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Short Communication

The Significance of Rock Glaciers in the Dry Andes – A Discussion of Azócar and Brenning (2010) and Brenning and Azócar (2010)

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INTRODUCTION

Two papers have recently been published in this journal (Azócar and Brenning, 2010; Brenning and Azócar, 2010) that are of interest to academia and to mining companies, practitioners, federal and municipal governments, and NGOs working in the High Andes of Chile and Argentina.

Sizable reserves of precious metals and other natural resources are concentrated in this area. Chile's political stability and favourable business climate as well as reasonably good access to prospective mines make this country a preferred location for exploration and mine development. Knowledge of the roles of the active layer, permafrost and ground ice in its different morphologies, as well as their influence on the annual and long-term hydrologic regime, is of major significance in the dry Andes. Agriculture and animal husbandry in the arid lowlands depend directly on summer runoff from the high mountain zones which also replenishes aquifers that are being exploited for the grape and wine industries.

Engineers and geoscientists involved in mine development depend to a considerable degree on published studies and base their conclusions upon their findings. The contents of environmental impact assessments (EIAs) are scrutinised by both government and NGOs, and so the validity of pertinent conclusions is important. Ongoing research on permafrost distribution, ground ice and specifically on rock glaciers is strongly supported by consultants and miners alike to further the scientific understanding of the Andean cryosphere. Recent legislative changes in Chile call for the preservation of glacial ice and large funds are being made available to study glacial ice loss (Dirección General de Aguas, 2010). Government regulators and NGOs have sharply criticised miners on several occasions based on the perceived hydrologic importance of permafrost. Because of this economic and political significance, such studies need to be well designed, carefully analysed and the conclusions based on transparent and replicable science. Unbalanced generalisation can unduly hinder mine developments and the application of false conclusions can be detrimental to the environment.

We believe that the two publications by Brenning and Azócar require discussion and clarification. Here, we (a) discuss the inclusion of ground ice outside of rock glaciers in the consideration of their hydrologic significance, (b) review the comparison of the hydrologic significance of glaciers and rock glaciers, and (c) address the methods used to determine spatial frequencies of rock glaciers.

HYDROLOGICAL SIGNIFICANCE OF ROCK GLACIERS AND GROUND ICE WITHIN THE PERMAFROST BELT

The two papers discuss important parts of the mountain cryosphere: (i) spatial distribution of rock glaciers (Brenning and Azócar, 2010), and (ii) water storage by rock glaciers (Azócar and Brenning, 2010). Ground ice present in other morphologic expressions of permafrost in the High Andes is not included in these analyses. Inclusion of ground ice outside of rock glaciers in the permafrost belt would enable a better perception of the hydrologic significance of rock glaciers and would allow firmer inferences with regard to total runoff from the permafrost-underlain areas.

Air photo interpretation and fieldwork in various locations together with test pitting, geotechnical drilling and geophysical surveying conducted by mining companies and their consultants at various locations in the High Andes demonstrate that vast areas in the dry Andes are covered by patterned ground, gelifluction forms, creeping slopes

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and ice-rich ground in areas devoid of rock glaciers. Consequently, it can be expected that the actual water equivalent stored in the ice-rich permafrost zones of the High Andes is significantly higher than in rock glaciers alone. However, as wide-ranging investigations on ground ice existence have yet to be conducted, we believe that estimating the potential water storage in the High Andes based on rock glaciers alone should be improved by adding estimates of the water balance from other permafrost-underlain areas. Furthermore, we encourage the authors to provide better justification of their reported uncertainties in rock glacier water equivalent estimations due to sampling variance, rock glacier thickness and ice content. While adding the individual error ranges results in a range of -64 per cent to +84 per cent, the authors summarise that the overall uncertainty may be in the order of -50 per cent to +100 per cent and should explain the substantial discrepancy.

Brenning (2005) studied rock glaciers in 12 areas in the Andes of central Chile that form the dataset on which the current articles are based. Brenning visited nine of these areas in the field (mapping at four sites, field reconnaissance at five sites). He states, 'The estimation of rock glacier thickness is based upon morphometric field measurements in the Andes of Santiago and is conservative if compared to the area-thickness relation used by Barsch (1977) in the Swiss Alps.' (Brenning, 2005, p. 24.) However, volume-area correlations as used by Brenning and Azócar (2010) may represent a spurious correlation because they compare a variable (area) with itself (area multiplied by depth used to obtain volume) thereby violating the principle of variable independence in regression analysis. The volume-area correlation reduces the large scatter in the relation between the originally measured areas and average thicknesses and suggests data quality that cannot be supported otherwise. Slope-dependent glacier thicknesses and volumes, for example, can be more reliably calculated from 3D glacier inventory data (e.g. Haeberli and Hoelzle, 1995; Linsbauer *et al*., 2009). For the calculation of the rock glacier water equivalent affected by the División Andina and Los Bronces mines, Brenning (2005, Table 2.9) further states, 'Own calculations assuming an average thickness of the ice-rich permafrost of 20–40 m, an ice content of 50% and an ice density of 0.9 g·cm^{-3}.' However, no test pitting, drilling, geophysical investigations, long-term terrestrial surveys or ground ice dating was carried out to support the assumptions underlying these estimates of the water equivalent of rock glaciers. In the absence of such investigations, the assumptions of an average ice-content of 50 per cent for rock glaciers based on references to rock glaciers in the European Alps appears simplistic. Reported ice contents of rock glaciers that have been drilled or in which ice contents have been established through geophysical means have a range from 10 per cent to 100 per cent, often varying significantly with depth (e.g. Potter, 1972; Francou *et al*., 1999; Haeberli *et al*., 2006; Hausmann *et al*., 2007). In the absence of similar data from Andean rock glaciers, the authors should use a similar range of values.

The statistical model provided by Brenning and Azócar (2010) should differentiate between active and inactive rock glaciers because water equivalents may differ, though this would need to be demonstrated through subsurface investigations. Inactive rock glaciers may be characterised by lower ice contents (no excess ice) because climate amelioration may have led ground ice to melt below a critical threshold that allows continued creep. However, even active rock glaciers may have average ice contents well below 50 per cent because a single ice-rich layer is sufficient to allow creep. Finally, core drillings from an active rock glacier in Switzerland showed volumetric air contents of up to 10 per cent (Arenson and Springman, 2005; Hausmann *et al*., 2007) that would further reduce the estimated water equivalent.

As indicated by Azócar and Brenning (2010), the hydrological significance of rock glaciers relates to the long-term storage of frozen water as well as the seasonal storage and release of water. Without direct runoff measurements, including detailed active-layer water balance measurements, it is very difficult, if not impossible, to quantify the various contributions to the annual hydrologic cycle. The statement that 30 per cent of stream discharge can be attributed to permafrost thaw (Azócar and Brenning, 2010, p. 50) may be based on a misunderstanding of Schrott (1996, p. 161) who wrote: 'Discharge measurements confirm that melting of frozen ground and meltwater from areas underlain by permafrost represent an important share (approx. 30%) of the river discharge during the summer months.' Schrott's statement does not quantify the amount of water that is thawing from degrading permafrost, but simply points out the importance of water contribution from the active layer and the significance of permafrost as an aquiclude. It is incorrect to attribute this amount of runoff to permafrost thaw and this may lead to incorrect conclusions regarding annual runoff from permafrost areas and the long-term role of ground ice on the hydrological regime in permafrost-underlain terrain. Furthermore, the hydrologic significance of rock glaciers cannot be equated with areas generally underlain by permafrost since rock glaciers only cover a fraction of the area underlain by permafrost in a given watershed and their hydrological behaviour may differ from the remaining terrain underlain by permafrost.

HYDROLOGIC SIGNIFICANCE OF ROCK GLACIERS AND GLACIERS

To emphasise the hydrologic significance of rock glaciers, the authors compare it with the water equivalent stored in glaciers (including surface ice and snow patches). This comparison needs to be improved by isolating the actual contribution of rock glacier ground ice to the hydrologic regime. Ground ice stored in rock glaciers is part of permafrost and therefore contributes very little to the annual runoff. In a typical year only water stored in the active layer may contribute to runoff. In particularly warm years, the active layer may deepen to liberate a small amount of water stored as ice in the uppermost part of the permafrost body, the transient layer (Shur *et al.*, 2005).

Rock glacier ice can be old (hundreds to several thousands of years; e.g. Haeberli *et al.*, 1999, 2006; Bachrach *et al.*, 2004; Berger *et al.*, 2004), in contrast to glacier ice, where a continuous mass exchange occurs at much shorter temporal scales (e.g. Paterson, 1994). The morphological processes and associated hydrologic significance on a range of spatial and temporal scales differ in the timing, amount and seasonality, and should be discussed to allow an unbiased comparison. Azócar and Brenning (2010) indicate that to date the hydrologic role of rock glaciers is unclear and there is a need for additional research. Nevertheless, comparisons between glaciers and rock glaciers are made with respect to the differences in sublimation and water storage (called 'sequestration' in the paper). These need to be supported by measurement and theoretical considerations.

SPATIAL FREQUENCY OF ROCK GLACIERS

Brenning and Azócar (2010) present an interesting tool to study the spatial frequency of rock glaciers. We believe that their analysis should be expanded by many more mapped samples to produce a statistically significant spatial frequency (referred to as 'density' in the paper) of rock glaciers. Microclimatic conditions that have been documented within topographic depressions (e.g. inversions) can result in permafrost at elevations significantly lower than the regional lower elevation limit found in an area, as has been shown for other areas in the world (e.g. Phillips *et al.*, 2009). We believe that the lower limit of active rock glacier occurrence, which follows a modern air temperature criterion selected by the authors, requires revision. Current climate conditions, such as mean annual air temperature are used in the statistical model to evaluate rock glacier occurrence. Since rock glaciers formed thousands of years ago, we believe that a number of climatic variables as well as geomorphic indicators need to be considered to evaluate historic rock glacier formation rather than merely present-day air temperatures. Ammann *et al.* (2001), for example, state that at latitude 27°S the present 0°C isotherm lies far below the modern and the late-Pleistocene equilibrium line altitude (ELA). The limiting factor for glaciers in this region is the lack of humidity rather than temperature. This lack of humidity likely affected rock glacier formation in the dry Andes and differs significantly from the climatic past in more temperate mountain permafrost regions of the world. Even though air temperatures favoured permafrost aggradation, the paucity of water limited the development of ice-rich frozen ground.

CONCLUSION

We commend the authors of the two papers for addressing a frequently debated and important topic, namely that of the hydrologic significance of rock glaciers. However, we observe that they use assumptions that require further calibration through field measurements and need to be linked to underlying theory. Reported error ranges for rock glacier ice content should be supported by data. The portrayal of rock glaciers as significant water resources needs to be tested through monitoring and theory. We do not believe that rock glaciers can be significant in supplying water annually at the watershed scale if for no other reason than in most watersheds rock glaciers encompass only a small percentage of the perennially frozen ground. Over the long term, and under an increasingly warming climate, we also expect the hydrologic contribution of rock glacier ice melt to be below what can reasonably be measured, because ice loss in a rock glacier is orders of magnitude slower than from a glacier. Heat diffusion at depth is slow, latent heat effects retard ice melt and the coarse-grained active layer promotes complex heat exchange processes between the atmosphere and the ground (Hanson and Hoelzle, 2004). The principal conclusion by Brenning and Azócar (2010) that rock glaciers are important stores of frozen water and thus of critical importance for EIAs of mining projects cannot be upheld with the data and analyses presented. While we concur with the authors that more research is needed and welcome further discussion, we believe that their conclusions as to the hydrologic significance of rock glacier ground ice on the hydrologic cycle will not help overcome existing misconceptions.

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REFERENCES

Ammann C, Jenny B, Kammer K, Messerli B. 2001. Late Quaternary glacier response to humidity changes in the arid Andes of Chile (18–29 degrees S). *Palaeogeography, Palaeoclimatology, Palaeoecology* **172**(3–4): 313–326. DOI: 10.1016/S0031-0182(01)00306-6.

Arenson LU, Springman SM. 2005. Triaxial constant stress and constant strain rate tests on ice-rich permafrost samples. *Canadian Geotechnical Journal* **42**(2): 412–430. DOI: 10.1139/t04-111.

Azócar GF, Brenning A. 2010. Hydrological and geomorphological significance of rock glaciers in the dry Andes, Chile (27°–33°S). *Permafrost and Periglacial Processes* **21**(1): 42–53. DOI: 10.1002/ppp.669.

Bachrach T, Jakobsen K, Kinney J, Nishimura P, Reyes A, Laroque CP, Smith DJ. 2004. Dendrogeomorphological assessment of movement at Hilda rock glacier, Banff

National Park, Canadian Rocky, Mountains. *Geografiska Annaler. Series A, Physical Geography* **86**(1): 1–9. DOI: 10.3959/1536- 1098-60. 1.59.

Barsch D. 1977. Eine Abschätzung von Schuttproduktion und Schutttrasport im Bereich aktiver Blockgletscher der Schweizer Alpen. *Zeitschrift für Geomorphologie* **28**: 148–160.

Berger J, Krainer K, Mostler W. 2004. Dynamics of an active rock glacier (Ötztal Alps, Austria). *Quaternary Research* **62**: 233–242. DOI: 10.1016/j.yqres.2004.07.002.

Brenning A. 2005. Climatic and geomorphological controls of rock glaciers in the Andes of Central Chile: Combining statistical modeling and field mapping. PhD thesis, Mathematisch-Naturwissenschaftliche Fakultät II, Humboldt-Universität, Berlin, Germany.

Brenning A, Azócar GF. 2010. Statistical analysis of topographic and climatic controls and multispectral signatures of rock glaciers in the dry Andes, Chile (27°–33°S). *Permafrost and Periglacial Processes* **21**(1): 54–66. DOI: 10.1002/ppp.670.

Dirección General de Aguas. 2010. Gobierno da a conocer estrategia nacional de estudio y protección de glaciares. Information by the Ministry of Public Works, 21 February 2010. http://www.conama.cl/portal/1301/article-47576.html [25 April 2010].

Francou B, Fabre D, Pouyaud B, Jomelli V, Arnaud Y. 1999. Symptoms of Degradation in a Tropical Rock Glacier, Bolivian Andes. *Permafrost and Periglacial Processes* **10**(1): 91–100. DOI: 10.1002/(SICI)1099-1530(199901/03)10:1<91.

Haeberli W, Hoelzle M. 1995. Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. *Annals of Glaciology* **21**: 206–212.

Haeberli W, Kääb A, Wagner S, Geissler P, Haas JN, Glatzel-Mattheier H, Wagenbach D, Vonder Mühll D. 1999. Pollen analysis and ^{14}C-age of moss remains recovered from a permafrost core of the active rock glacier Murèl/Corvatsch (Swiss Alps): Geomorphological and glaciological implications. *Journal of Glaciology* **45**(149): 1–8.

Haeberli W, Hallet B, Arenson LU, Elconin R, Humlum O, Kääb A, Kaufmann V, Ladanyi B, Matsuoka N, Springman S, Vonder Mühll D. 2006. Permafrost creep and rock glacier dynamics. *Permafrost Periglacial Processes* **17**(3): 189–214. DOI: 10.1002/ppp.561.

Hanson S, Hoelzle M. 2004. The thermal regime of the active layer at the Murtel rock glacier based on data from 2002. *Permafrost and Periglacial Processes* **15**(3): 273–282. DOI: 10.1002/ppp.499.

Hausmann H, Krainer K, Brückl E, Mostler W. 2007. Internal structure and ice content of Reichenkar rock glacier (Stubai Alps, Austria) assessed by geophysical investigations. *Permafrost and Periglacial Processes* **18**(4): 351–367. DOI: 10.1002/ppp.601.

Linsbauer A, Paul F, Hoelzle M, Frey H, Haeberli W. 2009. The Swiss Alps without glaciers – a GIS-based modelling approach for reconstruction of glacier beds. In R.S. Purves, S. Gruber , R. Straumann T. Hengl (Eds.) *Proceedings of Geomorphometry 2009*. University of Zurich, Zurich, http://www.geomorphometry.org (pp. 243–247) [25 April 2010].

Paterson WSB. 1994. *The Physics of Glaciers*. Elsevier Science Ltd.: Burlington, Massachusetts.

Phillips M, Mutter EZ, Kern-Luetschg M, Lehning M. 2009. Rapid degradation of ground ice in a ventilated talus slope: Flüela Pass, Swiss Alps. *Permafrost and Periglacial Processes* **20**(1): 1–14. DOI: 10.1002/ppp.638.

Potter N Jr. 1972. Ice-Cored Rock Glacier, Galena Creek, Northern Absaroka Mountains, Wyoming. *GSA Bulletin* **83**(10): 3025–3058. DOI: 10.1130/0016-7606 (1972). 3[3025:IRGGCN]2.0.CO;2

Schrott L. 1996. Some geomorphological-hydrological aspects of rock glaciers in the Andes (San Juan, Argentina). *Zeitschrift für Geomorphologie* **104**: 161–173.

Shur Y, Hinkel KM, Nelson FE. 2005. The transient layer: implications for geocryology and climate-change science. *Permafrost and Periglacial Processes* **16**(1): 5–17. DOI: 10.1002/ppp.518.

