

The Cryosphere Discuss., author comment AC2
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Reply on RC2

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Author comment on "Comment on "Ice content and interannual water storage changes of an active rock glacier in the dry Andes of Argentina" by Halla et al. (2021)" by W. Brian Whalley, The Cryosphere Discuss., <https://doi.org/10.5194/tc-2021-88-AC2>, 2021

Thank you for your comments. I fill in some detail here in direct response to your remarks (other information is provided below). I have tried to keep these succinct and directly related to what is particularly pertinent.

- As my comments were primarily about field observations (see 1, supra), I only included two papers about the rheology of ice rock mixtures. It is the mechanical nature of the mixture model (rock/ice-snow/water/air) that determines the rheology. A thin glacier (<30m thick, slope angle ca 10° , with an ablation-reducing debris cover) will flow at rock glacier velocities, $< 1 \text{ m a}^{-1}$. However, talus (scree or rockfill) as an 'ice sparse' composite will not flow unless the ice content is high (perhaps >60%) and in thick ($\approx 20 \text{ m}$) deformable bands or lenses. The geophysical signature of a rock glacier at any location depends upon the field-mixture model, as well as the volume examined, given its inhomogeneity and anisotropy. The permafrost model correlates geophysical signatures to a formational mode for all rock glaciers (i.e. exclusively of non-glacier origin, see 17 below). My commentary suggests there is directly observable field evidence for a glacial origin for the deforming ice at DL. But, as Lliboutry noted (1990) of a comment by Haeberli (1989), 'I do not deny that many (not all) rock glaciers are below melting point at depth'.
- Why don't all the slopes in the area show flow-features when, in a known permafrost area, there are plentiful scree slopes? The answer is that they will do so only if there is a thick enough body of ice, as a glacier in a conventional sense or with a thick snow/ice body covered with debris (5). On cliffed slopes with snow avalanching, this can be achieved if perennial snow accumulates (and is buried, perhaps sequentially, under debris). This is the point made by reference to rheology in Whalley and Azizi (2003) and the mixture model (see 5). It is the creep of massive ice, not rock debris – even if this is in a permafrost area. Permafrost is not necessary, but it is sufficient to keep creep rates lower than at ice pressure melting point. As an illustration, the transect, 1: $\{-30.2423, -69.7670, 260\}$ down the centre of DL rock glacier can be compared with a parallel transect, 2: $\{-30.24908, -69.76338, 270\}$. The latter, some 700 m to the south of 1, is representative of much of that mountainside and must be under the same environmental conditions, temperature, snowfall and ablation, as the rock glacier, 1. However, transect 2 shows no signs of flow. The reason must lie in the 'mixture model', debris from the upper slopes has covered a perennial snowpack of a 'buried glacieret', 'buried debris-rich glacieret' or '**glacier enterré**' (Lliboutry, 1961; Lliboutry, 1990).

That there is no glacier/glacieret remnant showing at 1 is because the thick ice mass necessary for flow is covered with debris from above. The top of this original, small and confined, glacier would have been under the cliffs in the vicinity of Google Earth locality [-30.2429,-69.7747] and fed down gullies higher on the slope. Extant equivalents can be seen at the top of gullied south-facing slopes in the vicinity of [-30.23512,-69.83599]. The glacier and its protecting debris load have now crept downhill and formed the DL rock glacier. A short transect {-30.24318,-69.77858,160} for about 150 m, i.e. some 250 m east of the Halla et al. 'root zone' transect, is lower in the centre (by 5-10m) from the edges. This shows that ice had flowed out of this area and has not been replaced. This effect is similar to other rock glaciers with extending flow regimes (Whalley and Palmer, 1998, Whalley, 2021b).

- Observations using GE brings to light further changes in surface topography of rock glaciers, notably the appearance of pools that show melting of ice below the surface debris. Recent coverage by GE shows meltwater pool exposures are becoming increasingly common. Ridges and furrows, piled up in lower (snout) regions are the result of basically compressive glacier flow with debris loads becoming increasingly thick near and at the snouts. This inhibits melting further from upstream amounts (where the debris load is thinner). Glaciers and rock glaciers may exhibit extending flow where, usually on steeper slopes and perhaps more restricted valley sections, transverse ridges and furrows are replaced by irregular or longitudinal features. Meltwater pools can form variously in them according to local topography and thickness of the debris cover.
- These meltwater pools can be of considerable size, that shown in my Fig 1 at [-30.2413,-69.8542] has a water area of about 3 000 m² and has been in existence at least between 2006 – 2019 (from GE imagery). The total 'missing' volume of rock glacier is some 40 x 10³ m³, suggesting that the mixture model is predominantly of high percentage (massive) ice from a buried glacier tongue. This is commensurate with the sides of a 'thermokarst depression' shown (Figure 4) of Trombotto-Liaudat and Bottegal (2020) at Morenas Coloradas debris-covered glacier [-32.9426,-69.3988] although the exact location is not given. Other long-lived meltwater pools can be seen up-valley to the exposed glacier at Morenas Coloradas, further examples can be seen in some of the images in Janke et al. (2015). Whether rock glaciers extend back into visible debris free and debris-covered versions (as suggested in the classification of Janke et al. (2015)) depends upon the relative inputs of glacier ice and weathered debris over time. The Colina Mountain example (Janke et al., 2015, Fig. 21B) [-34.3428,-70.0492] has a continuum of classes of debris-covered glacier/rock glacier with surface forms that include meltwater pools [-34.3437,-70.0486] & [-34.3494,-70.0583] and lateral erosion of pool with an exposed glacier ice cliff [-34.3571,-70.0718].