The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-107-AC2, 2020

Interactive comment on "The case of a southern European glacier disappearing under recent warming that survived Roman and Medieval warm periods" *by* Ana Moreno et al.

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Received and published: 8 September 2020

Answers to tc-2020-107 RC1 "The case of a southern European glacier disappearing under recent warming that survived Roman and Medieval warm periods"

Note: The referee comments start with "RC2" and the author's answers with "AR".

RC2. General The authors provide results from a focused local study on remains of a glacier at Monte Perdido (MPG) in the Pyrenees. Their comprehensive analyses concern a question of quite fundamental relevance: are glaciers and, hence, the climate system now changing beyond natural, pre-industrial variability ranges? The main

results of the analyses are that the maximum age of MPG can be constrained to the Roman period, and that no ice dating to the Little Ice Age remains present today. The results are interesting and certainly merit publication. They especially have the potential to encourage similar studies in other regions of the world. Some parts need clarification and more precise presentation as explained below.

AR. We acknowledge the positive view of Drs. Haeberli and Bohleber regarding the importance of this study and the interest to publish it in the TC journal. We provide answers below to their main concerns about sampling and age structure and about radiometric and glacio-chemical analyses.

RC2. Sampling and age structure

RC2. Since the inferred age structure is central to the manuscript's main conclusions, it deserves a more clear and detailed presentation. The description of the ice sampling (e.g. on lines 151-163) is difficult to follow and should be clarified. The samples are obviously taken perpendicular to the stratigraphy along a profile at the surface of the stagnant, regularly layered ice patch. The assumption that this ice is cold and frozen to its bed may be reasonable, because this ice cannot warm up above 0C in summertime but cool down far below 0C in winter. This effect can explain the low flow velocities but not the ice stratigraphy, which must have been influenced by the active flow of the much larger glacier during the past millennia in question. This leads us to the following concrete questions that should be addressed in more detail:

(1) What exactly is the reasoning behind the inferred age structure of the remaining ice patch? Is it purely empirical from the dating or is it based on considerations of ice flow? The 14C dates are clustered in three different age groups, but the use of a linear interpolation needs better justification. In particular, why can the existence of further (presumably shorter) periods of hiatus or ice loss really be excluded from the presented evidence? Relatedly, if the only support for the hypothesis of a hiatus at 73 m is coming from a distinct dark layer (lines 233 ff., 302-303) – how does this

interpretation of concentrated, impurity-rich dark layers fit with what is observed at the glacier surface today?

AR. We agree about the problems posed by the unknown ice stratigraphy, which certainly was the result of the glacier evolution during the last millennia. This problem is quite common to many high-mountain glaciers, even when coring is possible, since their detailed inner structure by physical analyses such as GPR is rarely available. When we applied ice flow models to MPG (using Elmer-ICE, in particular) the results indicated that the ice in MPG was at most 200 years old (the longest possible travel time of an ice particle deposited at the upper part of the current lower glacier), which was in contradiction with the obtained ages (210Pb, 137Cs, 14C). However, these models were just applied -given the lack of input data- assuming a steady-state surface (that of the current glacier), which is clearly incorrect. One explanation contributing to explain the old ages found is that the ice has been for long periods frozen to bedrock, and hence nearly stagnant. Moreover, we can just speculate about the inclination of the glacier bed necessary to account for the 30 m of maximum ice thickness previously measured by GPR in other sector of the glacier (López-Moreno et al., 2019). Our hypothesis that the oldest ice is found towards the base of the sequence and the newest towards the top is based on general arguments on ice flow of mountain glaciers. 14C dates confirmed this hypothesis, but we agree with Reviewers in that we cannot totally exclude the presence of other shorter hiatus besides the one at 67-73 m, which was the most evident. We set the hiatus at 73 m to be able to construct an age-depth model and use different interpolations below and above (before and after) it, depending on the growth rate indicated by the dating results.

RC2. (2) How are distances along the surface profile transformed into values of (ice?) depths? Does "depth" relate to a former, thicker and less inclined ice body and, if yes, to which geometry/time exactly?

AR. The reviewer is right about the "depth" concept here. It is related to our consideration of horizontal ice layers, since we obtained one sample every meter, measur-

ing these meters with the Jacob staff without taking any inclination into consideration. Therefore, the 100 samples would represent 100 m of thickness in the ice sequence if the ice bedding were horizontal. The exact thickness is unknown, but in the order of 30 m in the easternmost sector of the glacier. So, the internal layers of the MPG must be very inclined. An improved version of Figure S2 may help to understand this problem (Fig. 1).

RC2. (3) What are "stratigraphic thicknesses" and how are they determined?

AR. We are not using stratigraphic thickness anymore since we cannot measure it, as indicated in our response just above. We have now included "Sample ID" instead of "Depth" in the age-model figure.

RC2. (4) If the ice is frozen to bedrock and stagnant, why did the authors find no evidence of neoglacial ice at the base and which process would have led to its removal?

AR. We have constructed the figures about the evolution of the glacier based on what we have found sampling and dating the ice. Then, since we have not found the Neoglacial ice it likely was melted away at some point between 5000 years BP and the Roman Period. It is also possible that some ice from the Neoglacial periods remains in the base of the glacier but it was not cut by the vertical section of our surface sampling profile (see figure above), so we did not sample it. We have included this possibility in the new version of Figure 4 (see below Fig. 2).

RC2. (5) It also needs to be made more clear which part of the glacier was sampled (the lower portion?) and why the other (the upper portion?) was disregarded. Figure S2 should be included in the main text and supplemented with a zoom-in to the visual stratigraphy around the sampling sites for better visibility of the layering. Figure 4 suggests that neoglacial ice in the upper portion did not survive the Roman period, which is not supported by evidence in the manuscript. Are the authors assuming that this ice was removed by basal melting when the larger glacier was still warm-based, by thinning or ice flow? How does this align with the evidence for ice being frozen to bedrock now?

AR. The upper portion of the glacier was disregarded because it is really small today, with a slope very steep and the access for sampling was dangerous. Unfortunately, we do not have any date from that sector. Fig. S2 is now improved and will be included in the revised version of the manuscript (Fig. 1) with more details about layering and a closer picture of the glacier.

Regarding the Neoglacial ice survival, we can just hypothesize that it melted away at some point before or during the Roman period, since we don't find it in our dated samples. But, of course, it can remain in the upper glacier. It is also true that it may be found below the Roman ice that we sampled and is not exposed at the glacier surface today. We have to consider all of these possibilities in the new revised version of the manuscript and update Figure 4 with them. See below a first version of Figure 4 keeping part of the Neoglacial ice during the 2000-year period (Fig. 2).

We do not know when the glacier was frozen to bedrock. That situation might have happened once the glacier became sufficiently thin (after the Roman period? After the MCA?) and probably did not become warm-based anymore.

RC2. Radiometric and glacio-chemical analyses

RC2. The allocation of the samples to a position needs to be revised, at present much is left unclear to the reader. There seem to be two coordinates to consider: First, the position of the sampling site along the transect (MP1-100). Second, the depth below the surface / distance from bedrock. This information should be included in Table 1 to replace "sample depth (m from base)" – which is presumably referring to the distance from the glacier terminus? Again, a clear hypothesis should be stated why a systematic gradient in age of the samples in relation to their position on the glacier is expected? If the ice is stagnant, why is older ice expected closer to the terminus? The depth information should also be provided for the glacio-chemical datasets (especially Pb/Al and Hg of Figure 3).

AR. We totally agree with this comment about the difference among "position in the transect", "depth from the base" and "sample ID". The reviewer is right and we have replaced any reference to ice thickness or ice depth to sample position or sample ID. We expected the older ice closer to the terminus as a consequence of the bedding and due to the steep slope present today. Ice layers are cut by the glacier surface and older layers should appear closer to the terminus if they are tilted (see Figure 2 above). It is evident that more information on this is needed in the manuscript and will be included in the revised version. We do not have the depth information for Figure 3 but can include sample ID (from 0 to 100), if necessary.

RC2. The selection of 14C data for dating needs clarification, especially because a substantial number of samples is disregarded. The WIOC technique is state-of-the-art but only one WIOC sample is used to construct the chronology. Known difficulties with the interpretation of dating derived from macroscopic 14C, such as reservoir effects need to be addressed in more detail. Dark and dust-rich layers can be biased either through incorporation of already "old" carbon (e.g. Saharan dust) or accumulate at the surface over a longer time period without ice formation. Regarding the pollen dating, which are presumably too old, the authors hypothesize that they originate from older ice which had melted and percolated through the ice. If this is true, how can such a process be excluded for the other radiocarbon dates?

AR. Our first option for dating would have been the WIOC technique, but we had not enough material in most cases. We did not preserve all the ice samples frozen, just a few of them for studying bacteria and virus. Thus, we were able to attempt WIOC dating in just two samples that were frozen and were of larger size. Unfortunately, they had still very low amount of carbon for dating and the errors were too large. One had to be discarded because of that reason, and the other is included in the age model. More and better organized information is now included about the reasons to reject some of the samples. We agree about the possible reservoir effect when dating dark and dust-rich layers where organic and inorganic material is mixed but this unfortunately is still difficult to avoid. For the future, Dissolved Organic Carbon (DOC) technique for dating may replace WIOC and provide more accurate results with less amount of sample (Fang et al., 2020).

However, we are not too sure about the reasons to obtain so old dates with pollen samples. Dating with pollen concentrates can be an accurate tool for chronological reconstruction, employed in many studies (González-Sampériz et al., 2006). However, obtaining old dates from pollen is a quite common problem not yet solved in the literature (Kilian et al., 2002). Another reason to exclude pollen samples for 14C consideration in MPG age model -not discussed in the manuscript- is that the obtained palynological spectra from the same samples that were dated is not coherent with well-known palynological records from the region. In the MPG area we have a detailed palinological study in Marboré lacustrine sequence which is totally different in taxa and abundance of that obtained from coetaneous MPG samples. Therefore, we suspect the pollen samples were contaminated somehow and we can not use them. Additionally, the information of pollen studies in active glaciers (specially related to the mechanisms of deposition and preservation) is scarce and thus not solves this problem. In any case, the three dated samples in MPG coming from pollen concentration are not consistent with the other onesand should be excluded.

RC2. Dark and dust-rich layers

RC2. Percolation of meltwater can also lead to redistribution of chemical impurities – would this be relevant at MPG and if not, why not? Along the same lines, it is important to give more attention to the glaciological settings of the site when interpreting the glacio-chemical records. Based on the presented hypothesis (Fig. 4), the MPG would have undergone substantial changes regarding its ice formation, possibly from a typical firnication process during cold periods to hiatus and melting during warm periods. An exposed glacier surface can lead to concentrated values of impurities, which would be more frequently the case in warm periods such as the roman or medieval period. In this sense, it is not clear that the heavy metals and their ratios should directly reflect any

regional mining or smelting activities – this should either be removed or supplemented significantly by further discussion and justification. Notably, the connection between mining activities and heavy metal ice core records in the Alps was made at very high elevation locations (>4000 m asl) with a quasi-continuous snow sampling behavior.

AR. We appreciate these comments and partially agree about the problems of percolation and redistribution of chemical impurities, which are relevant for many mountain glaciers in the current climate context. Still, we think that we can assume that most of the material is in place since it correlates well with the Marboré geochemical record, now published (Corella et al., 2021), and supports the chronology indicating the absence of ice from the industrial period. We agree that an exposed glacier surface can lead to concentrate impurity values, but these impurities would still have the same origin if they come from atmospheric aerosols, and can still be interpreted as a result from mining activities. Nevertheless, taking into account the problems of redistribution of chemical impurities due to percolation, we have to be more moderate with our interpretation of these elements. The text will be modified accordingly, presenting the interpretation of Pb/Al peak in the Roman times as Roman mining only as a possibility, and including the issue of percolation. We will also reflect in the text that the ice cores in the Alps where Pb/Al was considered as resulting from Roman-time mining activities were more continuous and located at higher altitudes, thus not strictly comparable to our site.

RC2. Considering these points, the respective part of the manuscript dealing with the interpretation of the glacio-chemical analyses needs to be substantially revised and shortened.

AR. Yes, we agree, as indicated above and modified the text accordingly.

RC2. The main support for the conclusions of the manuscript provided by the impurity analysis is the absence of ice dating to the industrial period. This point has value for the manuscript. The relation to mining activities and chronological support through the comparison with the Marboré Lake record seems, at present, speculative.

AR. The comparison with Marboré Lake was carried out using an age scale obtained independently (age model from MPG presented in this study and age model from Marboré lake presented in Corella et al., 2021). Thus, the similarity of the Pb/Al records in both archives (lake and glacier) is at least interesting to show. We have given less weight to the interpretation of Pb/Al as mining in this new version, since we agree in that it can come from other sources. But we would like to keep the graph showing Marboré and MPG records together. From that graph, we will highlight the absence of ice dating to the industrial period, as suggested by the Reviewers.

RC2. Some minor technical comments can be found in the annotated file.

Wilfried Haeberli and Pascal Bohleber, 3 July 2020

AR. Many thanks for all these comments and suggestions to improve our manuscript.

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Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-107, 2020.

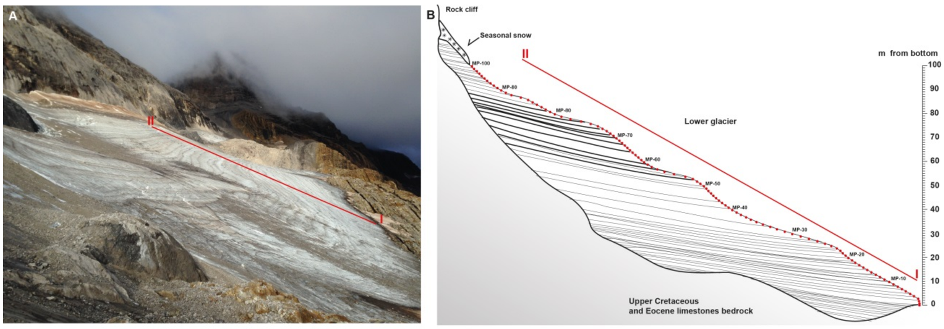

Fig. 1. This would be the new Figure 2 in the revised version, with an image of the glacier surface where we conducted the sampling and a scheme with the position of the 100 samples taken along the slope.

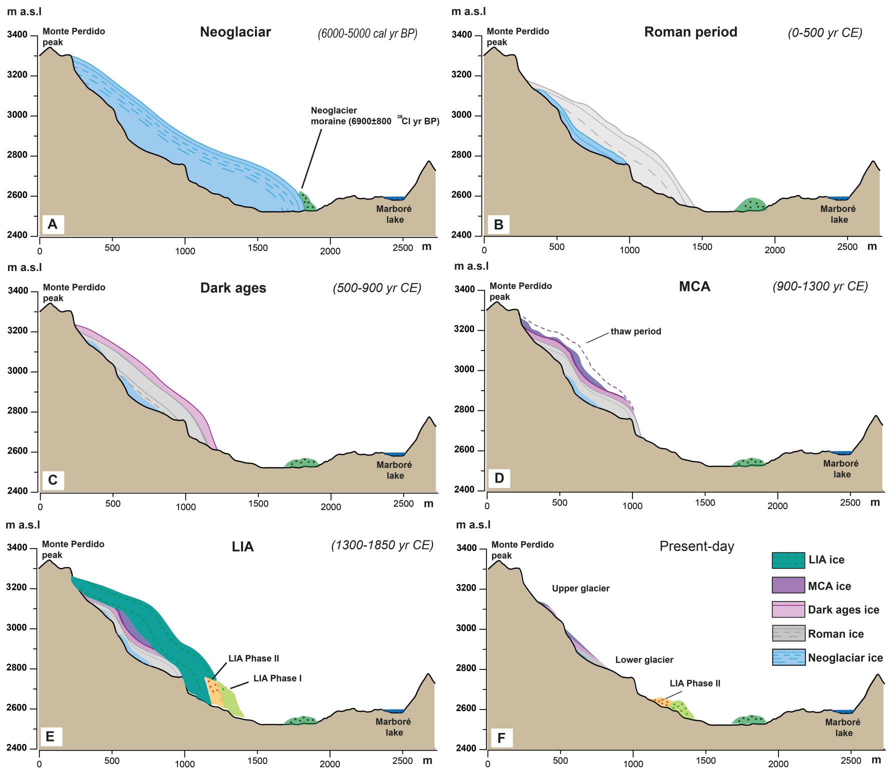

Fig. 2. This is an improved version of previous Fig. 4, including Neoglacial ice