www.ugb.org.br
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 13, nº 4 (2012)

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

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

Kátia Kellem da Rosa
Centro Polar e Climático – UFGRS; Universidade Federal da Fronteira Sul – Campus Erechim, Av. Dom João Hoffmann, 313, Bairro Fátima – CEP: 99700-000 – Erechim, RS, Brazil – e-mail: katiakellem@gmail.com

Rosemary Vieira
Laboratório de Processos Sedimentares e Ambientais (LAPSA) – Universidade Federal Fluminense – UFF, Instituto de Geociências – Depto de Geografia, Av. Gal. Milton Tavares de Souza, s/n, Campus da Praia Vermelha, Boa Viagem – Niterói/RJ – CEP: 24210-346, Brazil. – e-mail: rosemaryvieira@id.uff.br

Jefferson Cardia Simões
Centro Polar e Climático – Universidade Federal do Rio Grande do Sul – UFRGS, Av. Bento Gonçalves 9500 – CEP: 91501-970 - Porto Alegre, RS, Brazil – e-mail: jefferson.simoes@ufrgs.br.

Informações sobre o Artigo

Data de Recebimento:
10/04/2012

Data de Aprovação:
17/07/2012

Palavras-chave:
Modelo numérico de erosão glacial, taxa de produção sedimentar glacial, dinâmica glacial, variabilidade climática.

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 temperado 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.

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}.

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 and 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.

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.

The South Shetlands Islands are largely volcanic in origin (CURL, 1980). This 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).

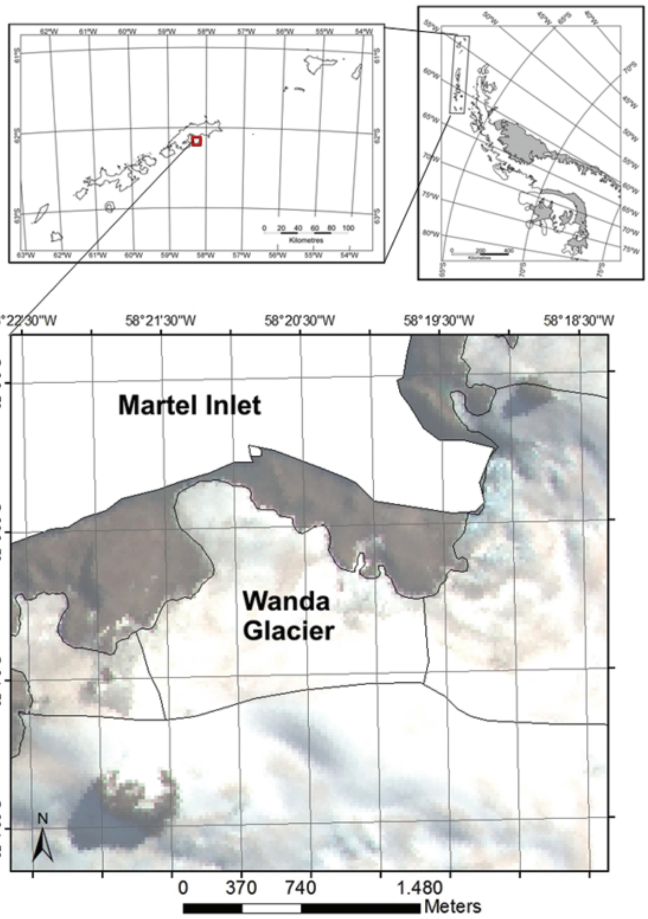

Figure 1 – Wanda Glacier location map in King George Island, South Shetlands. Inset shows this archipelago off the Antarctic Peninsula. (Centro Polar e Climático/UFRGS, SPOT image obtained in 2000).

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

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) (Figures 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 condition.

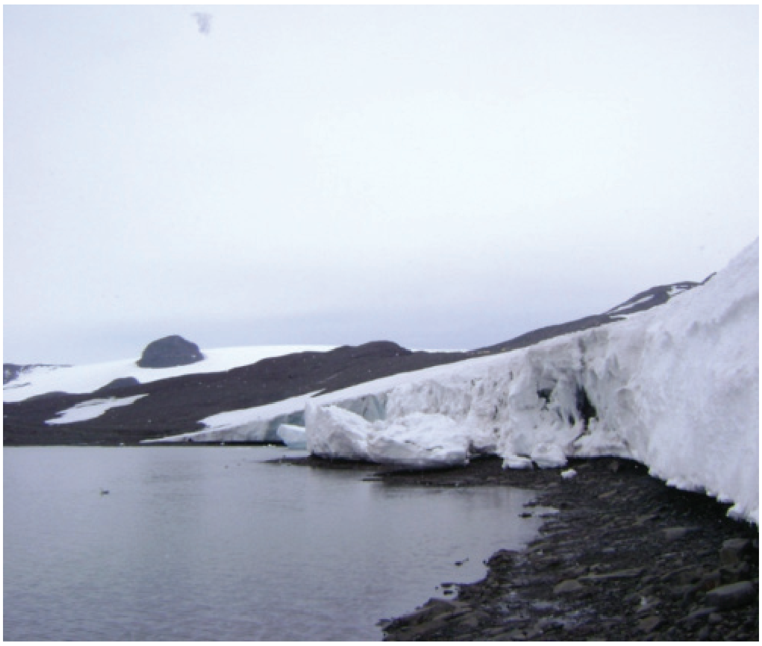

Figure 3 – Wanda Glacier front obtained in January, 2011 (Kátia Kellem da Rosa).

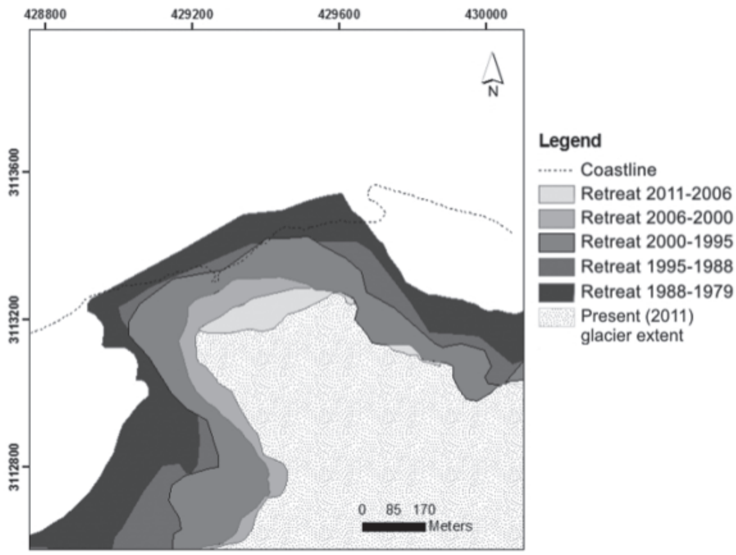

Figure 4 – Wanda glacier map showing different glacial retreat phases (Rosa et al., no prelo).

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

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). 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). 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 km²) 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.

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 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).

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

Results

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.

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.

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.

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.

Acknowledgment – The Brazilian National Council for Scientific and Technological Development (CNPq) project 573720/2008-8, the Center for Studies in Marine and Coastal (CECO/UFRGS) and the Brazilian Antarctic Program (PROANTAR) provided financial support for this investigation.

References

ANDERSON, R.S.; ANDERSON, S.P.; MACGREGOR, K.R.; WADDINGTON, E.D.; O'NEEL, S.; RIIHIMAKI, C.A. & LOSO, M.G. Strong feedbacks between hydrology and sliding of a small alpine glacier. **Journal of Geophysical Research,** v. 109, 2004. F03005, doi:10.1029/2004JF000120.

ANDERSON, R.S.; MOLNAR, P. & KESSLER, M.A. Features of glacial valley profiles simply explained. **Journal of Geophysical Research,** v. 111, 2006. doi:10.1029/2005JF000344.

ARENDT, A.A.; ECHELMEYER, K.A.; HARRISON, W.D.; LINGLE, C.S. & VALENTINE, V.B. Rapid wastage of Alaskan glaciers and their contribution to sea level rise. **Science**, v. 297, p. 382-386, 2002.

BENN, D.I. & BALLANTYNE, C.K. Reconstructing the transport history of glaciogenic sediments - a new approach based on the covariance of clast form indices. **Sedimentary Geology**, v. 91, n. 1-4, p. 215–227, 1994.

BENN, D.I. & EVANS, D.J.A. **Glaciers & Glaciation**. London: Arnold, 2010. 802 p.

BENNETT, M.R. & GLASSER, N.F. **Glacial Geology - Ice Sheets and Landforms.** Inglaterra: John Wiley & Sons Ltd, 1996. 364 p.

BLINDOW, N.; SUCKRO, S.K.; RÜCKAMP, M.; BRAUN, M.; SCHINDLER, M.; BREUER, B.; SAURER, H.; SIMÕES, J.C. & LANGE, M. A. Geometry and thermal regime of the King George Island ice cap, Antarctica, from GPR and GPS. **Annals of Glaciology**. v. 51, 55, p.103-109, 2010.

BOGEN, J. Erosion rates and sediment yields of glaciers. **Annals of Glaciology**, v. 22, p.48-52, 1996.

BRAUN, M. **Ablation on the ice cap of King George Island (Antarctica).** PhD. Dissertation, Albert-Ludwigs-Universitat Feiburg, 2001. 165 p.

BRAUN, M.; SAURER, H.; SIMÕES, J.C.; VOGT, S. & GOßMANN, H. The influence of large scale atmospheric circulation on surface energy balance and ablation on King George Island, Antarctica. **International Journal of Climatology**, v. 21, p. 21-36, 2001.

COLLINS, D.N. Quantitative determination of the subglacial hydrology of two Alpine glaciers. **Journal of Glaciology**, v. 23, n. 89, p. 347–362, 1979.

CUFFEY, K.M. & ALLEY, R.B. Erosion by deforming subglacial sediments: Is it significant? (Toward till continuity). **Annals of Glaciology**, v. 22, p.126-133, 1996.

CURL, J.E. **A glacial history of the South Shetland Islands, Antarctica.** Ohio State University, Institute of Polar Studies Report, v. 63, 1980. 129 p.

DOMACK, E.W. & ISHMAN, S.E. Oceanographic and physiographic controls on modern sedimentation within Antarctic fjords. **Geological Society of America Bulletin,** v. 105, p.1175–1189, 1993..doi: 10.1130/ 0016-7606(1993)105< 1175:OAPCOM>2.3.CO;2.

FERRANDO, F.A., VIEIRA, R. & ROSA, K.K. Sobre el calentamiento global en la Isla Rey Jorge: procesos y evidencias en el glaciar Wanda y su entorno. **Revista Informaciones Geográficas**, v. 41, p.25-40. 2009.

FERRON, F.A.; SIMÕES, J.C.; AQUINO, F.E. & SETZER, A.W. Air temperature time series for King George Island, Antarctica. **Pesquisa Antártica Brasileira**, v. 4, p. 155-169. 2004.

GURNELL, A. M. Suspended sediment. In **Glacio-Fluvial Sediment Transfer: An Alpine Perspective**, edited by A. M. Gurnell and M. J. Clarke. John Wiley. p. 305-354, 1987.

GURNELL, A.; HANNAH, D. & LAWLER, D. Suspended sediment yield from glacier basins. In **Erosion and Sediment Yield: Global and Regional Perspectives**, IAHS Publ. v. 236, p. 97–104, 1996.

HALLET. B. A theoretical model of glacial abrasion. **Journal of Glaciology**, v. 23, p. 39-50, 1979.

HALLET, B; HUNTER, L. & BOGEN, J. Rates of erosion and sediment evacuation by glaciers: A review of field data and their implications. **Global and Planetary Change**, v. 12, p.213–235, 1996.

HARBOR, J. & WARBURTON, J. Relative rates of glacial and nonglacial erosion in Alpine environments. **Arctic and Alpine Research**, v. 25, n. 1, p. 1-7, 1993.

HOOKE R.L.; BRZOZOWSKI, J. & BRONGE, C. Seasonal variations in surface velocity, Storglaciären, Sweden. **Geografiska Annaler**, v. 65A, p. 263-267, 1983.

HOWAT, I.M.; JOUGHIN, I.; TULACYK, S. & GOGINENI, S. Rapid retreat and acceleration of Helheim Glacier, east Greenland. **Geophysical Research Letters**, v. 32, 2005. L22502.

HUMPHREY, N.F. & RAYMOND, C.F. Hydrology, erosion and sediment production in a surging glacier: Variegated Glacier, Alaska, 1982-1983. **Journal of Glaciology**, v. 40, p. 539-552, 1994.

IVERSON, N.R. Potential effects of subglacial water-pressure fluctuations on quarrying. **Journal of Glaciology**, v. 37, n. 125, p. 27-36, 1991.

KOPPES, M.N. & HALLET, B. Influence of rapid glacial retreat on the rate of erosion by tidewater glaciers. **Geological Society America,** v. 30, n. 1, p. 47-50, 2002.

KOPPES, M. & HALLET, B. Erosion rates during rapid deglaciation in Icy Bay, Alaska. **Journal of Geophysical Research,** v. 111, p. 1–11, 2006. F2023,doi 10,1029/2005JF000349.

KOPPES, M.; HALLET, B. & ANDERSON, J. Synchronous acceleration of ice loss and glacier erosion, Glaciar Marinelli, Chilean Tierra del Fuego. **Journal of Glaciology**, v. 55, n. 190, p. 207-220, 2009.

KOPPES, M.; SYLWESTER, R.; RIVERA, A. & HALLET, B. Variations in sediment yield over the advance and retreat of a calving glacier, Laguna San Rafael, North Patagonian Icefield. **Quaternary Research**, v. 73, p. 84-95, 2010.

MACGREGOR, K.R.; RIIHIMAKI, C.A. & ANDERSON, R.S. Spatial and temporal evolution of rapid basal sliding on Bench Glacier, Alaska, USA. **Journal of Glaciology**, v. 51, n. 172, p.49-63, 2005.

MACGREGOR, R.S.; KELLY, R.; ANDERSON, E. & WADDINGTON, D. Numerical modeling of glacial erosion and headwall processes in alpine valleys. **Geomorphology**, v. 103, p. 189-204. 2009.

MOLL, A.; BRAUN, M. & LLUBERAS. A. Determination of glacier velocities on King George Island (Antarctica) by DInSAR. **Proceedings of the ESA FRINGE'06 Workshop**, Frascati. 2006.

MOREHEAD, M. D.; SYVITSKI, J. P.; HUTTON, E. W. H. & PECKHAM, S. D. Modeling the temporal variability in the flux of sediment from ungauged river basins. **Global Planetary Change**, v. 39, p. 95—110, 2003.

POWELL, R.D. Grounding-line systems as second-order controls on fluctuations of tidewater termini of temperate glaciers. In: Anderson, J. B. & G. M. Ashley, G. M. (Eds.) Glacial Marine Sedimentation: Paleoclimatic Significance. **Special Paper Geology Society America**, v. 261, p. 75-93, 1991.

RAKUSA-SUSZCZEWSKI, S; MIETUS, M & PIASECKI, J. Weather and climate. In: Rakusa-Suszczewski, S. (Ed.). The maritime Antarctic coastal ecosystem of Admiralty Bay. Warsaw: **Polish Academy of Sciences**, p. 19-25, 1993.

RIIHIMAKI, C.A.; MACGREGOR, K.R.; ANDERSON, R.S.; ANDERSON, S.P. & LOSO, M.G. Sediment evacuation and glacial erosion rates at a small alpine glacier. **Journal of Geophysical Research, Earth Surface**, v. 110, 2005. F03003, doi:10.1029/2004JF000189.

ROSA, K.K.; VIEIRA, R.; FERRANDO, F.A. & SIMÕES, J.C. Feições sedimentológicas e geomorfológicas do ambiente de deglaciação das geleiras Wanda e Ecology, ilha Rei George, Antártica. **Pesquisas em Geociências**, v. 36, p. 315-326, 2009. [Sedimentological and geomorphological features of the deglaciation environment of Wanda and Ecology glaciers, King George Island, Antarctica]. (In Portuguese).

ROSA, K.K.; VIEIRA, R.; Borges, G.; SIMOES, L.Felipe; SIMÕES, J.C. Formas glaciales y procesos glaciológicos del glaciar templado Wanda, Shetland del Sur. **Investigatciones Geográficas**, v. 43, p. 3-16, 2011.

ROSA, K.K.; VIEIRA, R.; FERNANDEZ, G.; MENDES Jr., C.W.; ARIGONY-NETO, J.; VELHO, L.F. & SIMÕES, J.C. (no prelo). Recent changes in the Wanda Glacier, King George Island, Antarctica. **Pesquisas em Geociências**, X–X.

RUBIN, D.M. & TOPPING, D.J. Quantifying the relative importance of flow regulation and grain-size regulation of suspended-sediment transport (α) and tracking changes in grain size on the bed (β). **Water Resources Research**, v. 37, n. 1, p. 133-146. 2001.

SUGDEN, D.E. & JOHN, B.S. **Glaciers and Landscape.** London: Edward Arnold. 1976. 376 p.

TURNER, J.; COLWELL, S.R.; MARSHALL, G.J.; LACHLAN-COPE, T.A.; CARLETON, A.M.; JONES, P.D.; LAGUN, V.; REID, P.; IAGOVKINA, S. Antarctic climate change during the last 50 years. **International Journal of Climatology**, v. 25, n.3, p. 279-294, 2005.

VAN DER VEEN, C.J. Tidewater calving. **Journal of Glaciology**, v. 42, n. 141, p. 375-385. 1996.

WEN J.; KANG, J.; XIE, Z.; HAN, J. & LLUBERAS, A. Climate, mass balance and glacial changes on small dome of Collins Ice Cap, King George Island, Antarctica. **Antarctica Research**, v. 5, p. 52-61, 1994.