Reply on RC3
Natacha Gribenski et al.

Author comment on "Cosmogenic 3He paleothermometry on post-LGM glacial bedrock within the central European Alps" by Natacha Gribenski et al., Geochronology Discuss., https://doi.org/10.5194/gchron-2022-1-AC3, 2022

Comment on gchron-2022-1
Gribenski et al. (2022)
Geochronology Review

Anonymous Referee #3
Summary: “Diffusion properties of cosmogenic 3He in quartz can be quantified to reconstruct the evolution of past in-situ temperatures from formerly glaciated areas.” For this study, authors apply cosmogenic 3He palaeothermometry on rock surfaces exposed from the LGM–Holocene from two deglaciation profiles in the European Alps. Results: “Lab experiments indicate variability in 3He diffusion kinetics between the two sites.” The authors interpret this as the presence of multiple diffusion domains. “Predictive simulations indicate that 3He abundance in all the investigated samples should be at equilibrium with present-day temperature conditions - but measured natural 3He concentrations in samples exposed since before the Holocene indicate a thermal signal colder than today. This cannot be explained by realistic post-LGM mean annual temperature evolution in the Alps. Hypotheses/interpretations: One hypothesis is that the diffusion kinetics and MDD model applied may not provide sufficiently accurate paleotemperature estimates in these samples. Alternatively, the 3He abundance may reflect complex geomorphic/paleoclimatic evolution with much more recent ground temperature changes associated with the degradation of alpine permafrost.”

Overall comments: This is a thorough manuscript and important study that provides detailed information on applying relatively novel methods to deconvolve temperature histories from formerly glaciated areas. The authors do a nice job talking through their interpretations, and all of their interpretations are valid. The amount of data collected and reported is impressive. My main concern with this paper is the sheer amount of information that is reported and the delivery of details that make it hard to follow at times. As a result, key takeaways are not obvious, and this diminishes the paper’s impact. For example, I noticed throughout the manuscript the author put statements in parentheses within sentences, and I felt this was quite distracting. More work into simplifying those statements and perhaps removing the text within the parentheses will help streamline the paper.

We thank the reviewer for their interest in the study and overall positive response.
We will improve the readability and clarity of the manuscript by (1) modifying the structure of some paragraphs, (2) reorganizing and changing the titles of
some sections, and (3) rewriting sentences to avoid parenthetical statements where possible. Please see our responses to the line and section comments below.

*Most of my comments below are my recommendations for how the authors can better streamline the paper’s structure. If a bit of work is put in on improving the structure of this manuscript, it will be much stronger.

Comments by section:
1 INTRODUCTION
General comment: The introduction does a nice job setting up background information for this study. Thank you.

Line 48: suggestion to change “thanks to” to “due to.”
We will modify as suggested.

Line 59: I’m a bit confused by the beginning of this sentence, "the recorded Alpine sequence" What exactly do you mean by it? Which ”recorded Alpine glacial sequence?” Perhaps reword to say: “Alpine glacial history is consistent with polar ice oxygen isotope records.”
We will modify this sentence as follows: “The timing and pattern of paleoglacier variations in the European Alps are consistent with polar ice oxygen isotope...”. (line 60)

Line 67: A suggestion to change “inappropriate” to “not viable.”
We will replace “inappropriate” by “not valid”. (line 68)

Line 91: Suggestion to change "today" to "presently," and remove "hence." So, it would read: "Presently, there is a crucial lack of..."
We will remove "hence”.

Line 93: Suggestion to reword to: “In this study, we attempt to reconstruct paleotemperatures in the high alps during the Late Glacial Period, specifically between the LGM and YD, by...”
We will modify the sentence as follows: “In this study, we attempt to reconstruct paleotemperatures in the high Alps during the Late Glacial by ...” (line 96)
Information about which period the Late Glacial corresponds will be provided earlier in the introduction: “Similarly, little is known regarding climatic conditions during the Late Glacial period between the LGM and the YD, ...”. (line 85-86)

Line 94-95: Perhaps add a brief statement at the end of this sentence for what the benefit of “exploiting the open-system behavior of cosmogenic 3He in quartz minerals” is? In other words, why is it important to “exploit the open system behavior?” As of now, this statement seems like jargon, and elaborating on your meaning behind this will fix the ambiguity.
We will replace “open-system” by “diffusive”. The benefit of this property (diffusion of 3He in quartz at Earth surface temperatures) is described in the sentence immediately following this one, which we will modify to be more explicit: “Using forward models of cosmogenic 3He production and thermally-activated diffusive loss, quantitative constraints on the thermal history of an exposed rock surface can thus be inferred from the difference between surface-exposure ages derived from the diffusive 3He system and from a cosmogenic nuclide that does not experience diffusive loss (Tremblay et al., 2014a, b; 2018)”. (line 98-101).
I think this manuscript would benefit if you briefly describe what you mean by "predictive models."

We will replace the word “predictive” here and elsewhere with the word “forward,” as this is a more intuitive and accurate description of the modeling that was done.

“Leaky” is a bit confusing. For readers that are not experts in 3He palaeothermometry, what do you mean by “leaky”? Be more specific please. (I think you’re referring to open-system behavior? Perhaps just say that instead of leaky if so).

We will replace “leaky” by “diffusive”.

I think you need to define "a priori," I’m not sure what you mean by this, it feels out of place. We will delete this word.

2 STUDY SITES AND SAMPLE MEASUREMENTS

General comment: Permafrost degradation is one of your hypotheses to explain your results, yet there is no mention of permafrost extent in the “settings/study sites” section of your paper. I think you should mention modern and/or past permafrost extent in your study area.

We will add the following brief description of the present-day permafrost distribution in both study areas: “Continuous permafrost is expected above ~3000 m a.s.l in the north faces of the Mont Blanc massif (permafrost index ≥0.9; Magnin et al., 2015a) but can be found more discontinuously down to 2300 m a.s.l. (permafrost index ≥0.5) and as low as 1900 m a.s.l. in especially favorable conditions (permafrost index ≥0.1). Along the Gelmersee ridge on the western side of the Haslital Valley, continuous permafrost is expected above ~2700 m a.s.l., with sporadic patches down to ~2150 m a.s.l. (Boeckli et al., 2012b).” (line 126-130)

Figure 1 is really great! I appreciate the visual. Thanks!

A suggestion for Figure 2 is to add a key box to panels b and d that state "3He/10Be" with a yellow circle symbol. I realize it's in the x-axis label, but consistency with the keys will be more apparent to readers. Also, a suggestion to not use a dash ("-") but instead a comma in your caption because I think of "a-c" as being "a, b, and c... but you only mean a & c.

While more visually consistent with panels a and c, we decided to not add additional key boxes in panels b and d for Figure 2, as this would be redundant with the x-axis label (on the contrary to panel a and c where the key boxes really bring an additional information). We will however modify the x-axis label to be more explicit with “3He exposure age/10Be exposure age”. We will also replace the dashes ("-“) by commas in the figure caption.

“3He palaeothermometry requires at least two additional pieces of information. First, predictive models of thermally-activated 3He diffusion rely on quartz sample-specific 3He diffusion kinetics parameters...Second, measurement of the total natural cosmogenic 3He accumulated in the quartz sample permits us to estimate the loss by diffusion...” I think you should incorporate more summation sentences like this within your manuscript to help streamline the flow.

We agree with the reviewer, and will work on more statements like this (see next responses).

3 ANALYTICS APPROACH

General comment: As someone who is not an expert on 3He palaeothermometry, I’m a bit confused of the significance of this section. Why do you need an analytics approach? Is it to perform quality control metrics on your data? Or do you need to run these Matlab codes
to actually produce your results? Please start this section with 1-2 sentences briefly explaining why you need to run these Matlab codes. *In the previous section, you just said how you need “predictive models of thermally-activated 3He diffusion...” is this why you’re running the Matlab code? If so, a suggestion is to start this section with, “To determine predictive models of thermally-activated 3He diffusion, we used Matlab codes...”

We appreciate that it was difficult to follow the description of methods in our original manuscript. In response to this, we will significantly restructure this part of the paper to have a Methods section with subsections that have clear, descriptive titles. We will also add a synoptic summary at the beginning of the methods section which clearly delineates the different measurement methods and modeling methods used, what the purpose of each method is, and how each of these parts relate to one another. We will also remove the specific references to Matlab code, as this detail isn’t particularly relevant.

Line 186: This is the first mention of “multi-diffusion domain (MDD),” but there is no explanation for what this is? Please provide a bit of an explanation for what MDD is. Please refer to our answer above (comment: 3 ANALYTICS APPROACH General comment). We will explain what MDD is in both the synoptic summary at the beginning of the Methods section as well as in this subsection on the diffusion kinetics modeling (section 3.3 in the revised manuscript).

General comment: Once again, I think this section would benefit from an opening sentence briefly stating/reminding the reader of why you need to run these Matlab codes. For example, why do you need to determine 3He diffusion kinetics, and why do you need to numerically simulate 3He loss? *I see at Line 300 you state “to explore the theoretical sensitivity and potential variability of the MBTP and GELM quartz, we numerically evaluated the time required...” Is this why you ran the Matlab codes? If so, please clarify this in section 3 above, instead of waiting to the results section to explain this. Please refer to our answer above (comment: 3 ANALYTICS APPROACH General comment).

Line 199: Please be more specific with what you mean concerning “longer timescales.” >1 year? Decadal? *I see at Line 229 that you define “long-term” as “several years.” Please add this clarification to Line 199. We will specify that longer timescales mean 1 to 10^5 years.

Line 249: You can remove the word “next.” We will make the change as suggested.

4 RESULTS
General comment: I think this section could be improved if you added an introductory paragraph summarizing all the different results you are going to report. For example, as it is now, you jump right into diffusion kinetics parameters, which is a bit confusing/makes me think these are the most important results, even though you delve into many more below this section.

We will add this introductory paragraph: “First, we examine the characteristics of the 3He diffusion kinetics parameters we modeled for our quartz samples and explore the sensitivity of the 3He signal in those samples to Earth surface EDTs. We then present forward model results for the evolution of the cosmogenic 3He concentrations recorded along each deglaciation profile for two different sets of thermal histories. The first set of thermal histories we investigate assumes a constant EDT since the exposure of the sampled rock surfaces following ice retreat. We then investigate a set of more climatologically-interesting thermal histories, wherein a change in EDT occurs at some point during the exposure time of each sample.” (line 319-324)
Line 285: The wording of “and which in addition predict” is confusing. Do you mean the range of diffusion kinetics parameters predict the observed natural $^3$He concentrations from the Holocene calibration samples? If so, please remove “and which in addition” and replace with “which predict” wording only.

We will modify the sentence as follows: “Figure 3 shows the range of diffusion kinetics parameters ($E_a$ and $\ln(D_0/a^2)$) that fit the laboratory stepwise-heating experiments (one representative sample for each site; Fig. 3a and 3b), and which permit us to reproduce the observed natural $^3$He concentrations from the Holocene calibration samples for a constant EDT equivalent to the modern EDT (Figs. 3c-e).” (line 326-328)

Line 315: Figure 4 - a suggestion to make the diamond symbols transparent because the circles are often hidden behind them, and this would show their clear overlap. Also, are there errors of these isoEDT estimates?

We will make the scale of the y-axis in Figure 4 linear. Consequently, most of the symbols will not be overlapping. We will also put the circles on top of the diamond symbols, such that none are hidden where there is overlap.

There are no errors for this figure, as this figure presents illustrative synthetic tests where we varied the isoEDT and predicted the time it would take for the $^3$He concentration in quartz to reach steady-state, and for diffusion kinetics parameters were held constant.

5 DISCUSSION

Lines 417-421: These sentences belong in the results section; they distract from your interpretations. A suggestion is to move these statements to the above results section and Line 434: “We attribute…”

These two sentences summarize the results presented in details in the preceding result sections.

We find them helpful to start the discussion of the presented results in regard to the existing knowledge of climate evolution since the LGM in the European Alps. We therefore will keep them.

Line 423: Remove the word “furthermore,” and add “set of” after “mean.” So, it reads: “Such large EDT differences would not be supported by any set of mean temperature reconstructions for the…”

We will modify the sentence as suggested.

Line 434: Suggestion to reword this sentence to: “We attribute our results of lower modeled $^3$He concentrations to observed $^3$He observations to the dampening effect...”

We will rework this sentence as follows: “We attribute the result of modeled $^3$He concentrations that are significantly lower than the observed ones to the damping effect...” (line 479)

Line 435: What do you mean by the “dampening effect?” Perhaps clarify more, I’m not sure how “relatively stable mean temperature conditions similar to present day” relate to this.

We mean that the long exposure of quartz systems to temperatures similar to today during the Holocene period (~10 ka), will result in a partial to total re-adjustment of the $^3$He thermal signal, with little to no inherited signal (i.e., signal memory) from prior exposure to colder Late Glacial conditions. We will add a sentence with this explanation to the text (line 481-483).

Line 436: You can remove “first appears,” and just say “This hypothesis contradicts...”

We opt to keep the word “appears.” As explained in this paragraph, the proposed hypothesis is in fact consistent with our tests when the limited pre-Holocene
samples exposure time is considered.

Lines 459-464: The parentheses are distracting in the reporting of your interpretation. I think you can reword this paragraph as: "Even greater EDTs are needed to explain the observed GELM 3He concentrations using either diffusion kinetics approach, including temperature changes from 15-35ºC when using Holocene-calibrated diffusion kinetics and >40ºC when using laboratory diffusion kinetics."

*We agree that the amount of details in this paragraph is overwhelming and might be confusing for the reader. We will simplify this paragraph and refer the reader to the supplementary material for further detailed information as follows:*

"If instead we use diffusion kinetics solely derived from laboratory experiments without Holocene calibration (Fig. 3, Table 2), a ΔEDT of 15ºC or greater is required to explain observed MBTP 3He concentrations for changes within the last 10³ years (Fig. S2b). Such large ΔEDTs are significantly greater than expected EDT variations from changes in mean annual temperatures and/or in annual/diurnal temperature amplitudes during the Holocene. Even greater ΔEDTs are needed to explain the observed GELM 3He concentrations using either diffusion kinetics approach (Fig. S3b)." (line 503-508)

Then, remove the statements in the parenthesis and make Line 464 its own sentence as:

"Both cases are clearly incompatible with..."

*We will modify as suggested.*

Line 466: Suggestion to remove the word “Finally” at the beginning of this sentence.

*We will modify as suggested.*

Line 470: Remove “(i.e., recent)” statement, it is not needed.

*We will modify as suggested.*

Line 479: Suggestion to remove the words “permit to,” so it reads: "For GELM samples, correcting modern/recent EDT does not reproduce the observed 3He concentrations...”

*We will replace “does not permit to” by “is not sufficient to”.* (line 530)

Line 490: Remove the parentheses in front of “contrary,” and reword as two full sentences: “...during glacier coverage. This is in contrary to 10Be, which would experience...”

*We will reword the section as two sentences: “[...] during glacier coverage, even at subzero temperatures and EDTs (Fig. S4). On the contrary, 10Be would experience only minor radioactive decay over 10-100 kyr timescales.”* (line 541-543)

491: Suggestion to remove the parenthesis and the word “hence” and just reword as: "This scenario of inheritance and/or complex exposure history would result in...“. This streamlines your interpretation.

*We will modify the text as follows: “This scenario of inheritance and/or complex exposure history would result in [...] This scenario is also valid for post-LGM episodic coverage.”* (line 543-545)

Section 5.3 (Line 538): I’m a bit confused how this discussion differs from Section 5.1. Aren’t the 3He diffusion kinetics and 3He thermal signal needed to interpret paleoenvironmental signals? Why is this discussion lumped in a different section?

*We agree that the current structure of the discussion part and focus of the different subsections may be confusing.*

In order to clarify this part, we will slightly reorganize the distribution of the different paragraphs and modified the title of the subsections as follows:

- 5.1 Paleoclimatic interpretation of 3He signals
5.2 Sources of uncertainty: this section contains now three subsections focusing on the methodological uncertainties associated with 1) the estimates of modern EDTs; 2) the interpretation of cosmogenic nuclide measurements; 3) the characterization of $^3$He diffusion kinetics

5.3 Potential role of permafrost processes