Reviewer 2

We thank Reviewer 2 for the review of our paper and for providing constructive suggestions. Please find our responses in the following:

The manuscript of Gabrielli et al., presents a revised dating of three non-polar ice cores drilled in a distance of a few meters in 2011 at the glacier Alto dell'Ortles (3859 masl, Eastern Alps, Italy), and for which a first dating was published in 2016 (Gabrielli et al., 2016, denoted as TC2016 in the following)). To achieve a refined common chronology of the three cores, the depth scale matching of the tree cores is revisited on the basis of the 18O records of all three cores, and by adding additional depth match markers by using the Pb concentration profile from two of the three cores.

The absolute timescale of the common depth scale is then obtained by:

a) using the already existing chronology of 2016 which was based on 210Pb, tritium, beta activity and 14C determinations,

b) using additional time markers originating from:

- one 14C dating of an organic fragment giving a time marker at 232 ± 126 BCE,

- the synchronization of the excess (non-crustal) Pb flux record to the one of a well-dated Arctic ice core record (McConnell et al., 2018) from ~1900 CE to ~200 BCE,

- automated and visual counting of annual layers based on pollen and d18O and dust records from 2011 to 1900.

c) applying the obtained time markers in a continuous timescale on which the depth-age Monte Carlo based model COPRA (developed by Breitenbach et al., 2012).

Finally a 1D flow model (Dansgaard et al., 1969) was used to test the revised depth age relation and to test the hypothesis of steady-state conditions of the glacier side with a 1D flow model.

This study addresses the for ice-core archives very important scientific question of the ice core depth age relation, which is in the scope of CP. The study presents new data and the manuscript is structured adequately with respect to the aim of the manuscript. In my opinion the manuscript may be suitable for publication after major revisions were made.

One of the major concerns I have, is the use of the 14C data within the revised dating attempt, since at least two recent dating studies of high alpine ice cores showed that it cannot be necessarily assumed that the depth-age chronology of small scaled alpine ice cores is free of any discontinuities or age reversals (see e.g. Hoffmann et al., 2017, Preunkert et al. 2019).

Having that in mind, a critical look on the 14C raw date published within the first dating attempt (TC2016), one becomes aware that the Ortles chronologies are not free of doubt of a discontinuity in the depth-age scale, although glaciological investigations did not show any hints on such an occurrence (see TC2016). Note that this was neither the case in the study of Hoffman et al. 2017 at Colle Gnifetti (4450 m asl Swiss Alps) neither within the study of Preunkert et al., 2019) at Col du Dome (4250 m asl French Alps). Therefore, a potential occurrence of such a feature should be addressed in the revised dating attempt.

We agree with the reviewer that per-se “it cannot be necessarily assumed that the depth-age chronology of small scaled alpine ice cores is free of any discontinuities or age reversals”. We also observe that this is an already widely accepted statement particularly when dating ice cores close to bedrock.

We are aware that, based on 14C dating, indications for ice folding were reported in the study of Hoffman et al. 2017 at Colle Gnifetti and of Preunkert et al., 2019 at Col du Dome. However, we would like to note that the data-set and data structure in the two studies cited are different from what is presented in our manuscript (and in TC2016). In Preunkert et al., 2019, the possibility of an age reversal is mentioned, based on a single data point for which a slight contamination could not be excluded (the potential reversal is disregarded later in the paper for the reconstructed pollution record). In Hoffman et al. 2017, the potential reversal does not seem to rely on one single data point only. However, the data over the section in question is generally rather noisy making a firm conclusion difficult based on statistics (data scatter, also see e.g. Fig 8 in Liciulli et al., 2020). In addition, in the case of the Colle Gnifetti drilling site, 14C dating of another core does not suggest any age reversal (Jenk et al., 2009, Sigl et al., 2009), which is in contrast with the result of Hoffmann et al.,2017.

Remarkably, as the referee also points out, our glaciological investigations illustrated in TC2016 do not show any hint of such an occurrence and no indication for ice folding was observed. We note this is reinforced by the excellent match of the Pb Ortles and Russian Arctic records at that depth. Below we also show that an indication of disturbance/age reversal is unlikely to be inferred from our 14C data.

I took the liberty to draw a graph (see Figure 1 below) in which the available non averaged 14C results from TC2016 Table 2 (see also below) and the 14C result of this manuscript are reported over the depth of core 3. To do so the depth scale of core 1 between 68 and 72 m depth was roughly matched core 3 by applying: depth core3 = depth core1 - 1m.

As could be seen there are in core 1 as well as in core 3 independent signs of a depth-age disturbance around 71m depth (equivalent of core 3).

Within the TC2016 dating attempt the age reversal in section 102 of core 1 was eliminated using the mean age of the three subsamples of section 102, the subsection 103 sample of core 1 was not used since it would have represented a chronological inversion, and it had a increased risk of contamination during sample preparation.

We thank the reviewer for the effort to compile and plot this data. We note that the three WIOC 14C measurements that we averaged at 71 m depth (orange points in the graph prepared by the Reviewer) show what is technically considered a "resolvable reversal" (Breitenbach et al., 2012) where a stratigraphic coherent temporal solution can always be found within the provided error bars. Thus, from a statistical point of view, these three points cannot be used as evidence of a reversal. In addition, based on the final age scale, the depth interval of these three subsamples is less than 1 m, containing around 200 years. It is clear that an age reversal in this section cannot be resolved, considering the achieved 14C dating uncertainty of > 200 years. Based on these observations, we have high confidence in the mean age of the three combined samples, at least within the uncertainty assigned.

Concerning the #103 sample (in blue at 71 m depth in the graph prepared by the Reviewer), this was indeed not adopted in TC2016 (as well as in this revised chronology) where for this specific sample we reported in our previous publication that "*the amount of filtered WIOC from the first subsample* (out of the three composing this sample) *was estimated to be insufficient, and therefore the three subsamples were filtered together, resulting in a total ice volume exceeding our standard dimensions, possibly introducing a larger blank because of the modified treatment (i.e. increased potential for contamination due to a higher number of steps during sample processing)".* In other words this particular sample was most likely affected by small variations in the corresponding process blank. Thus this single data point is most likely indicative of a single outlier whose occurrence outside the 2 sigma range can however be statistically expected in a set of 10 samples. Thus sample #103 also cannot provide evidence of an age reversal.

These two observations are strongly supported by the compelling match of this ice section with the Arctic Pb record at that depth /time (please see the combined info in Figures 2 (~71 m depth) and 4 (~350 CE age). This comment has been summarized within the text.

As mentioned above since the time of the publication of the first dating attempt in 2016, it became obvious that one cannot expect a continuous undisturbed depth-age relation at non alpine glacier sites.

Please see replies above.

Therefore, either additional 14C analysis should be undertaken at the depth between 70 and 72m (depth equivalent of core 3) to confirm or exclude a depth age disturbance,

We agree that additional 14C measurements over that 2 m depth section could add additional evidence. While we are confident this would not change our conclusions (see replies above) unfortunately no such additional measurements are possible with the available ice left from Mt. Ortles, as relatively large amounts of ice mass are required for the 14C dating (for the Mt Ortles ice around 400-600 g of ice per 14C measurement to ensure sufficient mass of carbon > 10 µgC, for the analysis by gas-ion source AMS) that is unfortunately not available in any of the cores at that depth that was already intensively sampled for 14C and other analyses.

or address this point in this manuscript and discuss the consequences of a potential disturbance of the continuity in the depth age profile around 71 m depth (equivalent of core 3) in detail throughout the manuscript (i.e. within the comparison of the non-crustal Pb Ortles data with the Arctic Pb ice core data (section 3.2), and within the application of the COPRA model (section 4) and the Dansgaard-Johnsen model (section 5).

While we believe we have now clarified why a discussion of an age reversal would not be justified in the context of this manuscript, we report within the text why continuity at this depth is likely. Specifically:

In section 3.2 we now mention that in general the excellent match between Alto dell'Ortles and the Russian Arctic record at that depth/age provides strong evidence of the stratigraphic and temporal continuity of the basal ice core record.

In section 4, linked to the COPRA model, we already report the concept of maximum resolvable differences for the 14 C sequences which are stratigraphically coherent, considering their uncertainties.

Another major concern I have is the traceability of the proceeding of depth and time scale matching using d18O and Pb profiles, i.e. for the depth scale matching of the three cores and dating of the common Ortles depth scale between 1907 CE and ~200 BCE by matching the non-crustal Pb Ortles profile with the Pb data of a well dated Arctic ice core.

Although the authors describe their proceeding very detailed, it is not easy to follow their proceeding and arguments.
To improve that:
1. A table or a scheme should be added in section 2, which gives an overview on: which parameters are available in which parts of which of the three cores, and their respective use in view of the dating procedure. Since different reference depth scales are used in the Figures (Fig 1. reference depth from core 2, Fig 2 reference depth of core 3, Fig 5 reference depth of core 1)

that will be an important guidance for the reader throughout the different sections of the manuscript.

We thank the reviewer for this excellent suggestion. A table describing the parameters used for dating in each of the three cores is now provided within the main text.

In addition, a SI table would be very helpful which reports the used tie point depths of the three cores in absolute and water equivalent depths for each core.

We now also report in the supplementary Table2 the depths in m and m we of the tie points in the original cores from where they were obtained. It will be possible to obtain any other depth by interpolation using the map depths (illustrated graphically in Fig. 1) that will also be uploaded on the public repository.

2. Figure 1 is as it stands not useful for the reader since the matching of d18O profiles is not traceable. It would be better to use an illustration type as used in Fig. 2 means keep the individual depth scales and highlight tie point and their connections between the cores. Hereby prescind the principal tie points used to anchor the depth scale matching and their connections between the cores, vice versa the refinement tie points set afterwards. In addition, the y axis should be extended, in order that the variations of the d18O profiles become more obvious, especially in the lowest part of the cores.

We have now fully revised Fig. 1 visualizing the stable isotopes records before and after the match, allowing the traceability of this operation. We have also extended the Y axis in panel b to make the d18O variations in the lowest part of the cores more visible.

3. Figures 2, 4, S2, S3, S4 should be changed. As it stands, the reliability of the depth scale matching via the comparison of the non-crustal Pb profile cannot be assessed by the reader since in the above-mentioned illustrations the non-crustal Pb data were logarithmized or logarithmic axes are used to present the Pb data. In addition the Pb and the non-crustal Pb data are not made available for the reader (at least I did not find them). Therefore, to make the reasoning of the Pb profile matchings of the three cores and between Ortles and the Arctic core traceable for the reader, no logarithmic data and y axis scales should be used in Fig4, Fig S2, S3, S4.

Because of the very large range of Pb values, using a linear scale would make visible only the highest values while it would make invisible all the features linked to the lower Pb values. The reliability of matching could not be assessed in this way. As a compromise, the log of the Pb values is used. In this way all the large and small features adopted to select the tie points remain visible for the reader and allow the best possible assessment of the matching.

We understand the point raised by the reviewer however and in our revised version we have adjusted the Y scale of the bottom panel in Fig. 4, Fig. S2, S3 and S4 to better illustrate the correlations resulting from the match.

Among other things, this would allow:

- *to see clearer at which point the two Ortles Pb records agree or differ between core 1 and core 3. Differences seem to be up to half a log scale and over up to one m depth which makes up several hundred years at this depth (e.g. around 65, 68 and 70 m depth of core 3). Since for the moment, only one of the profiles is chosen for the age matching with the Arctic ice core, this is an important point to be discussed.*

  Different Pb concentration levels in the two cores are visible using the log scale. These are due to the different acid leaching time between continuous flow analyses (CFA) using online acidification (core #3) and the discrete analyses using conventional pre-acidification of the aliquots (core #1). Differences are larger for low Pb concentration levels probably because these are characterized by crustal Pb that, unlike anthropogenic Pb, is less acid-leachable. Different methods do not affect the Pb features used for matching the cores. This point is now discussed within the main text.

  In addition, about 1 m difference in depth between the same layers is relative. While it is correct that at this depth a 1 m difference within the same core corresponds to a few 100 years, it is much less of a concern when considering the same depth interval between the two individual sites (about 10 meters apart from each other). In this later case, a difference in the average annual net accumulation rate less than 2% between the two sites does explain well the offset in depth. Resolving these differences in depth is the entire point of this paragraph.

- *to give the reader the opportunity to see the quality and reliability of the matching between the Ortles and the Arctic (and the CG) non-crustal Pb profiles. E.g. the authors state in line 1 of page 10 "In general, the match between Alto dell'Ortles and SZ is excellent, except during 1650-1900 CE ..." however Fig 4, Fig.S2, Fig. S3 and suggest that the matching is rather arbitrary especially after ~ 600 CE the course over time of the Ortles non-crustal Pb and Arctic Pb differs significantly.*

First of all we note that, overall, the linear correlation between the Ortles and the Arctic Pb records is r=0.58 which is significant at $p < 0.01$. This is quite compelling considering the distance and different conditions of the Mt. Ortles and the Arctic drilling sites. This correlation is now mentioned within the text.

Fig 4 and Fig S2-S3-S4 have now been revised to better show the quality and reliability of the Pb matching. In general we note that, while some degree of arbitrary choices is unavoidable in this kind of wiggle matching, in our study this is minimized thanks to the 14C dating that constrains the matching within the uncertainty of these absolute measurements. This is a kind of remarkable and unique guidance that highly limits the arbitrary choices made during this procedure.

As we already pointed out in our manuscript, it is correct that the matching in the 1650-1900 CE time period is not excellent. This is mostly due to the decoupling of the *relative* Pb levels in the two records, Ortles and Arctic (much lower in the Ortles core during that period, see Fig 4 and S2, probably due to snow erosion during the LIA, as discussed in section 5). However, when adjusting the Y axis for this relative decrease, the trends of the two records can be better reconciled and a better matching is observed (please zoom panel in Fig. 4 and Fig S3). This idea is supported by the comparison with the independent CG record that, starting with 1350 CE, shows a trend that is consistent with the Ortles core until 1800 AD (Fig. S2 and S3). In any event, the conservative large uncertainty adopted during the LIA interval (10 % of the age, 20-30 years) should account for any kind of less accurate matching during this period.

As it stands (logarithmic scale) I am not convinced that the Pb matching with the Arctic core is reliable enough to shift the age of the 14C data to the limit of their 68% probability, and to neglect the 14C sample at 1361 ± 204 CE in section 4.

The Pb match at around that time is now better illustrated in the revised Fig. S3. We would also like to clarify that the revised age scale passes only two 14C sample dates at its 68% probability limit (out of 10), which are the one at 1361 ± 204 CE and sample #103 which was already excluded in TC2016 (as already discussed in detail in the reply above; see also Fig. 6c). In any case, as already mentioned within the text, we do take the arising uncertainty of the dating for this section into account by providing a dating error at around 10% of the respective age to acknowledge the discrepancy between the Pb-matched and the 14C ages. This uncertainty is fully included in our final dating derived by the application of the Monte Carlo simulation (COPRA).

It will be also very important to see, whether the assumption of a depth age disturbance would improve the Pb matching agreement of Ortles and the Arctic ice core or not.

We hope we have now clarified that there is no evidence to assume an age disturbance. In particular, matches of the Pb records of Mt. Ortles cores #1, #3 and the Arctic core are excellent at around 71 m depth (around 350 CE; Fig 4 and S2). We thus feel we do not have sufficient evidence to justify a speculative alteration of the excellent match obtained using the Pb records at that depth. Again, in any event, the final dating comes with an uncertainty of around 10%.

An alternative to showing the Pb and non-crustal Pb data on non-logarithmic scales and making them public within this manuscript, might be to join the refined dating addressed here to the aimed environmental discussion of the Pb data in a common manuscript.

We carefully considered this possibility. However, we have concluded that the original dating method presented and all the details needed to properly describe the revised chronology largely justify a stand-alone paper to present the revised chronology. Another paper linked to the environmental interpretation is in preparation, making the remaining part of the data set available on the designated public repository.

Other comments:
The application of the Dansgaard-Johnsen 1D model (see Dansgaard et al., 1996) on the revised depth-age relationship at the end of the manuscript (section 5) should be shortened. Only synthesized essential information of the model, the different input parameter, the outcome and the discussion of the results stay in the manuscript. Model description, input parameter determination of glaciological observations should be put in the SI.

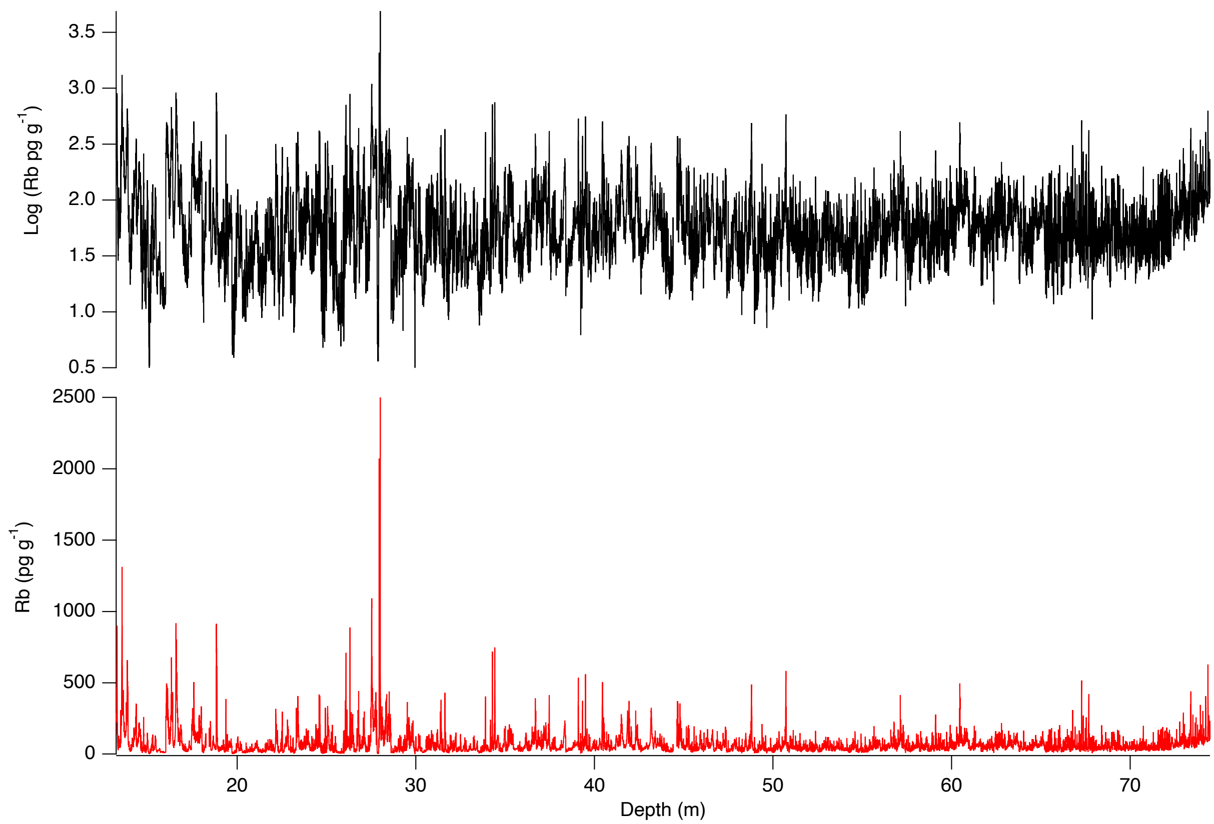
We believe the ice-flow modeling section deserves an important amount of space in this manuscript. Future efforts in combining ice core dating and ice-flow modeling are much needed in order to increase our understanding of the behavior, dynamics and temporal variations in small scale alpine glaciers. Aiming at providing some outline of the major questions, challenges and perhaps the different perspectives coming from related research fields (ice core research, glaciology), we decided to include some of the basic concepts to make it understandable for an extended community. Particularly, we consider the input parameter determination to be essential in this context. The excellent agreement between measured and modeled horizontal flow velocities shown in Figure 7 is, to our best knowledge, likely unique. The fact that a simple 1D model is able to accurately reproduce the observations further provides strong support to our conclusions and we feel it needs to be kept within the main text. The different approaches used to find the model parameters (showing that they do result in very comparable values) are also a crucial part of this section. However, to accommodate the suggestion of the referee to reduce the length of the manuscript we have now shortened the modelling section by transferring the major part of the general model description to the supplementary information.

For the comparison of non-crustal Pb Ti is used at CG and Rb at Ortles (Figures S2, S3, S4). Why Ti was not used as well at Ortles for consistency? Please report in the text the crustal values used for the Figures. Also discuss and provide errors in calculating non-crustal Pb. How large are the changes of Rb with age in the Ortles ice (please report the Rb profile in the Supplementary material).

Analyses of the CG and the Ortles cores were part of different projects conducted in different labs, times and by different people. As a consequence Ti was not determined in the Ortles ice cores while Rb was not determined in the CG cores. However, the selection of the crustal reference (Ti, Rb, Al, Ba etc.) does not typically influence the extent of the crustal corrections and thus we are confident that trends in non-crustal Pb levels in Ortles and CG are fully comparable. The crustal ratios used for the correction of the crustal component of Pb are i) Pb/Rb=0.51 for Ortles core #3 (obtained from a deep (69.55-69.94 m) Ortles core #3 section characterized by the lowest Pb concentrations in the record) and ii) Pb/Ti= 0.00545 (obtained from Wedepohl GCA 1995) for the CG core. These values are now reported within the text.

The error in calculating the non-crustal Pb and Ti is governed by the uncertainty in their determination by ICP-SFMS (typically the order of 5%) that provides a maximum uncertainty in the order of 10% in their respective non-crustal components.

The Rb concentration profile in core #3 is displayed below in linear and log scale.



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References which are not cited in the manuscript but which should:

Hoffmann, H., Preunkert, S., Legrand, M., Leinfelder, D., Bohleber, P., Friedrich, R., & Wagenbach, D. (2018). A new sample preparation system for micro-14C dating of glacier ice with a first application to a high alpine ice core from Colle Gnifetti (Switzerland). Radiocarbon, 60(02), 517–533. https://doi.org/10.1017/rdc.2017.99.

Preunkert, S., J.R. McConnell, H. Hoffmann, M. Legrand, A. Wilson, S. Eckhardt, A. Stohl, N. Chellman, M. Arienzo, & R. Friedrich (2019) Lead and antimony in basal ice from Col du Dome (French Alps) dated with radiocarbon: A record of pollution during antiquity, Geophys Res Lett, doi:10.1029/2019GL082641.

These two papers are now cited within the manuscript.