Upscaling of geophysical measurements: A methodology for the estimation of the total ground ice content at two study sites in the dry Andes of Chile and Argentina

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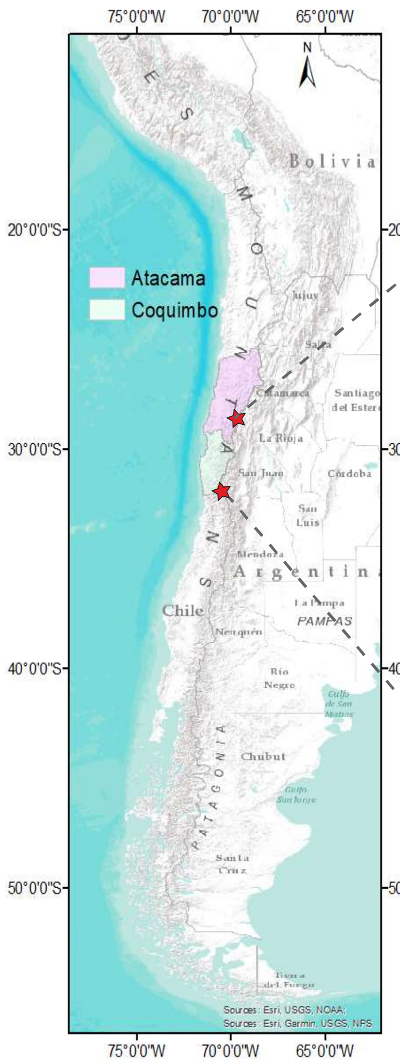
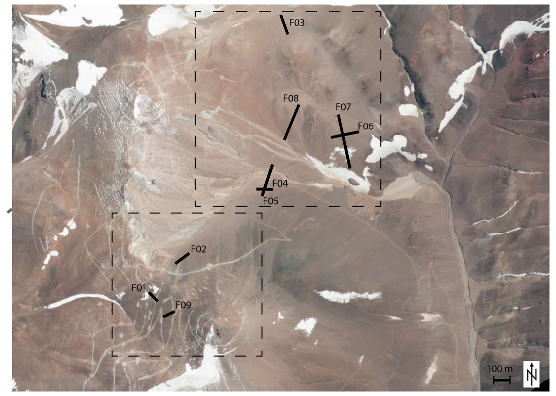
It is currently debated, whether ground ice from permafrost terrains can be considered as a significant water reservoir and as an alternative resource of fresh water. In the Central Andes, data on permafrost and understanding of the Andean cryosphere in general is scarce, especially in areas devoid of glaciers and rock glaciers. Furthermore, assumptions on ground ice contents exist solely for rock glaciers and estimated ground ice contents are predominantly based on a questionable empirical rule of thumb (Brenning, 2005; Azocar and Brenning, 2010; Arenson and Jakob, 2010). The main goals of this study were to (i) **estimate ground ice contents based on in-situ geophysical measurements (ERT and RST) and using the Four Phase Model (4PM)** (Hauck et al., 2011), (ii) **develop an upscaling methodology** to estimate ground ice contents over a larger area and (iii) c**ompare non-rock glacier permafrost terrains to rock glacier dominated sites** with regard to their respective ground ice contents.

Study Sites



Site 1

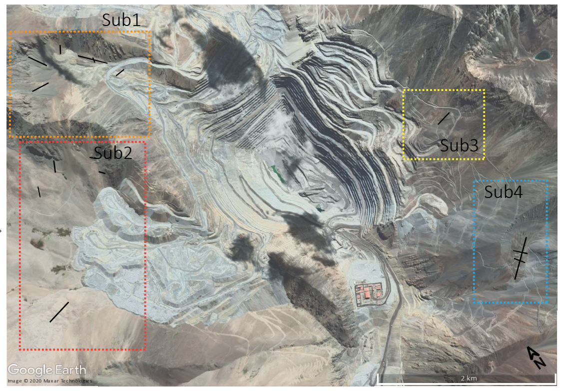
field campaign in 2018



- 5000- 5500 m a.s.l
- **Thick, fine grained sediment layer**
- Solifluction lobes and patterned ground
- Uniform landscape and homogeneous subsurface structure
- Ground ice in form of sediments with interstitial ice or ice-lenses

Site 2

field campaign in 2016 and 2017



- around 3500 m a.s.l
- **Rock glaciers**
- other distinctive landforms (e.g. talus slopes,...)
- Permafrost limited to rock glaciers (and partly talus slopes)

Methodology

Refraction Seismic Tomography (RST)

Electrical Resistivity Tomography (ERT)

Four Phase Model (4PM)

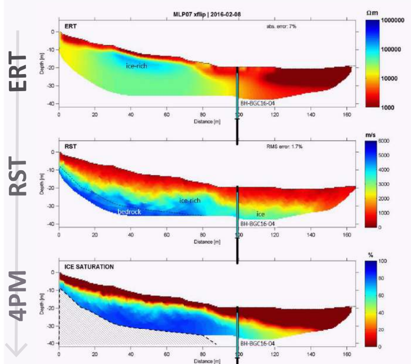
(Quantitative) Ice Content Estimation

Data Basis:

Site 2:
- 13 RST profiles
- 17 ERT profiles

Site 1:
- 4 RST profiles
- 21 ERT profiles

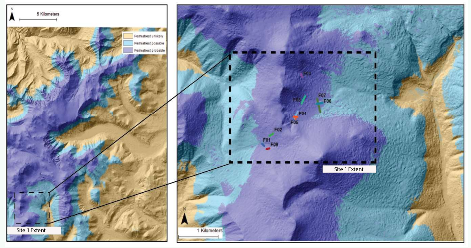
Example Data



Source: Hilbich et al., 2018

Testpits | DEMs | Boreholes | Geophysics

Permafrost distribution model



Very simple permafrost distribution model:

$Y(x) = b_0 + b_1$ **elevtion(x)** $+ b_2$ **PISR(x)**

Allows to exclude areas where permafrost is unlikely

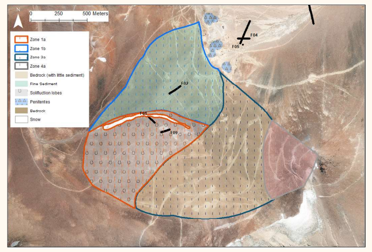
Classification of the catchment

Notes from Fieldwork

Photo interpretation

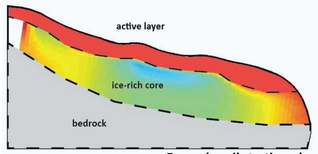
DEMs

Geophysics



Catchment classification:

- Mapping of **surface type and/or landforms**
- Consideration of **slope** (sediment cover = less thick) and **aspect** (important factor for energy balance)
- **Results of geophysics** to detect and analyze differences in subsurface conditions (e.g influence of surface type)



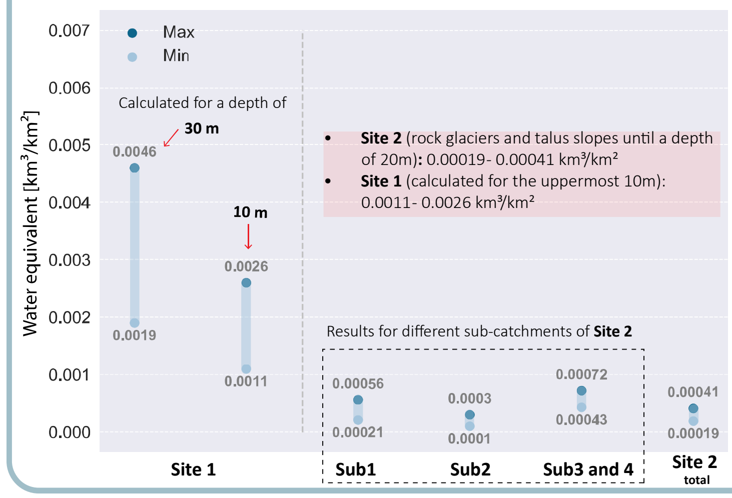
Example soil stratigraphy from ERT: 3 layers (active layer, ice-rich layer, bedrock)

Assignment of one conceptual soil stratigraphy model (based on geophysics) per upscaling class:

- **Number of layers detected from the geophysics**
- Estimation of **thickness**, **ice saturation** (**4PM using petrophysical relations** where available, otherwise by interpretation of the ERT results and observations, test, pits and boreholes) and **porosity** of each layer (i)

Calculation of total ground ice content [km^3] of each catchment
(& conversion to water equivalent assuming an ice density conversionfactor of 0.9 g cm^{-3})

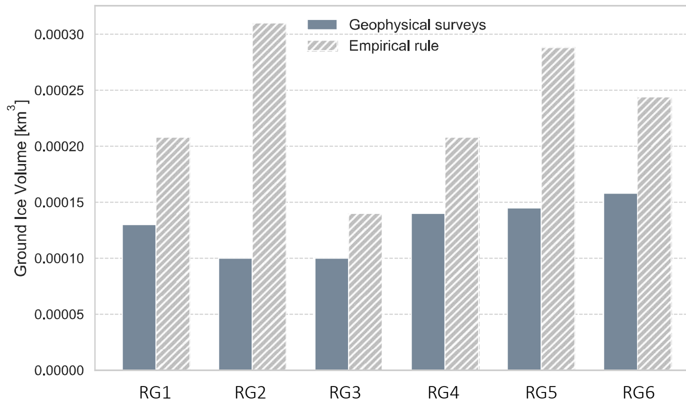
Results



This summary figure of our results shows the water equivalents calculated based on the geophysical surveys and upscaling methodology for the two study sites. In each case an estimation for a minimum, maximum and mean ground ice content was made, resulting in the water equivalent ranges displayed in the figure to the left. When considering the entire catchment areas the **water equivalent contained in the ground ice of Site 1 is significantly larger than what was estimated for Site 2.** This is because ground ice is limited to rock glaciers in Site 2, whereas Site 1 is in a zone of continuous permafrost.

Discussion and Conclusions

Our results have shown that ground ice within non-rock glacier permafrost may contribute significantly to the total ground ice content of a catchment (and may even be larger in total than ground ice within rock glaciers).



- This figure compares ground ice volumes for rock glaciers in Site 2 a.) based on the presented method (geophysics + substrate classification + simple PF distribution model and b.) based on the empirical rule by Brenning (2005) for the same rock glaciers. **Rock glacier thickness and corresponding ground ice contents are largely over-esimated when using the empirical rule established by Brenning (2005) in comparison to the results of our geophysical surveys.** Using an empirical rule clearly overgeneralizes the complex subsurface conditions and ground ice contents of rock glaciers. The comparison demonstrates the importance of in-situ measurements (e.g., geophysics) for the estimation of ground ice contents. This is also highlighted by the results of Halla et al., 2020.
- **Ice-rich permafrost terrain aside from rock glaciers may contain significant volumes of ground ice over large areas** and should therefore be considered for the assessment of the **hydrological importance** of permafrost as well.

References:

Arenson, L. and Jakob, M. (2010). The Significance of Rock Glaciers in the Dry Andes – A Discussion of Azocar and Brenning (2010) and Brenning and Azocar (2010), Permafrost and Periglac. Process., 21: 282-285.

Brenning; A. (2005). Climatic and Geomorphological Controls of Rock Glaciers in the Andes of Central Chile: Combining Statistical Modelling and Field Mapping, Ph.D. thesis, Humboldt-University, Berlin.

Halla, C. Blöthe, J.H., Tapia Baldis, C., Trombotto, D., Hilbich, C., Hauck, C. and Schrott, L. (2020). Ice content and interannual water storage changes of an active rock glacier in the dry Andes of Argentina, The Cryosphere Discuss.

Hilbich, C. and Hauck, C. (2018). Geophysical surveys in Filo del Sol, Chile/Argentina, Report, University of Fribourg

Azocar, G.F. and Brenning, A. (2010). Hydrological and Geomorphological Significance of Rock Glaciers in the Dry Andes, Chile (27°- 33° S), Permafrost and Periglac. Process., 21: 42-53.

Hauck, C., Böttcher, M., and Maurer, H. (2011). A new model for estimating subsurface ice content based on combined electrical and seismic datasets, The Cryosphere, 5: 453-468.

Hilbich, C., Mollaret, C. and Hauck, C. (2018). Geophysical Surveys Mineras Los Pelambres (2016) and Rio Blanco (2017), Chile. Report, University of Fribourg.