the removal of the ablation area snowpack. Relatively poor correlation between runoff and meteorological variables during some days probably reflects a more complex relationship between meteorological variations and meltwater generation during periods of high precipitation. Since incident radiation generally outleads air temperature by a couple of hours, this may have contributed to the decline in lag between runoff and meteorological variables.

Discharge fluctuations during the studied period have an impact on the morphology of the proglacial channels cross section (Figure 6) and on development of proglacial multiple channels at glacier front. Thus, it has hydrological implications for geomorphologic studies in the area.

Analysis of proglacial streams flow records (Figure 7), near the ablation area of Wanda Glacier, during two consecutive years in the same month (January) shown an increase in SSC and an enlargement of the cross section channel, which reflects an increase in meltwater processes.

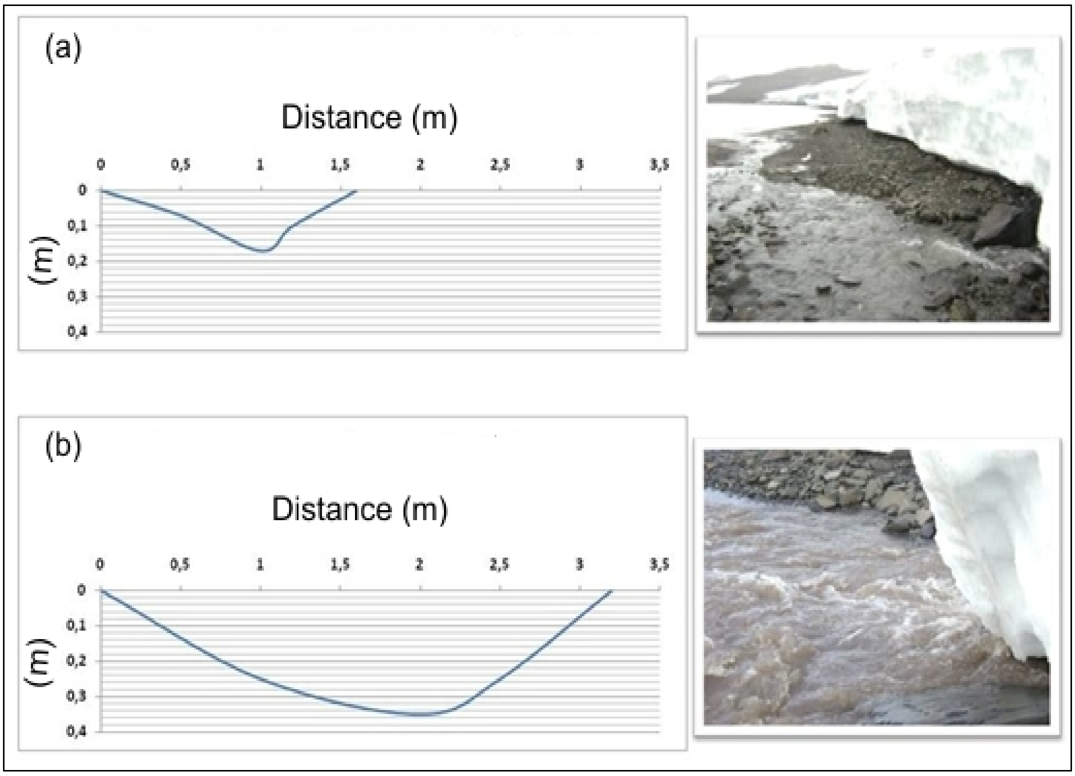

Figure 6 - Fluctuations of the channel cross section morphology due peaks in proglacial discharge.

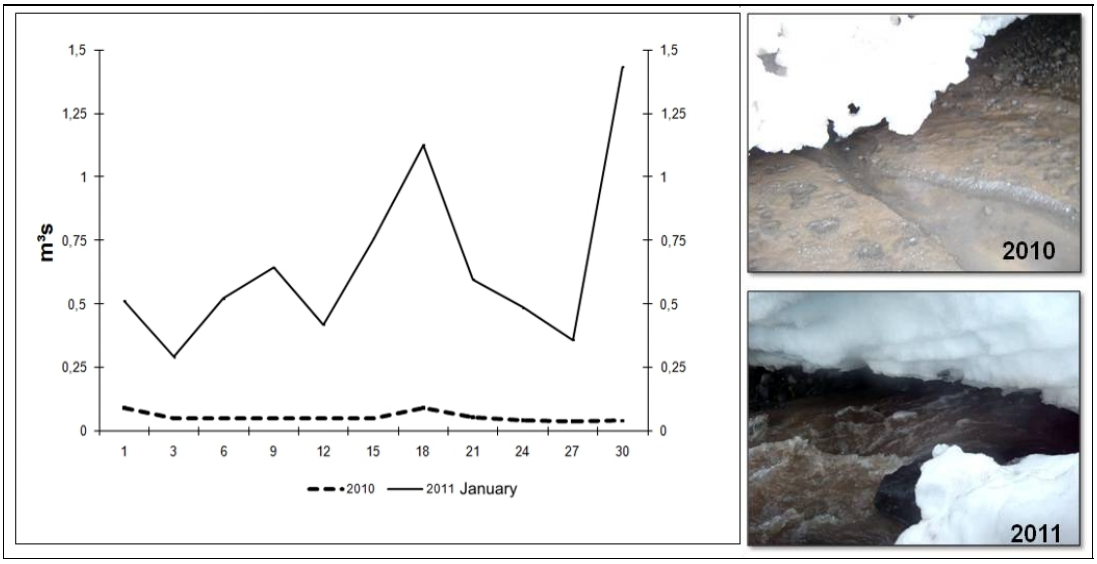

Figure 7 - Increase of discharge in proglacial channels when comparing January 2010 and 2011.

5. Discussion

We demonstrate a correlation between the hydrological and sedimentological processes in proglacial area of the Wanda Glacier. Results provide conditions for interpretations about the configuration of the meltwater drainage system and basal sediment transport rate in study area.

We assume that glacial meltwater is the main water component in proglacial streams throughout the melting season. Other possible sources of water include proglacial snowmelt in the melting season and rainfall. Observations show that subglacial zone cavities are connected to the englacial zone, but meltwater has predominantly a subglacial origin. According to Menzies (1995), the nature and configuration of the subglacial drainage system are controlled by meltwater runoff rates.

Granulometric analyses show that there is integration between channelized and distributed drainage systems. According to Nienow et al. (1998) and Swift et al. (2005) distributed drainage systems exist where meltwater is derived only by basal melting and predominates during spring and summer in temperate glaciers.

The internal glacier drainage system expands as increasing volumes of meltwater are delivered to it near late spring and summer (Hooke 1989, Richards et al. 1996, Nienow et al. 1998, Anderson et al. 2004). The release of stored water is thought to induce a change in the subglacial drainage system, from distributed to channelized structure (Fountain & Walder 1998, Nienow et al. 1998). With high discharge rates in proglacial channels the flow of meltwater becomes sufficiently concentrated to develop channeled subglacial drainage systems. Thus, in summer, with a higher surface melting and rainfall registered in the study area, there is the formation of efficient and developed meltwater channels towards the ablation area.

Channelized and distributed drainage systems differ markedly in terms of hydraulic efficiency; the configuration of the subglacial drainage system is probably critical control on the basal sediment evacuation efficiency (Alley et al. 1997, Swift et al. 2005). Channelized systems are composites for efficient hydraulic conduits that transport high volumes of basal sediments. This channelized conduits, observed in the study area, suggest that they are large enough to transport sand grains during large flow velocity events. The distributed drainage system is likely to control the mobilization and transport of basal sediments. Data (Figure 5) show that the peak of suspended sediment concentration occurred during increased discharge. According to Tranter et al. (1996), this occurs due to changes in some parts of the subglacial drainage system during these events.

The variability in the basal sediment availability, according with SSC in proglacial channels, reflects the presence of a hydraulically efficient subglacial drainage in the studied glacier. Swift et al. (2005) indicate that the drainage system configuration exerts high control over glacial erosion rates, sediment yield, glacial sediment transport pathways and ice-marginal sedimentation. High sediment concentrations in proglacial channels can indicate seasonal development of an efficient subglacial drainage configuration (Clifford et al. 1995, Swift et al. 2005, Riihimaki et al. 2005).

Velocities were high during those periods with high-peaked runoff cycles that produced highly efficient basal sediment evacuation. The highest sediment availability, therefore, occurred during January, but a reduced efficient basal sediment evacuation results in limited transport capacity. Runoff cycle evolution during January 2011 resulted in increased efficiency in the basal sediment evacuation due to the establishment of hydraulically efficient channelized subglacial drainage. Increasingly peaked runoff cycles also appear to increase basal sediment availability, probably due to high diurnal water pressure variation within subglacial channels.

Observed discharge variations recorded significant changes in Wanda Glacier drainage patterns during the analyzed period and that are related to meteorological conditions.

Direct measurements in proglacial channels, that communicate the glacier proglacial lagoon to Admiralty Bay, allowed estimating a sedimentary contribution of 19.4x 10^{-3} kg s^{-1} to the glacimarine environment. Sediment load in meltwater is an indicator of erosion and sediment yield processes beneath the glacier. Sediment discharge from glacier melting reflects variations in sediment supply as meltwater pathways change. Our results suggest limited subglacial storage and agree with observations of rapid meltwater transfer from the ice bed interface at the peak of the melting season.

Runoff fluctuations in the study area might, therefore, exert a significant control on glacial erosion rates and sediment yields. Increasing diurnal discharge variations within subglacial channels may also have enhanced basal sliding rates and hence sediment yield.

6. Conclusions

Hydrologic data from proglacial channels in Wanda Glacier obtained in January – February 2010 and 2011 indicate variations in meltwater discharge and the transport of subglacial sediment load. Subglacial events, as observed in 2011, are probably controlled by meteorological conditions during the melting season, meltwater input into the glacier could induce peaks of SSC and discharge. Long-term observations of discharge and sediment load are thus needed to clarify the climate variability could induce an increase in sediment yield due to strong melting processes in the study area.

High sediment concentrations in proglacial channels are related to efficient rates of basal sediment transport. This process is controlled by a developed subglacial drainage system, and quantifies the Wanda Glacier sediment contribution to Martel Inlet.

The abundant amount of fine sediments in the proglacial channels in Wanda Glacier shows the presence of the meltwater in ice-bedrock contact. These sediments result from erosive glacial action and are transported by a subglacial developed drainage system, probably from a wet basal thermal regime, in an accelerated and continuous process of retraction.

Wanda Glacier has a high sediment supply (19.4x 10^{-3} kg s^{-1}), derived from processes of glacial erosion and deposition. These processes are interconnected with high summer temperature presented responsible for the relatively high rates of meltwater production and sediment supply to glacimarine environment with consequences for the sediment dynamics of the study area.

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Capítulo 9

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Glacial hydrological system characterization of Wanda glacier ablation area, King George Island, Antarctica, using Ground Penetrating Radar

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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, through the use of data obtained by a 100 MHz GPR (Ground Penetration Radar) survey. Wanda Glacier has a high retreat rate through fusion processes and reduced ice thickness if compared to other ice masses in KGI. This site is characterized by accelerated retraction and melting processes as consequence of a recent regional warming. The radar survey was conducted along profiles located in the ablation area of the glacier in late January 2011. 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.

Keywords: ground-penetration, glacial drainage system, temperate glacier, dynamic glacier.

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, 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.

Study site

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.

Figure 1 – Location of Wanda Glacier in King George Island, South Shetlands. The small square identifies the area show in Figure 4.

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).

Figure 2 – Wanda Glacier viewed from Admiralty Bay.

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.

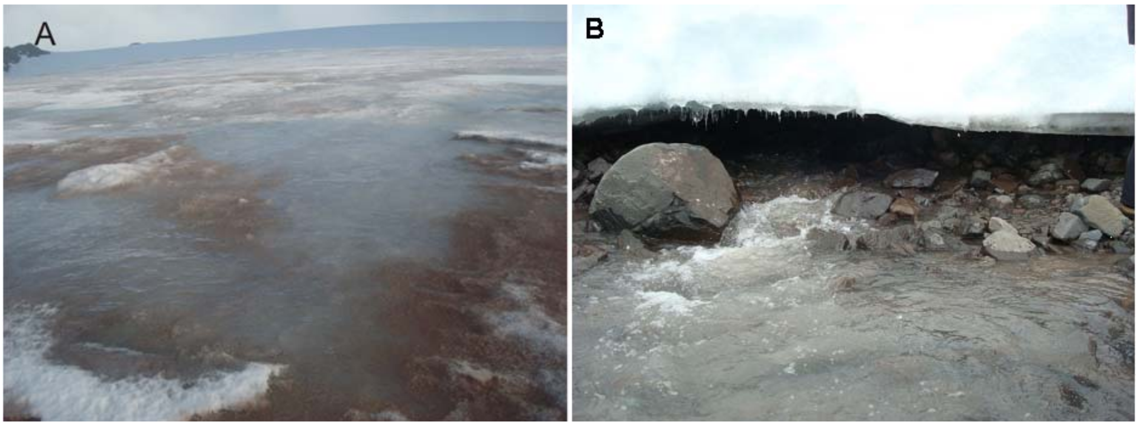

Figure 3 – (A) Interconnected supraglacial melting pools located in the eastern margin of Wanda Glacier; (B) Subglacial conduits emerge from the glacier front.

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 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-offset mode. Positions were acquired with Differential Global Positioning System (GPS) TechGeo.

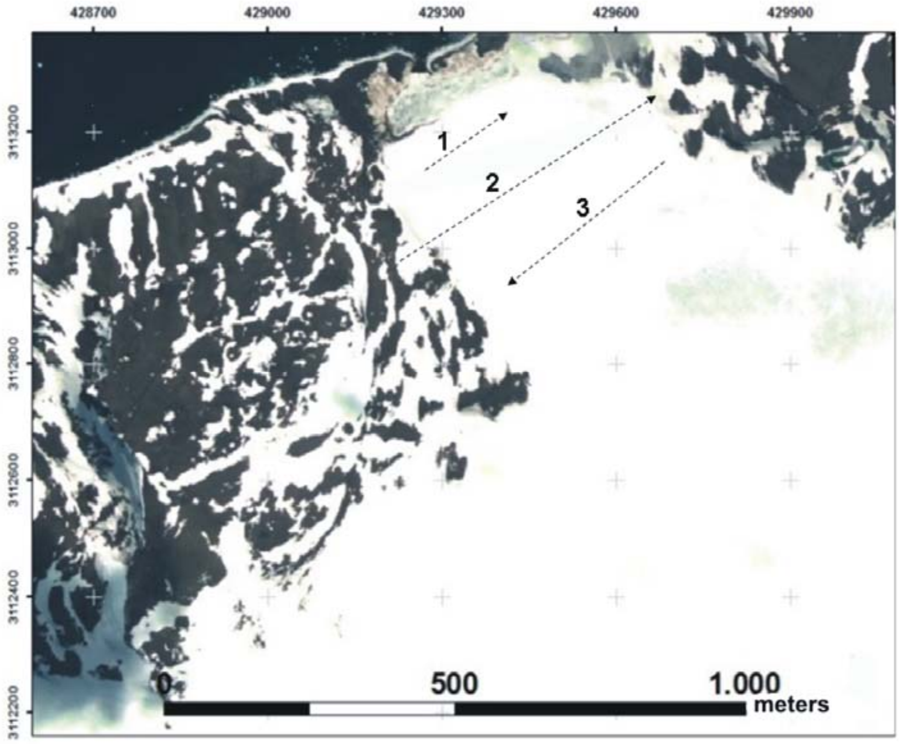

Figure 4 – Location of the GPR radar profiles on the Wanda Glacier.

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 easier interpretation, the profiles were vertically exaggerated and topographically corrected.

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 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 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.

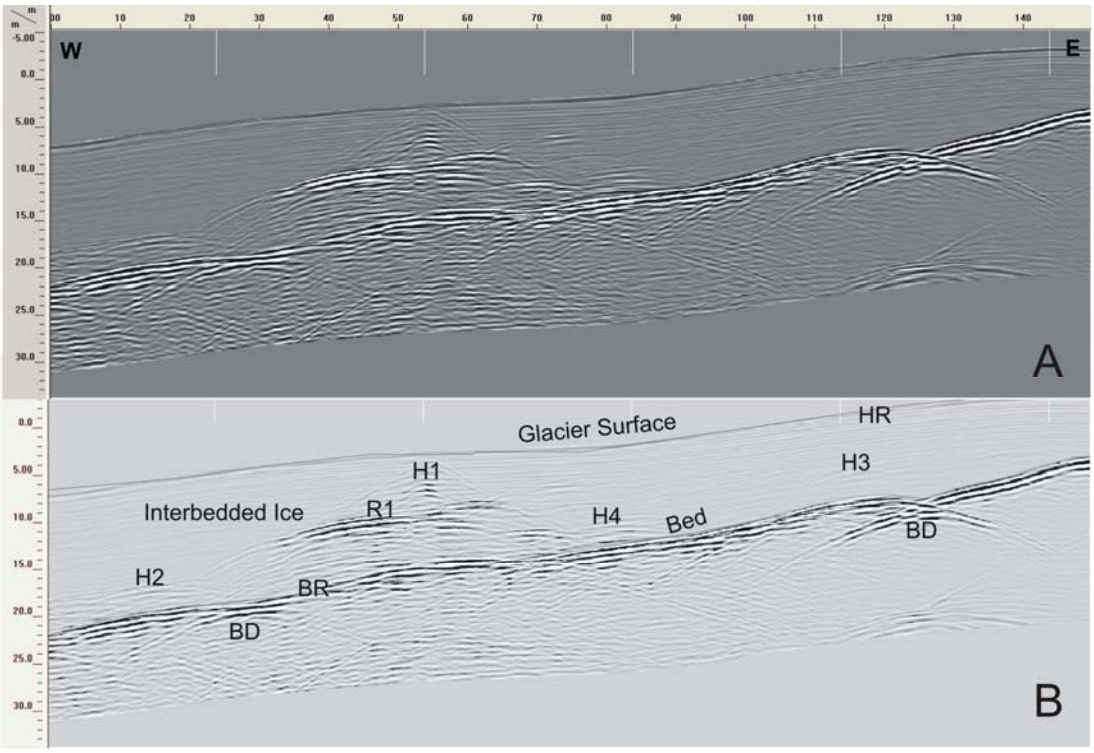

Figure 5 – (A) Processed transversal GPR profile from W to E along 140 meters shows a continuous reflector at approximately 15 meters depth. (B) Unmigrated and elevation corrected profile. Interpretation indicates H Hyperbole diffractions; ID diffraction within ice; BR bed reflection; BD bed diffractions and HR horizontal reflections.

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.

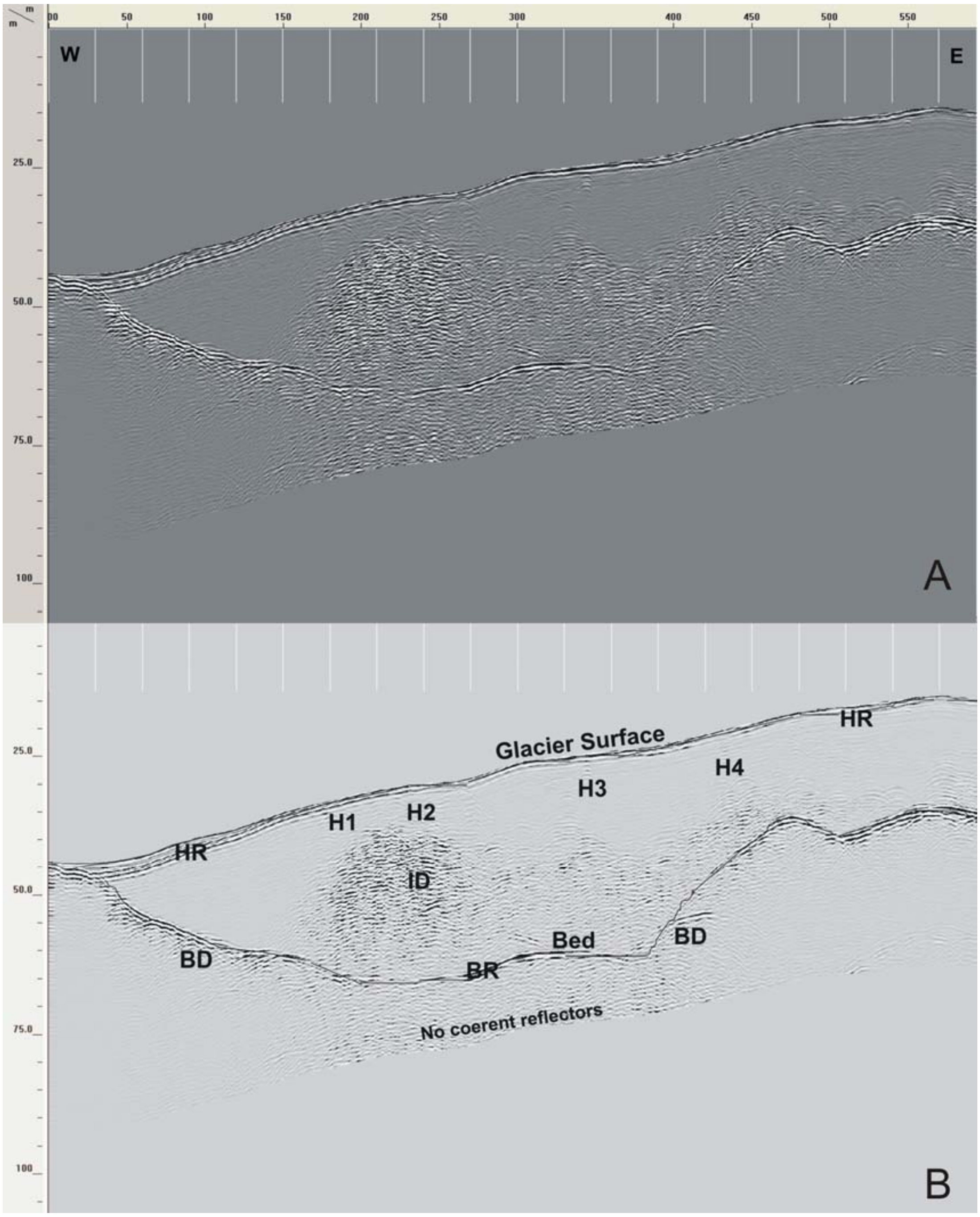

Figure 6 – (A) Processed transversal profile running W - E along 570 meters. Interpreted profile (B) shows HR horizontal reflections in the upper layer that reflect one direct airwave and one direct ground wave, and a continuous horizontal reflection (HR).

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. BD diffractions, located below this layer 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.

Discussion

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 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 developes 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 12) 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.

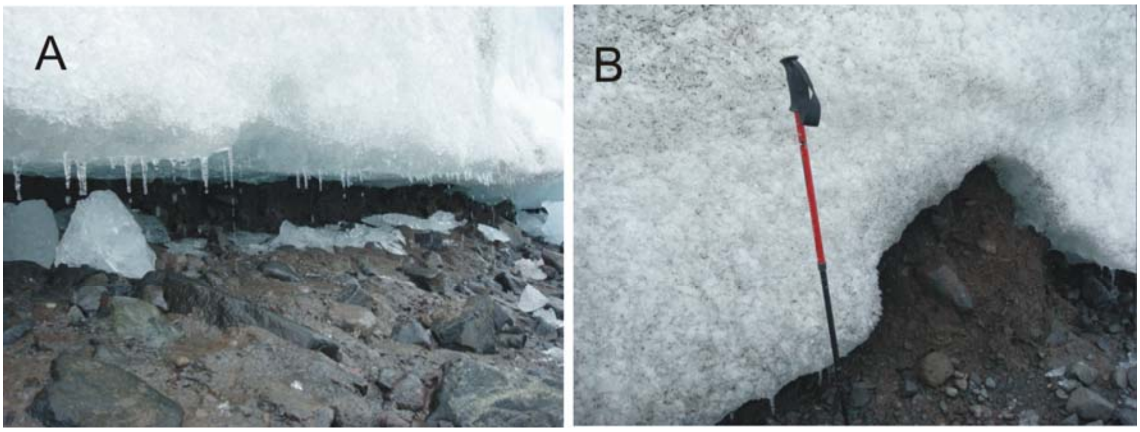

Figure 7 – (A) No frozen sediments in the subglacial zone at front of Wanda Glacier. (B) Sediment filled subglacial conduits emerge at the front of the glacier.

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 and thermal conditions, Wanda Glacier may be respond rapidly to environment studies.

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Capítulo 10

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ESTIMATION OF THE WANDA GLACIER (SOUTH SHETLANDS) SEDIMENT EROSION RATE USING NUMERICAL MODELLING

ESTIMATIVA DA TAXA DE EROSÃO SEDIMENTAR DA GELEIRA WANDA (SHETLANDS DO SUL) COM O USO DE MODELO NUMÉRICO

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Abstract

Glacial sediment yield results from glacial erosion and is influenced by several factors including glacial retreat rate, ice flow velocity and thermal regime. This paper estimates the contemporary subglacial erosion rate and sediment yield of Wanda Glacier (King George Island, South Shetlands). This work also examines basal sediment evacuation mechanisms by runoff and glacial erosion processes during the subglacial transport. This is a small temperate glacier that has seen retreating for the last decades. The glacial erosion rate at Wanda Glacier, estimated using a numerical model that consider sediment evacuated to outlet streams, ice flow velocity, ice thickness and glacier area, is 1.1 ton m yr^{-1}.

Keywords: *numeric model glacial erosion, glacial sediment production rate, glacial dynamics, climatic variability.*

Resumo: A produção sedimentar glacial resulta da erosão glacial e é influenciada por vários fatores incluindo o grau de retração glacial, velocidade do fluxo de gelo e o regime termal. Este artigo estima o grau de erosão atual e a produção sedimentar da geleira Wanda (Ilha Rei George, Shetlands do Sul). Este trabalho também investiga os mecanismos de remoção sedimentar pela água de degelo e por processos de erosão glacial durante o transporte subglacial. A geleira Wanda possui pouca extensão e condições termais temperados com retração nas últimas décadas. O grau de erosão glacial para a geleira Wanda é de 1,1 ton m a^{-1}, estimativa utilizando modelo numérico de erosão que considera os sedimentos transportados em canais, velocidade de fluxo de gelo, espessura do gelo e área glacial.

Palavras chaves: *modelo numérico de erosão glacial, grau de produção sedimentar glacial, dinâmica glacial, variabilidade climática.*

1- Introduction

Glacial erosion has become a principal issue in contemporary research on landscape evolution (KOPPES and HALLET, 2006). Some studies have, empirically, determined erosion rates in glacial environments, however most of them are focused mainly on Alaska and Northern European valley glaciers (POWELL, 1991; HUMPREY and RAYMOND, 1994; VAN DER VENN, 1996; KOPPES and HALLET, 2002). Estimated erosion rates from

< 10^{-3} to >10^{-2} m yr^{-1} for Alaska and Greenland glaciers were reported by POWELL (1991), HARBOR and WARBURTON (1993), GURNELL *et al*. (1996), HALLET *et al*. (1996) and KOPPES *et al*. (2009). KOPPES *et al*. (2009) have estimated < 10 to >120 m yr^{-1} erosion rates at the temperate Martinelli Glacier, Tierra del Fuego, Chile.

During subglacial transport toward the ablation area, abrasion and crushing processes progressively alter the particles (BENN and BALLANTYNE, 1994; and BENN EVANS, 2010). The erosion action varies, depending on several factors: regionally, erosion is controlled by the basal thermal regime, but locally is influenced by several variables that are related to glacier dynamics, topography and substrate characteristics (BENNETT and GLASSER, 1996).

The thermal regime is an important control of the glacial erosion rates; the presence of basal meltwater creates a more efficient sediment evacuation (IVERSON, 1991; CUFFEY and ALLEY, 1996; and RIIHIMAKI *et al*., 2005). The basal thermal regime varies between glaciers, but it also may vary within a particular ice body (BENNETT and GLASSER, 1996). Some glaciers are frozen to their beds and others are composed of warm ice. Temperate glaciers are everywhere at the melting point, except for a surface layer a few meters thick that is subject to seasonal temperature cycles. Basal sliding and meltwater flow may, therefore, operate (BENN and EVANS, 2010). A warm ice glacier has a greater potential to modify its bed by erosion (SUGDEN and JOHN, 1976; COLLINS, 1979; HOOKE *et al*. 1983; BENNETT and GLASSER, 1996; KOPPES and HALLET, 2002; RIIHIMAKI *et al*., 2005; ANDERSON *et al*., 2006; and MACGREGOR *et al*., 2009).

The sediment yield is influenced by the catchment area and glacier thickness (GURNELL, 1987, HALLET *et al*., 1996), and therefore related to the glacial retreat rate. Correlation between sediment yield and retreat rate have been reported by Arendt *et al*. (2002), Howat *et al*. (2005), Koppes and Hallet (2006) and Koppes *et al*. (2009; 2010).

This paper estimates the subglacial erosion rate under Wanda Glacier. The numeric model used in this study relates glacial dynamic conditions (retraction rate, ice flow velocity, catchment area and thermal regime) to substrate characteristics. This work also examines basal sediment evacuation mechanisms by runoff and glacial erosion processes during the subglacial transport.

2. Study area

Wanda Glacier is in King George Island, South Shetlands (61°54'- 62°16'S and 57°35'- 59°02'W), maritime Antarctica (Figures 1 and 2). Since 1997-2011, systematic field activities have been carried out Wanda glacier (ROSA et al., 2009). More recently, the main emphasis of research activities has been extensive investigations of glacier hydrology and ice flow dynamics. The glacier is 1.4 km long, 0.4 to 1 km wide and has a mean surface slope of approximately 20%-30%. Crevasses are observed in ablation area and the subglacial conduits emerge at the front of the glacier.

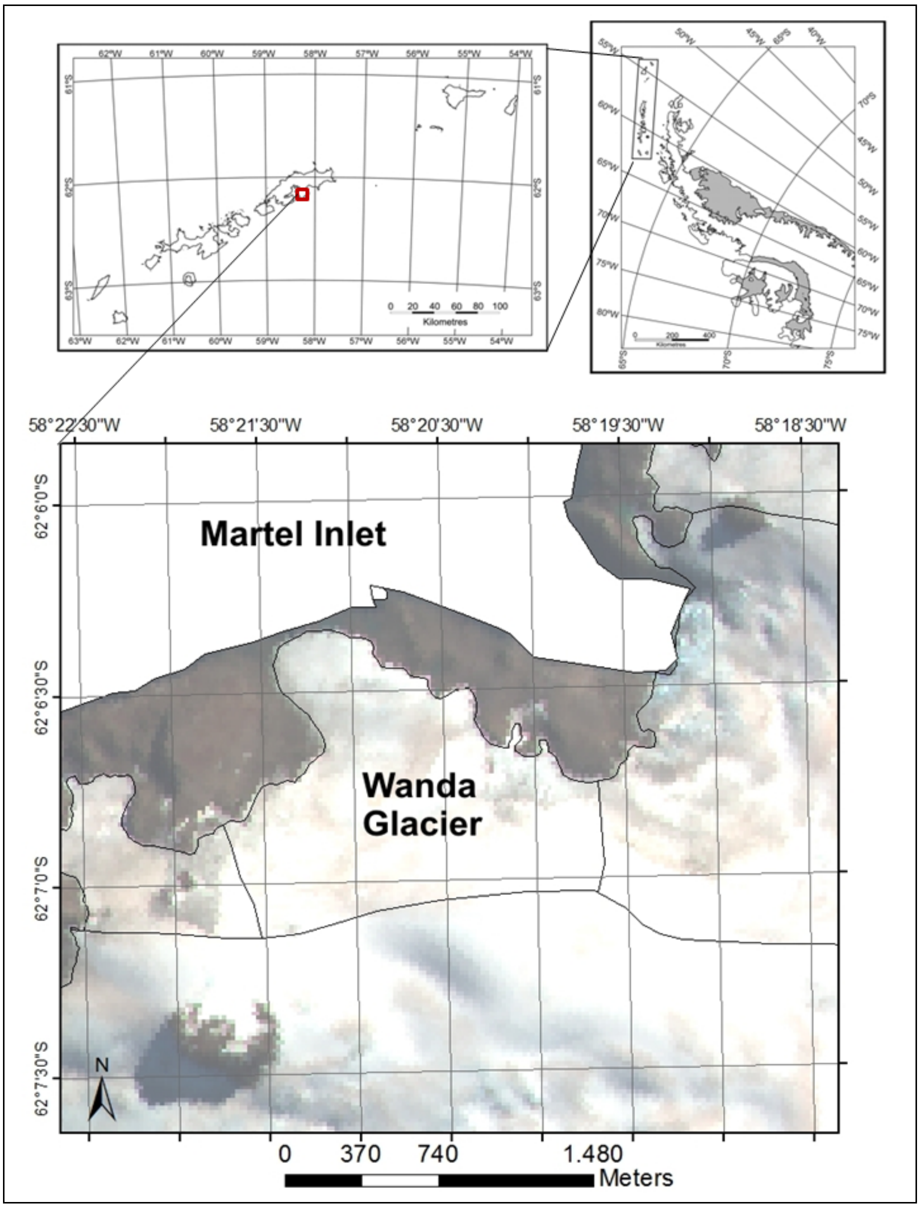

Figure **1** –Wanda Glacier location map in King George Island, South Shetlands. Inset shows this archipelago off the Antarctic Peninsula. (Centro Polar e Climático/UFRGS, SPOT image obtained in 2000).

Figure **2** – Wanda glacier, photo taken from Martel Inlet, obtained in January, 2011 (Kátia Kellem da Rosa).

The South Shetlands Islands are largely volcanic in origin (CURL, 1980). It is characterized by a proglacial front and a proglacial lagoon, consequence of the recent glacier melting and retreat. Subglacial conduits emerge at the glacier front, and fine sediments are transported towards Martel inlet through proglacial channels (ROSA *et al*., 2009).

King George Island has a typical maritime climate, with small atmospheric temperature variations along the year (RAKUSA-SUSZCZEWSKI *et al*., 1993; WEN *et al*., 1994). Significant positive trends of monthly surface air temperatures have been determined for the summer and annual record (DOMACK and ISHMAN, 1993; BRAUN, 2001; FERRON *et al*., 2004; TURNER *et al*., 2005). According to BLINDOW *et al*. (2010), the island mean annual temperature increased by 1°C during the past three decades. For the past 30 years, the number of days with liquid precipitation has increased in the summer. These processes have accelerated snowmelting and increased the negative mass balance of local glaciers (BRAUN *et al*., 2001; FERRANDO *et al.*, 2009).

Since 1970s, when Wanda Glacier had a tidewater terminus, it has experienced accelerated retreat rates simultaneously with a glacier front thickness reduction (ROSA *et al*., no prelo) (Figure 3 and 4). Proglacial streams are now observed in front of glacier (Figure 5). The exposure of several landforms and proglacial deposits are a consequence of this glacier retreat and indicates wet thermal basal conditions.

Figure 3 – Wanda Glacier front obtained in January, 2011 (Kátia Kellem da Rosa).

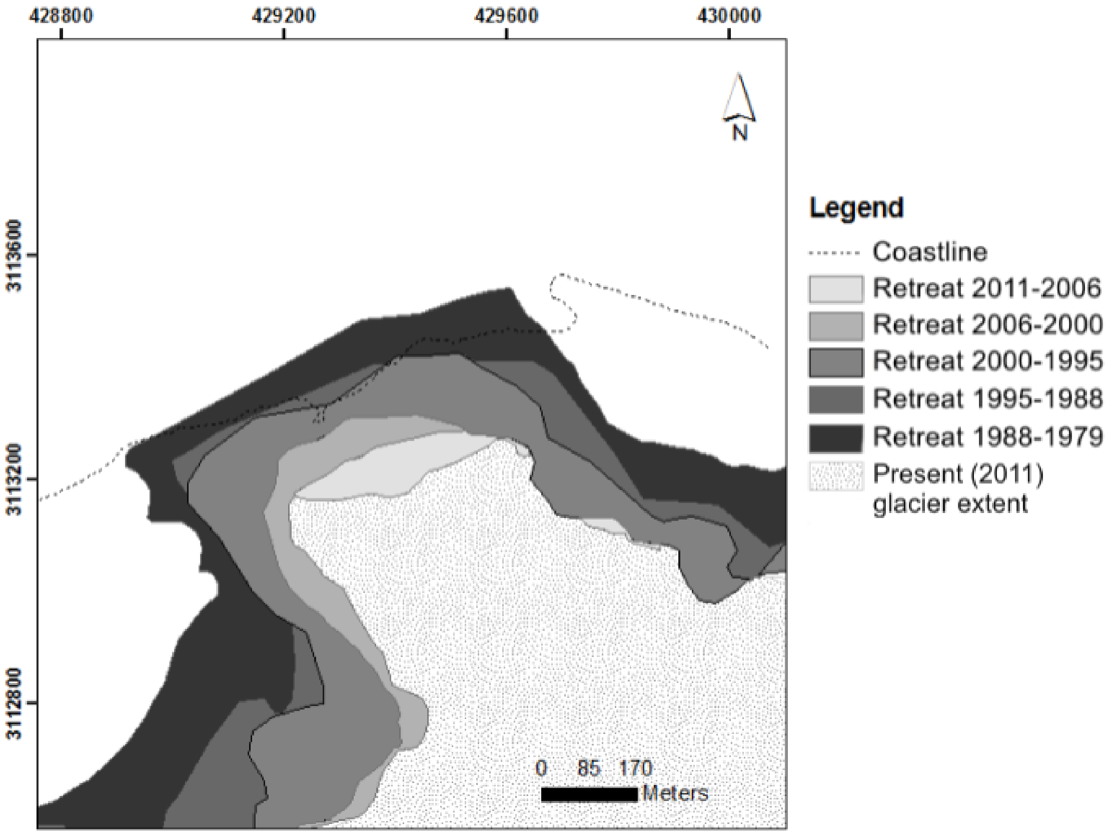

Figure 4 - Wanda glacier map showing different glacial retreat phases (Rosa et al., no prelo).

Figure 5 – Subglacial channels in front of the Wanda Glacier, obtained in January, 2011 (Kátia Kellem da Rosa).

3. Material and methods

The Wanda Glacier erosion rate (E) was estimated from the application of a numeric model (Formula 1) that takes into account: volume of sediment evacuated to outlet streams located at the terminus (Se); ice flow velocity (v); ice thickness (e), and glacier area (A), thus relationing to the glacial retreat. This model also considers the rock density (volcanic rocks=3.5) (d) and takes in consideration the linear correlation between erosion rates and sliding velocity determined by Humphrey and Raymond (1994). Fine subglacial storage variations are considered inexpressive due to an efficient subglacial meltwater evacuation process in the study area.

$$E = \frac{Se}{A.d.e.v}$$ (Formula 1)

Sediment yield transport by subglacial channels (Se) at the Wanda Glacier front (Figure 4) was estimated by meltwater discharge and suspended sediment load daily measurements during the months of January and February, in 2010 and 2011. Proglacial streams daily discharge (Q) was multiplying the cross-sectional area (A) with water flow velocity (Vm) (Q= A.Vm). The partial discharge of each section was estimated by multiplying the water flow velocity by its influence area. The water sample is collected in the field and filtered to extract suspended matter. The filtered material is then dried, weighed and divided by the sample volume to obtain SSC concentration (mg/L). The total sediment load transported in proglacial streams was quantified by multiplying total discharge by the sediment load. The suspended sediment concentration (SSC) was determined by processing of the water samples collected in meltwater channels (in January of the 2010 and 2011) and was analyzed at CECO/UFRGS (Center for Studies in Marine and Coastal/Federal University of Rio Grande do Sul State).

Sediments produced predominantly by abrasion processes are easily transported by subglacial meltwater drainage. According to Rubin and Topping (2001) and Morehead *et al*. (2003), if fine sediments transport is regulated only by meltwater discharge, the sediment load in proglacial streams will predict correctly the sediment bulk transported by glacier. Sediment evacuation rates reflect erosion rates only where there is no change in subglacial sediment storage (RIIHIMAKI *et al*., 2005). Therefore, as Riihimaki *et al*. (2005) considered for these conditions, sediment evacuation rates can be used to deduce subglacial erosion rates.

Wanda Glacier area (A=1.1 km^2) was based on Rosa et al. (no prelo) with Cosmo-SKymed image obtained in 2011, and glacier mean thickness (e=40 meters) (e) was determined by a Ground Penetrating Radar (GPR) survey using a Geophysical Survey Systems Inc. (GSSI) SIR System control unit with a 100 MHz transceiver during a field work in late January 2011. The antenna was polarized orthogonally to transect and longitudinal directions (following the central flowline), and the data were collected in form of 1024 samples,with a time window of 600 and 800 ns. GPR data were corrected for topography and were processed using the software RADANTM 6.5 from GSSI (Geophysical Survey Systems, Inc). Position correction was applied to remove distortion of the depth at upper part of the reflection profiles and, to create zero-offset traces. Distance and surface normalization for time was performed utilizing topographic profiles from total station and differential GPS data. The glacier profiles were migrated to collapse to correct the orientation of steeply dipping layers.

Ice flow velocity (v) is an important glaciological variable controlling sediment yields (HALLET, 1979; 1996). In 2007, twenty stakes were placed along the glacier central axis (Figure 6) to determine the surface ice velocity according to the techniques of Anderson *et al*. (2004) and MacGregor *et al*. (2005). These stakes positions were determined using a static GPS TechGeo (Rosa et al., no prelo).

Numeric modeling shows that the Wanda Glacier presents a contemporary mean erosion rate of 1.1ton m yr^{-1} of sediments (in January and February, 2010 and 2011 - summer) on average. The highest sediment amount yield is related to high runoff processes influenced by basal thermal conditions and subglacial drainage.

High glacial erosion rates can be related to the accelerated and continuous retreat processes and reduction of the glacier ice thickness over the last decades. This is evidenced by a significant amount of the sediments deposited in landforms such as flutes and moraines in proglacial area as a result from recent glacial retraction. Striated surface rocks have been exposed and is observed in morphoscopy analyzes (ROSA et al., 2011). Abraded and subglacially transported sediments predominate at the deglaciation environments, with meltwater flow in the bed. According to Bogen (1996), a thin and slow glacier has low glacial erosion rates.

Figure 6 - Stakes along the Wanda Glacier central axis to determine surface ice velocity obtained in January, 2011 (Rosa et al, no prelo).

4. Results

Velocity stakes measurements show maximum speeds of 2.2 cm day^{--1} during the period 2007 - 2011. This record is in agreement with values obtained by Moll *et al*. (2006), who inferred a mean velocity of 10 cm day^{-1} for Wanda glacier in 1995 using Differential Radar Interferometry (DInSAR). The record shows that the ice flow is slowing due to ice thickness and area reduction of the glacier (Rosa et al, no prelo).

The Wanda Glacier retreat may be a result from sediment supply increase and high runoff by proglacial streams. Meltwater from these streams transport significant amounts of fine grained sediments into the glaciomarine environment, mainly during summer.

High rates of sediment production during the measured period (January and February of the 2010 and 2011) are also related to the glacier thermal regime. The estimated erosion rate can be compared to the ones of small area temperate glaciers located in King George Island. An active subglacial erosion, inferred from the analysis (striated grain surfaces revealed in morphoscopy analyzes) of sediments collected at the base of the glacier, is related to subglacial abrasion and an efficient subglacial drainage system. Thereby, these processes indicate rapid melting of the Wanda Glacier.

Quarrying processes generate coarse sediments, which are transported by the subglacial ice flow. These processes require a glacial basal sliding under enough mechanical stress to fracture and mobilize the rock (IVERSON, 1991; HALLET *et al*., 1996). According to observations in proglacial area recently exposed, there is a poor efficiency for the glacier to remove large amounts of basal zone coarse sediments.

Contemporary erosion rates reflect climatic conditions and present glacier dynamics. The model used estimates erosion rates, but does not consider its variability due to high meltwater discharge pulses, as our observation recorded during the short investigation period.

5. Conclusion

A high contemporary glacial erosion rate in Wanda Glacier averaging 1.1 ton m yr^{-1} was determined from sediment yield. This value is comparable to erosion rates for others glaciers with similar catchment area, and basal thermal conditions. Probably, erosion rates were higher when the glacier had tidewater conditions, resulting from stronger basal sliding and greater than the present glaciarized area, but these studies need more period of the analyzes.

Subglacial abrasion by erosion processes predominates and this can be related to efficient basal sediment evacuation rates. The numerical model used incorporates glacial dynamics conditions and bedrock (vulcanics rocks) characteristics to estimate subglacial erosion rates. Our results show the Wanda glacier efficiency to erode landscapes and mobilize sediments. Thus, the numerical model contributes to monitoring of erosion rates and sediment yield delivery (summer period) associated with glaciomarine environments.

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Capítulo 11

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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.

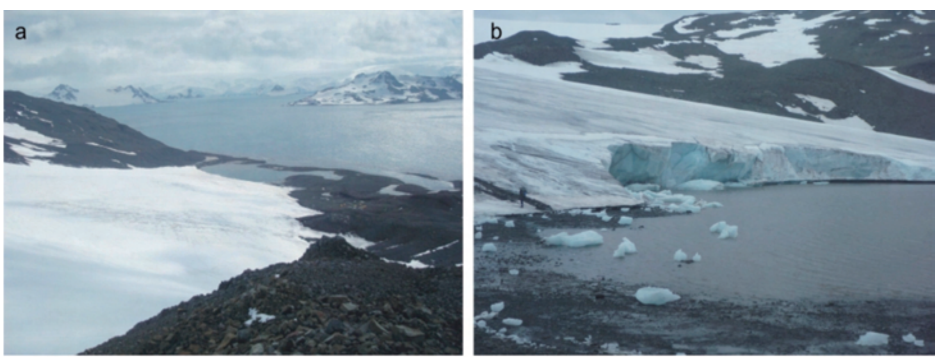

Fig. 1. Wanda Glacier (a) and its proglacial front close to the proglacial lagoon (b).

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

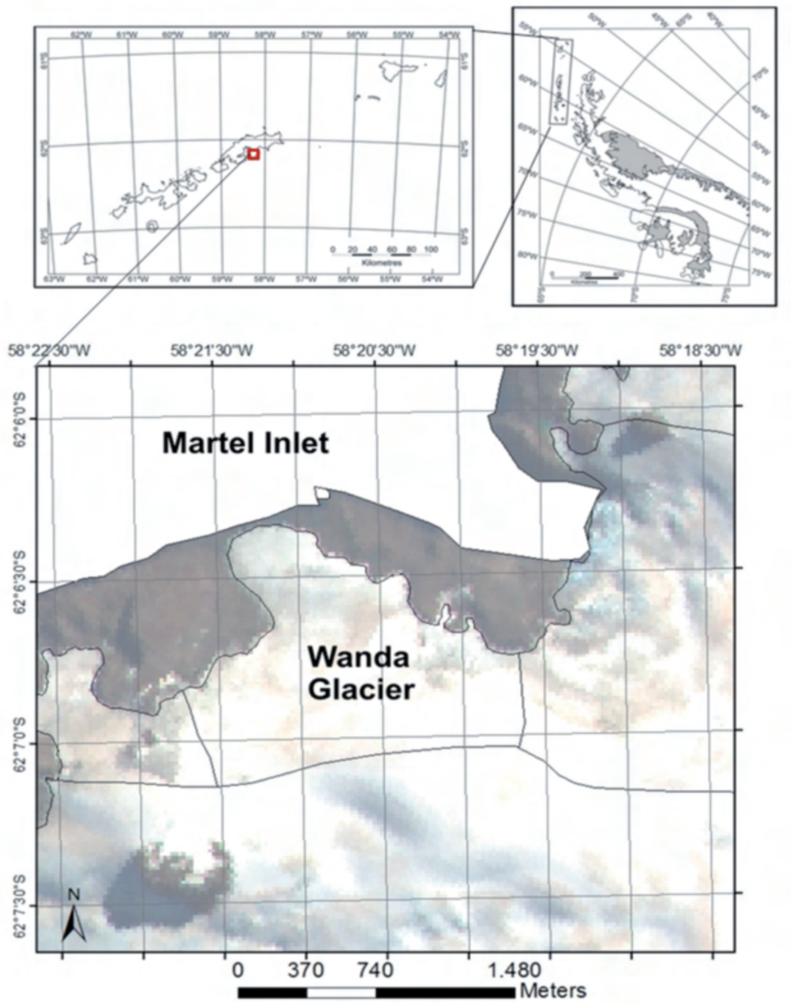

Fig. 2. Situation of the study area.

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).

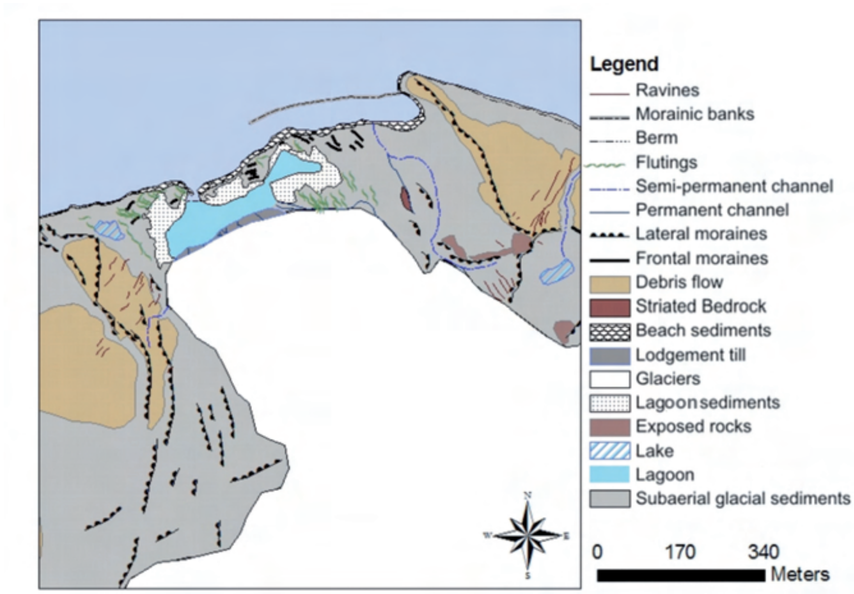

Fig. 3. Geomorphological map of Wanda glacier.

Fig. 3. Mapa geomorfológico del glaciar Wanda.

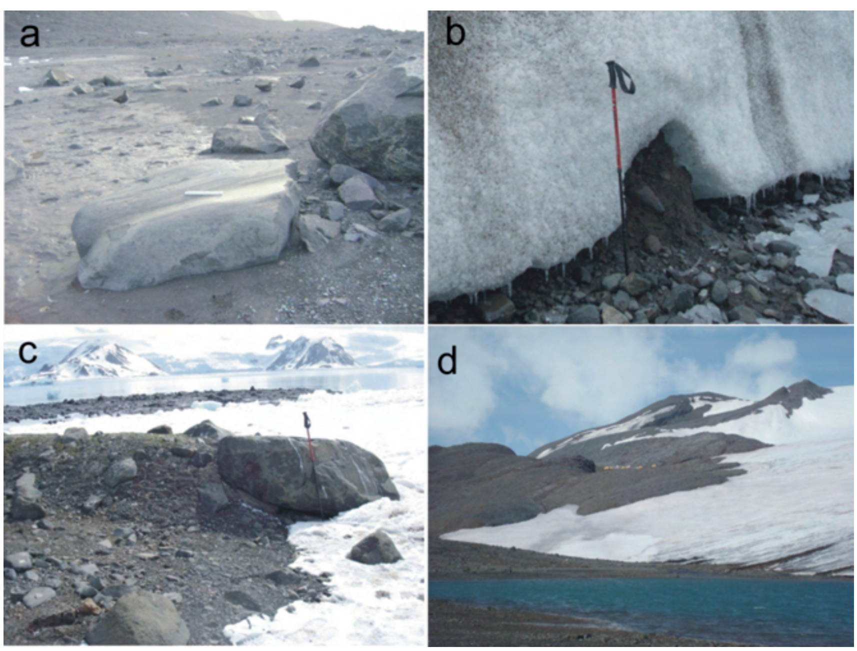

Fig. 4. Surface striated stoss and lee clasts (a); subglacial fluting deposition (b); flutes (c) and lateral morainic ridges of different positions and elevations indicating the different positions reached by the glacier during the retreat process.

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).

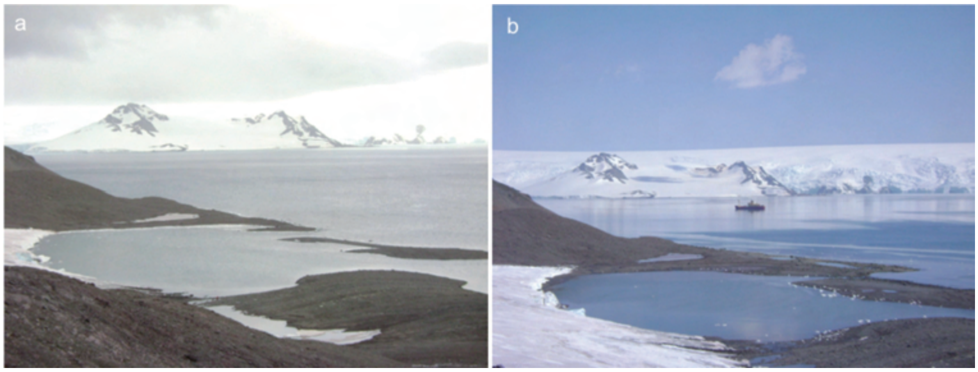

Fig. 5. Terminal moraines form a lagoon system at Wanda glacier proglacial area. The barrier undergoes processes of reworking during high (a) and low tides (b) fluctuations.

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).

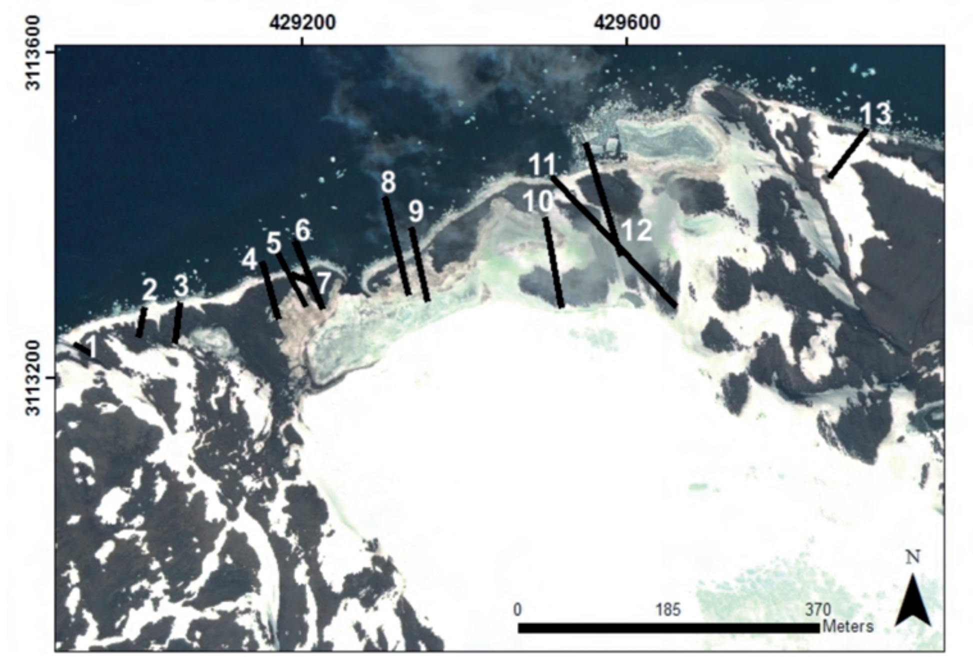

Fig. 6. Location of topographical profiles at the Wanda glacier proglacial area. Profiles 1-6 are represented in Figure 7 by letters a-f; profiles 7-13 are represented in Figure 8 by letters a-f.

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.

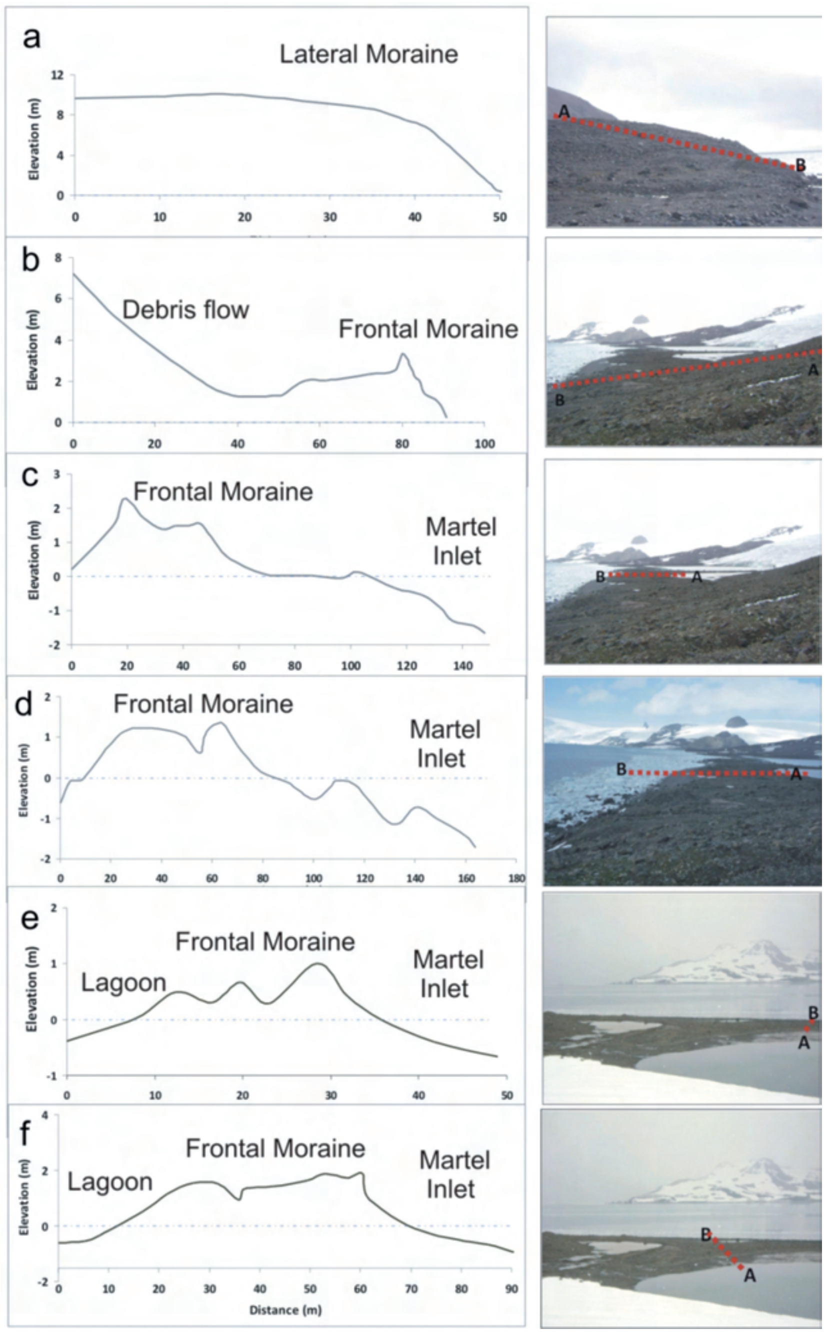

Fig. 7. Topographic profiles located in the western area of the Wanda glacier proglacial zone.

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

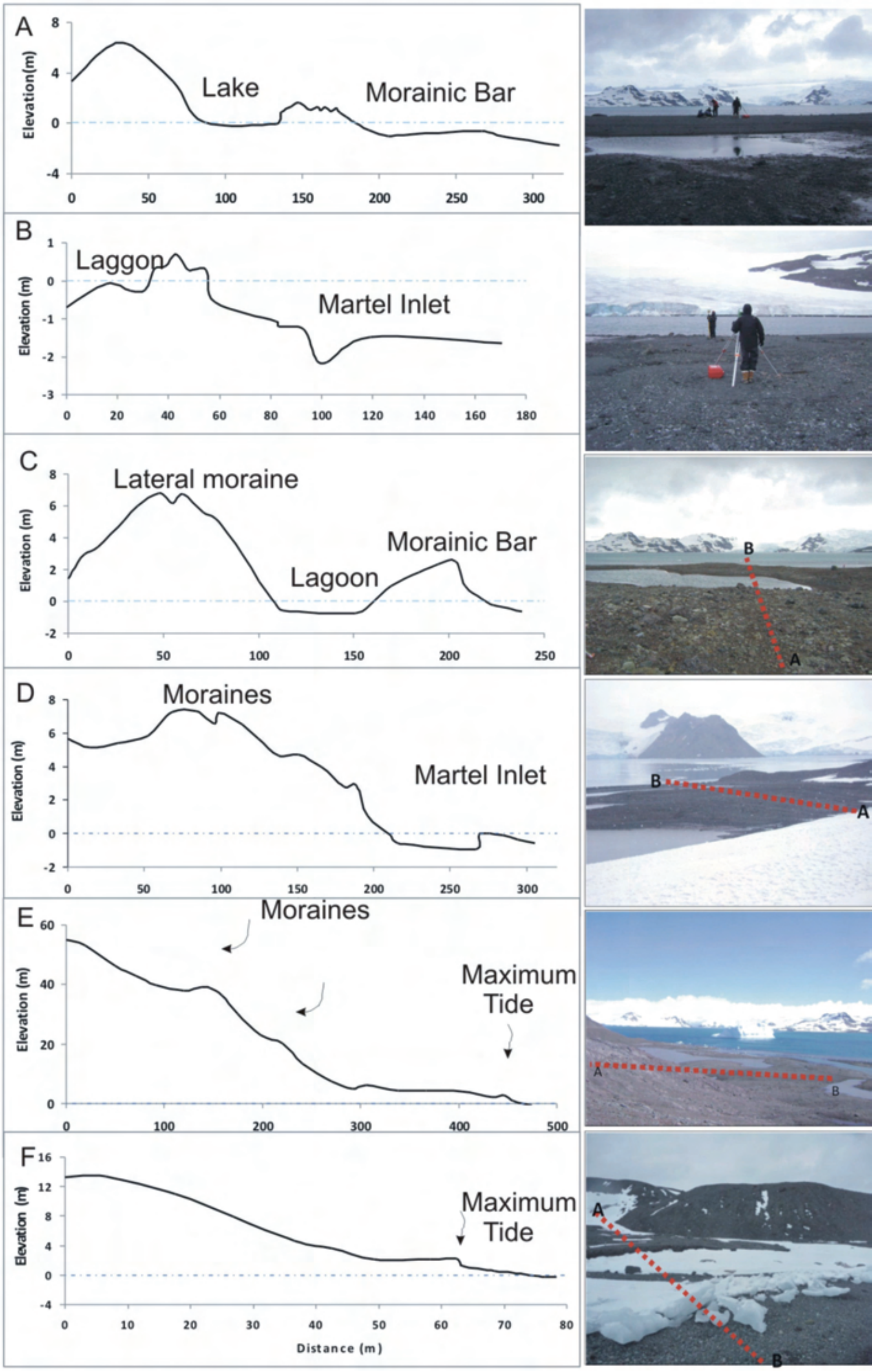

Fig. 8. Topographic profiles in the eastern area of Wanda glacier proglacial area.

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.

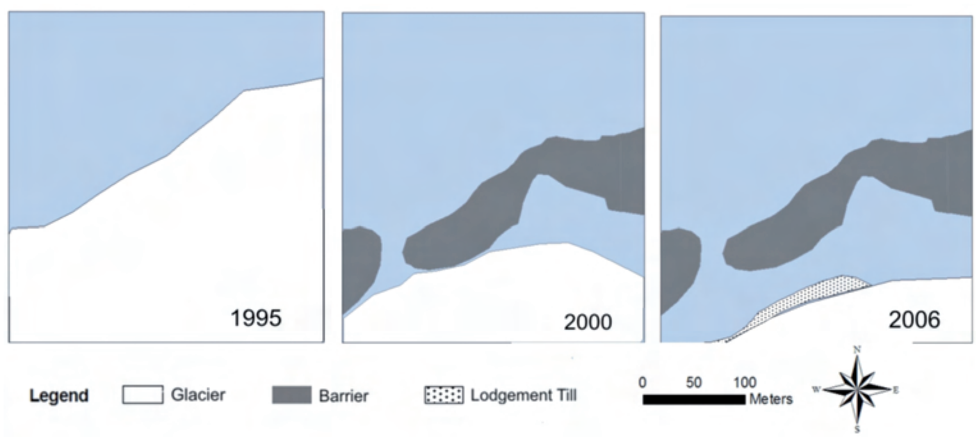

Fig. 9. Evolution of the barrier-lagoon system during retreat stages.

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

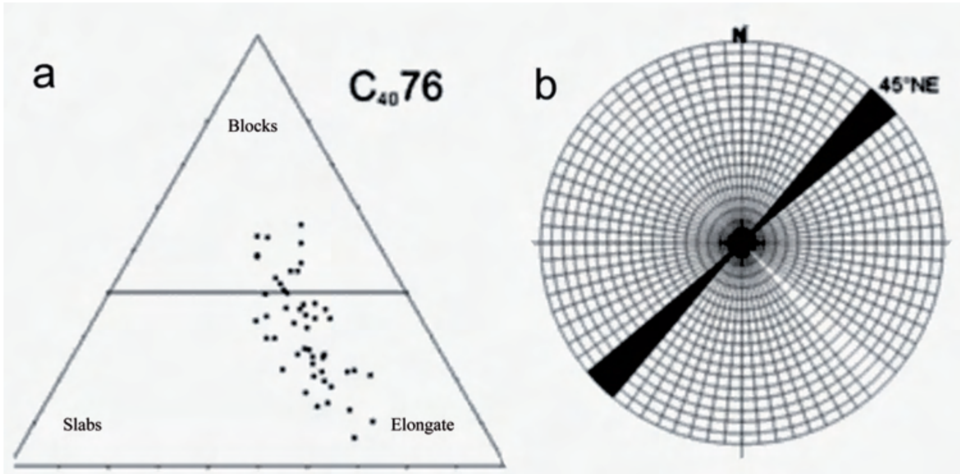

Fig. 10. Scatter plot representing the C40 index (a) and predominant orientation of striate and striated bedrocks exposed (b).

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

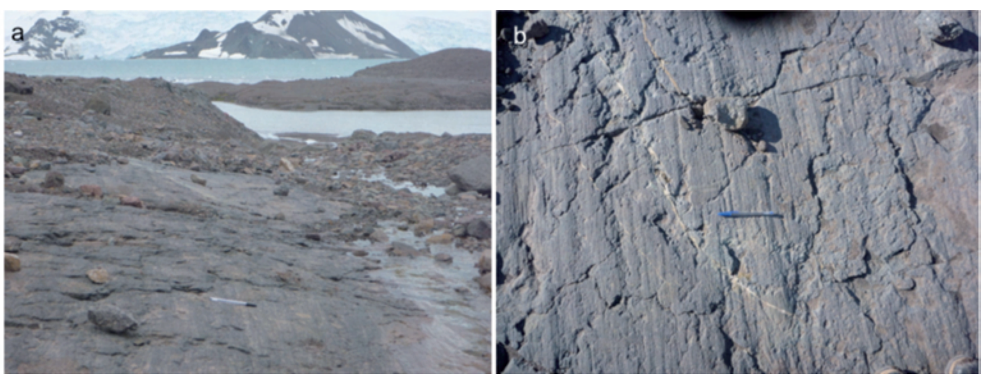

Fig. 11. Striations exposed on the rock indicate the predominant direction of ice flow - 45° Northeast.

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.

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Capítulo 12 - Considerações finais

Ao longo desta tese mostrou-se a aplicação de metodologias para a caracterização das condições glaciológicas e mecanismos de transporte sedimentar e interligações com o sistema subglacial, supraglacial, proglacial e glacimarinho na enseada Martel. Investigações da dinâmica glacial (estrutura termal, variabilidade de estocagem hídrica, sistema de drenagem intraglacial, velocidade de fluxo do gelo e retração glacial) foram relacionadas aos processos de produção sedimentar pela geleira Wanda.

A caracterização do sistema de drenagem na geleira Wanda, usando dados de variabilidade de descarga de água de degelo, SSC e perfis de GPR, possibilitou inferir condições de estocagem hídrica líquida com um sistema interconectado de canais subglaciais, englaciais e supraglaciais (capítulo 9). A presença de água de degelo, indicada pela interpretação dos perfis de GPR e canais proglaciais, revelam que esta se caracteriza pelo regime termal temperado (capítulo 7 e 9).

A concentração de sedimentos em suspensão em canais proglaciais, permite estimar o atual aporte sedimentar de $19{,}4\times10^{-3}$ kg s^{-1} pela geleira Wanda para o ambiente marinho (capítulo 8). Esses processos estão relacionados à configuração do sistema de drenagem glacial e com as altas temperaturas e precipitação líquida no verão, responsáveis por altos graus de produção de água de degelo e sedimentos para o fiorde. A variabilidade temporal e espacial no aporte sedimentar é de interesse para o contínuo monitoramento devido a sua consequência para a dinâmica sedimentar e ao ecossistema marinho.

Características da hidrologia subglacial, velocidade do fluxo glacial, retração das geleiras e processos dinâmicos associados foram relacionadas para a elaboração de um modelo numérico de estimativa do grau de produção sedimentar pela geleira Wanda (capítulo 6, 8, 10). A carga de sedimentos transportada em canais subgglaciais é um indicador de processos de erosão da geleira. Os resultados da aplicação deste permitiram identificar o mecanismo de abrasão como principal mecanismo de erosão glacial, com a geração de partículas de menor granulometria para o transporte pela água de degelo. Os resultados do modelo foram fundamentais para a identificação do padrão sedimentar e para a realização de comparações com outras geleiras com condições glaciológicas semelhantes.

Nesta tese é apresentada uma avaliação do uso de imagens COSMO-SkyMed (capítulo 2), no modo *spotlight* e com diferentes polarizações (VV e HH), para a análise geomorfológica glacial em áreas subpolares. A aplicação de filtros específicos em determinadas polarizações, aliada à alta resolução espacial das imagens, provêu uma melhor distinção de feições geomorfológicas do que por imagens óticas. Bancos morâinicos também foram identificados com a utilização de imagens COSMO-SkyMed. Análise textural e filtros *Wallis adaptative*, *morphological, high pass* e filtros direcionais como *Prewitt* possibilitaram o reconhecimento de feições geomorfológicas, desta forma, essa metodologia releva-se com potencial para aplicar em estudos dos processos geomorfológicos glaciais e monitoramento de processos paraglaciais em regiões subpolares.

O MDT (resolução de 0,7 m no terreno), a geração de dados morfométricos (capítulo 3) e perfis transversais e longitudinais da área de estudo também possibilitaram a interpretação da geomorfologia glacial das áreas proglaciais e providenciaram inferências sobre a direção de fluxo de gelo. A análise sedimentar de amostras coletadas em campo, também, foi utilizada como base para a elaboração de um mapeamento geomorfológico subaéreo e glacial para toda a área de estudo. A caracterização geomorfológica possibilitou a identificação dos principais processos glaciais (abrasão glacial com água de degelo na interface gelo-rocha) que operam na sua gênese relacionada às condições termais úmidas das geleiras analisadas. Feições geomorfológicas glaciais, incluindo morainas, *flutings*, bancos morâinicos, *tors, arêtes*, canais fluvioglaciais, circos glaciais, vales em forma de U e superfícies rochosas estriadas foram identificadas na área de estudo (capítulo 11 e 5). Nessa área predomina terrenos com relevo ondulado, com vertentes com orientações sul e sudoeste. A presença de áreas de maior declividade nas áreas rochosas recentemente expostas dá condições para o desenvolvimento de fluxo de detritos. Mudanças nos processos geomorfológicos foram analisadas, como a ocorrência de processos paraglaciais que evidenciam alterações ambientais na área recentemente deglaciarizada.

Nos vários capítulos apresentados, detectaram-se mudanças recentes nas características glaciológicas, sedimentares, hidrológicas, paraglaciais e mostraram-se como as geleiras localizadas na área de estudo respondem às variações climáticas evidenciadas para esta região da Península Antártica.

Os resultados mostram que as geleiras da área de estudo estão em uma continua fase de rápida retração, com a formação de ambientes de deglaciação recentes. A área total estudada perdeu aproximadamente 13,21% de sua área de cobertura de gelo original no período 1979–2011 (estimada com o uso de fotografias aéreas e imagens de satélite de diferentes anos) (50,3 km^2). Essas geleiras apresentaram um taxa anual de 25,9 metros de retração. As geleiras Dobrowolski, Wanda, Dragão e Professor apresentaram as maiores taxas de retração anuais (capítulo 5). A primeira foi a que teve maior retração anual (75 m^2a^{-1}) e apresentou maior concentração espacial de plumas de turbidez em seu término (capítulo 4). As geleiras que fluem para a enseada Martel apresentam pequenas bacias de drenagens, regime termal temperado, alta retração por fusão se comparadas com outras massas de gelo da ilha Rei George. Devido as suas características (regime termal, dimensões e espessura), elas respondem rapidamente as variações climáticas, sendo assim, o monitoramento destas é considerado relevante para estudos ambientais. Nos ambientes recentemente expostos é possível perceber significativa descarga de água de degelo e sedimentos em suspensão para o ambiente glacimarinho.

Evidenciaram-se, nesta tese, as relações entre os processos glaciais, subaéreos e glacimarinhos com a dinâmica sedimentar e de processos de fusão glacial. A interligação estabelecida entre a pesquisa glaciológica e subaérea contribuem para o entendimento das mudanças ambientais ocorridas nesses sistemas, incluindo decréscimo da massa de gelo pelas geleiras, em reflexo ao aquecimento atmosférico regional observado. Adicionalmente, investigações dos mecanismos que controlam a produção sedimentar glacial proporcionam uma maior compreensão dos processos e geoformas resultantes, e possibilita a interpretação das informações registradas em sedimentos glacigênicos (proporção de sedimentos finos e morfologia superficial dos grãos).

Sendo assim, têm-se importantes informações para estabelecer comparações do padrão de retração com outras geleiras subpolares com tamanho de bacia de drenagem, configuração de término, velocidade de fluxo de gelo e regimes termais semelhantes. Ainda, apresenta-se o desenvolvimento de uma metodologia de análise integrada de registros sedimentológicos e aplicação de métodos glaciológicos, hidrológicos, geofísicos, processamento digital de imagens e de Sistema de Informações Geográficas para caracterizar a dinâmica glacial para detectar variações ambientais temporais, tais como mudanças morfológicas, balanço de massa glacial e mudanças volumétricas e de estocagem hídrica nas geleiras.

Os resultados obtidos nesta tese revelam o comportamento da dinâmica glacial e sedimentar das geleiras localizadas na área de estudo e suas transformações já em curso, tornando-se fundamental a manutenção de pesquisas de monitoramento dos processos glaciais e sedimentares que atuam para o melhor entendimento de suas relações com o clima, o ambiente marinho e os ecossistemas presentes.