On rock-glacier permafrost in global climate observation – Reply to community comments

We thank Stephan Harrison and Brian Whalley/Fethi Azizi for their Community Comments. Their texts document their personal ideas, beliefs and opinions concerning rock-glacier origins. Their argumentation is essentially based on intuitive landform interpretation from visual surface inspection and in view of "airing competing (and sometimes contradictory) views in science", as Harrison formulates it.

Our contribution relates to internationally coordinated permafrost and glacier programs for UN/ICSU-related global climate-system observation that are based on consensus from multiple rock glacier researchers. Within this policy-relevant framework, science has the responsibility to strictly relate to measured facts about the involved conditions, materials, processes and time scales. Referring to the measured evidence provided in our contribution and based on the advanced state of quantitative knowledge available in the modern literature about permafrost and glaciers in cold mountain regions (cf. the references in our article), we here briefly repeat and summarise some most essential points.

1. The long-term existence of subsurface ice in rock glaciers first of all relates to thermal conditions. To define such thermal conditions is, therefore, a basic requirement for climate-related research and observation of permafrost and rock glaciers. Quantitative information is obtained from climate data, miniature temperature logging, borehole measurements or numerical model calculations (e.g., Haq and Baral 2019, Baral and Haq 2020, Li et al. 2023), optimally in combination, and if possible supported by geodetic measurements of flow characteristics to define activity levels (cf. Bertone et al. 2023). The results are clear, especially also in view of specifically cold microclimatic conditions (mountain shadow, ventilated blocks at the surface, long-lasting seasonal snow), which characterise most rock glaciers: active, ice-containing rock glaciers occur where mean annual temperatures are typically negative or have until recently been negative. The technical term permafrost defines this specific geothermal condition (negative subsurface temperature throughout the year; Muller 1947). With other words: Ice-containing rock glaciers are – independently of any material characteristics – thermally in a permafrost condition.

2. As a consequence, the question "is it permafrost or is it a glacier?" as it seems to be central in the Whalley/Azizi comment and in the theoretical concept of "equifinality" of rock glacier origins as maintained by Harrison, is inconsistent. The real question is whether and, if yes, under what conditions and to what extent various forms of buried surface ice can be part of mountain permafrost.

3. Negative subsurface temperatures in nature induce freezing processes. In the case of rock glacier permafrost, freezing processes are forced by negative sub-zero temperatures typically lasting over millennial time scales as documented by numerous absolute age determinations. Such slow and long-term freezing at depth produces large amounts of ice inside the affected rock material. An increasing number of core drillings and borehole geophysics, together with hundreds of sophisticated geophysical soundings definitely document that rock-glacier permafrost consists of perennially frozen ice-rock mixtures with characteristic electrical resistivities of tens to hundreds of kΩm (Herring et al., 2023). Ice contents by volume are locally variable but mostly far larger – on average by about a factor of two – than the pore volume of

the original rock material under unfrozen conditions (Hausmann et al. 2007; Monnier and Kinnard 2015). Small and large lenses of massive ice from ice segregation in frost-susceptible materials (silts, fine sands) are common.

4. Mostly thin and isolated remains of surface ice with extreme electrical resistivities (MΩm) can in cases be embedded in these ice-rich frozen sediments, primarily in upper parts of rock glaciers. They are clearly the exception rather than the rule. The belief that rock glaciers could entirely be debris-covered Little Ice Age glaciers has long been disproved by drillings, geophysical soundings and absolute age dating. It is difficult to understand for us, how the Whalley/Azizi comment can maintain such an unrealistic idea against the rich quantitative information available for decades already from modern research on mountain permafrost.

5. The development by long-term freezing processes of excess ice or ice-supersaturation inside the affected rock material induces fundamental changes in the material properties and geotechnical characteristics of originally non-cohesive talus/debris material with high internal friction. The rheology of such materials in perennially frozen, ice-supersaturated condition with high cohesion and reduced internal friction constitutes a classical topic in permafrost engineering. It is generally defined as a function of applied stress, temperature and ice content, all of which vary spatially. Unfrozen water contents, which depend on the unfrozen water characteristic of the sediments present in the rock glacier (mainly driven by the fines content), increase at near-thawing temperatures and thereby certainly induce important effects (including a reduction in effective stress). Such characteristics help with explaining the documented ongoing, warming-induced increase of creep rates in rock-glacier permafrost. Again, it is difficult to understand for us how the Whalley/Azizi comment can continue to deny this long-established quantitative knowledge and understanding.

6. The focus and primary interest of climate-related glacier and permafrost observation in cold mountains concerns the ongoing dynamic evolution. Using modern geodetic/remote-sensing methods, coherent flow fields and their changes in time can be determined with high precision and over large areas, including remote sites (cf. Figures Sup.-3 and Sup.-4). The obtained results can be compared with measured or numerically modelled changes in thermal conditions. Related inventory work concerning rock glaciers and (debris-covered) glaciers should focus on landforms, which are clearly recognizable as such and which can be discriminated from each other. The permafrost and glacier networks (GTN-P and GTN-G) of GCOS/GTOS under the umbrella of international scientific associations (IPA, IACS) are well organized for such work. Complex contact zones of surface ice and permafrost, however, are beyond straightforward "either-or" landform schemes, should neither be included in permafrost nor glacier inventories, but need further exploration.

7. Exploring contacts and combinations of surface and subsurface ice with their strikingly different response characteristics concerning atmospheric warming is indeed a growing field of advanced research. It involves quantitative treatment of material properties and processes. This by far exceeds the possibilities of speculative interpretations based alone on visual surface inspection. A recent example illustrating the potential of multimethod field measurements to be used in such complex cases is the comprehensive investigation at the Chauvet site in the French Alps (Cusicanqui et al. 2023).

Specific remarks on the Whalley/Azizi comment:

- Gruben glacier is not “indicated as a ‘cold, debris-covered glacier tongue’ with no evidence for its temperature regime”. Gruben glacier is documented to be polythermal based on published borehole temperatures, radio-echo soundings and glacier-bed resistivities as explained in our contribution.

- Gruben rock glacier is not “interpreted … as a permafrost body because of the low surface velocity (<1m/a); a kinematic explanation“. Gruben rock glacier is documented (a) to be in permafrost condition based on measured temperatures combined with spatial permafrost mapping/numerical modelling, and (b) to consist of perennially frozen debris based on comprehensive geophysical soundings and core drilling; few, thin and isolated remains of buried surface ice only exist in the former contact zone with the Little Ice Age glacier.

- Melt pools preferentially form in massive buried ice, especially where those are embedded in permafrost. The reason is, that the low hydraulic permeability of ice-rich frozen ground underneath the melting buried ice helps keeping the water in the thermokarst depressions. The well-documented thermokarst lake at Gruben is a striking example. The generally limited areas and depths of melt pools indicates limited spatial extents and thicknesses of buried surface ice occurrences on rock glaciers.

- The statement “steep frontal RG slopes are not ‘over steepened’, they are at the appropriate resting angle of the granular material“ is a fundamental misunderstanding, ignoring the involved dynamic processes and multiple field measurements. The fronts of actively advancing rock glaciers like Gruben rock glacier, and of distinct as well as indistinct creep features at Yerba Loca are constantly being over-steepened by the forward movement of the creeping frozen body with highest velocities at its top as documented by borehole deformation (cf. also Figure Sup.-3 in the supplement). The oversteepening in the upper part of the rock glacier front is caused by suction that forms in the unsaturated material, which may also be referred to as an apparent cohesion. Constant over-steepening is the reason why the upper parts of actively advancing fronts of rock glaciers and even of less distinct features of permafrost deformation remain unstable, causing continued rock falls, as the creeping body deforms, or the suction decreases, for example during a rainfall when water enters the ground. Such rock falls can include coarse blocks from the rock-glacier surface and build up the characteristic talus aprons at the foot of many fronts (cf. Figure Sup.-3) . This principle has already been explained by Wahrhaftig and Cox, references to modern precise measurements are found in our contribution. The constant oversteepening, destabilization and material-detachment process continuously exposes fresh material from the inside of the moving body in the upper parts of active rock glacier fronts. As illustrated with the Yerba Loca site in our contribution, the often strikingly bright appearance of freshly exposed rock material in upper frontal parts of actively advancing rock glaciers constitutes a characteristic and easily recognizable indication of continued creep in perennially frozen talus/debris. Luminescence dating documents that such freshly exposed materials had been underway inside the creeping body for thousands of years.

- The creeping material inside rock glaciers is not “partially to fully saturated rockfill”. Such material indeed undergoes damped creep with finite deformation as documented, for instance, in the frozen ice-saturated blocks at depth underneath the main shear horizon of the Murtèl 1987 borehole. However, core drillings, borehole deformation measurements and numerous geophysical soundings again and again confirmed that long-term creep of rock glaciers takes place in highly supersaturated talus/debris, where the excess ice – in addition to strengthening cohesion – reduces internal friction (Springman et al. 2012). It is this ice-supersaturation, which enables secondary or steady-state creep with unlimited cumulative deformation. To put it in simple words: The frozen material of rock glaciers undergoing long-term creep is not “rocks with ice inclusions” as assumed in the Whalley/Azizi comment but “ice with rock inclusions” – geotechnically a fundamentally different material. The IPA/IACS task force report about permafrost creep and rock glacier dynamics includes a discussion of the mechanics involved (Haeberli et al. 2006; cf. also Arenson et al. 2021 concerning the physics of frozen ground/permafrost).

- This basic misunderstanding explains why the argument that “substantial (>20m) ice thicknesses are required for observable creep to occur in frozen debris, even on steep hillsides, particularly at ‘low’ temperatures” (Whalley and Azizi, 1994, 2003 as cited in the Whalley/Azizi comment) is not supported by field observations. Rock glaciers, for which borehole deformations are available (Arenson et al. 2002; Buchli et el. 2013; Fey and Krainer 2018) clearly demonstrate the presence of shear horizons where most of the observable deformation occurs. Such “shear horizons”, which are actually zones of increased creep of the frozen material, can be less than 20 m deep as shown in these referenced publications. A simple, Glen-type flow law that does not consider the ground thermal regime of the permafrost and the complex geotechnical characteristics of typically heterogenous ice-rich frozen talus/debris materials, will just not reproduce the full range of observed deformation and velocity changes (e.g. Müller et al. 2016, Cicoira et al. 2021).

Personal note by Wilfried Haeberli: I am sorry for Louis Lliboutry to see his rude 1990 formulations being brought to the public again. In personal communication with me, the Journal of Glaciology had apologized for having published such wording. In my former function as Director of the World Glacier Monitoring Service (WGMS), I had – over several years – direct contacts and collaboration with Louis Lliboutry in his former function as president of the International Commission on Snow and Ice (ICSI; today IACS). I learned many things from this outstanding scientist, and I highly appreciated his always critical but nevertheless constructive and strong support of internationally coordinated glacier monitoring (comparable permafrost monitoring only started later). Lliboutry, on the other hand, changed his mind concerning rock glaciers and mountain permafrost after having read my 1985 publication and the first reports on the Murtèl core drilling. He even started encouraging younger colleagues in France to do similar quantitative field measurements on the topic. French scientists today are among the international leaders concerning research on mountain permafrost, rock glaciers and sites with complex contacts between surface and subsurface ice.

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