Authors' Comments AC_tc-2022-165

Brief communication: Combining borehole temperature, borehole piezometer and cross-borehole electrical resistivity tomography measurements to investigate changes in ice-rich mountain permafrost (Phillips et al.)

Reply to Referee #1

Dear Referee 1,

thank you very much for your positive and constructive feedback. Please find our replies to your suggestions below (in blue, **suggested changes in bold script***).*

With kind regards,

Marcia Phillips, Chasper Buchli, Samuel Weber, Jacopo Boaga, Mirko Pavoni and Alexander Bast.

L20: Consider one or two sentences that briefly summarize the major advances related to modern quantitative measurements of geophysical parameters on rock glaciers in the Alps, from e.g. Vonder Mühll and Haeberli (1990) until today.

We suggest adding the following to the Introduction (Line 29 onwards):

Many Alpine rock glaciers are close to their melting point (PERMOS 2019), and borehole temperature data do not allow to distinguish between ice and water close to 0°C, so relative changes in ice-/water content have to be monitored using geophysical methods detecting changes in resistivity (Mollaret et al., 2019). **Electrical resistivity methods have been established in mountain permafrost terrain in the past few decades and deliver increasingly detailed information, including quantitative estimation of water storage, ice contents, water flow and temperature (Hauck 2013).** Continuous surface electrical resistivity data (ERT) provide valuable 2D information on resistivity changes in ice-rich permafrost substrates.

(*We will thus add the following reference):*

Hauck, C.: New Concepts in Geophysical Surveying and Data Interpretation for Permafrost Terrain, Permafrost and Periglacial Processes, 24, 131-137, https://doi.org/10.1002/ppp.1774, 2013.

L23-27: Maybe worth mentioning one or some previous studies on rock glaciers that used similar approach as your study, with a combined application of geophysical techniques with cross-hole experiments (georadar cross-hole tomography). e.g. Maurer et al. 2003., Musil et al. 2006 and Springmann et al. 2012. Although these studies aimed at delineating internal structure and investigating the stability of rock glaciers, there are some relevant findings that could be discussed in light of your results.

Thanks for the useful literature! We propose to modify the introduction thus:

Line 27 onwards:

…However, there is little direct information on the internal hydrology of rock glaciers (Zenklusen Mutter and Phillips, 2012), changes in ice-/water contents or talik formation. A substantial unfrozen water content can persist well below 0°C, depending on soil properties, salinity and pore water pressure (Arenson et al., 2022), **as was shown by Musil et al. (2006), using crosshole georadar measurements in the Muragl rock glacier.**

Line 33 onwards:

However, 2D ERT soundings can only provide limited information with increasing depth. **Cross-borehole measurements such as georadar (Musil et al 2006) or cross-borehole ERT overcome this limitation by using at least two vertical boreholes for instrument locations (Binley, 2015).** Until present, **cross-borehole ERT** has primarily focused on groundwater research, especially on the remediation of contaminated groundwater (Binley and Slater, 2020) or to determine substrate characteristics, but has never been applied in mountain permafrost environments.

L44: The use of "continues measurements" in this respect is somewhat misleading as data presented are only for one day in summer and for one day in mid-winter. Consider rephrase.

To clarify we suggest the following change (please note: the measurements are designed to be carried out continuously and are running, but we only show two data snapshots in this Brief Communication):

'Here we present **first data snapshots from** a novel combination of borehole temperature, borehole piezometer and cross-borehole ERT measurements designed to investigate the changes occurring in an ice-rich rock glacier, in particular modifications of ice-to-water ratio near 0°C, with continuous measurements'.

L137-138: Is there a citation to backup the statement regarding piezometer data and how ice formation might affect the pressure?

To our knowledge, this is a first-time application of piezometers in ice-rich permafrost terrain. However, Harris & Davies (1998) made the following observation regarding their laboratory experiments:

'In the present case it is argued that the rapid transition from negative to positive readings during freezing is in response to the sealing of the pressure transducer within an effectively closed frozen soil system. The transducer became isolated from pore fluid films and dominated by the positive ice pressures which develop during heave. Since there is considerable uncertainty as to the mechanism of pressure transfer from the heaving soil to the transducer it cannot be assumed that pressure readings necessarily accurately reflect ice pressures'.

We therefore propose to add:

The piezometer data must be interpreted with care: if ground temperature drops below 0°C, ice formation might strongly affect the pressure measured in the sensor's housing and thereby not fully represent the dominant pressure condition at a given depth. **Similar challenges were encountered by Harris and Davies (1998) in laboratory experiments. Further laboratory experiments will be necessary…**

L157-159: Include a couple of sentences with some more details about the future plans for this work and monitoring. What could a more in-depth analysis, and e.g. more data from all seasons and inter-annual variability add to new knowledge?

To address future work and the associated increase in knowledge, we propose to delete the last sentence and replace it with a new paragraph:

Nevertheless, future analysis will reveal daily but also medium- to long-term interannual and inter-seasonal changes in rock glacier water content, which will be correlated with meteorological variables. This information contributes towards i) closing the gap regarding the direct quantification of rock glacier water content and ii) a better understanding of climate change impacts. The unique combination of methods presented here will provide valuable insight on local rock glacier substrate characteristics and relative ice-to-water ratios, thus contributing to understanding factors driving accelerating rock glacier kinematics and future water availability from these landforms.

Literature suggested by Reviewer 1: *(we propose to cite Musil et al. (2006) in the Introduction)*

H.R. Maurer, S.M. Springman, L.U. Arenson, M. Musil, D. Vonder Mühll Characterisation of potentially unstable mountain permafrost — a multidisciplinary approach. Proceedings of the 8th International Conference on Permafrost, Zurich, Switzerland (2003), pp. 741-746

To be added to the references:

Musil, M., Maurer, H.R., Hollinger, H. and Green, A.G., 2006. Internal structure of an alpine rock glacier based on cross hole georadar travel times and amplitudes. Geophysical Prospecting, 54 (3), 273–285.

Springman, S.M., Arenson, L.U., Yamamoto, Y., Maurer, H., Kos, A., Buchli, T. andDerungs, G., 2012. Multidisciplinary investigations on three rock glaciers in the Swiss Alps: legacies and future perspectives. Geographiska Annaler: Series A, Physical Geography, 94, 215–243. doi:10.1111/j.1468- 0459.2012.00464.x

Vonder Mühll, D. and Haeberli, W., 1990. Thermal characteristics of the permafrost within an active rock glacier (Murtèl-Corvatsch, Grisons, Swiss Alps). Journal of Glaciology, 34 (123), 151–158.