Review of A multimillennial Alpine ice core chronology synchronized with an accurately dated Arctic Pb record, by Paolo Gabrielli et al.

A preliminary absolute timescale of a low latitude-high altitude Alpine ice core drilled in 2011 at the glacier Alto dell'Ortles (3859 m, Eastern Alps, Italy) was obtained in 2016 based on a peak in ^{3}H activity, ^{210}Pb, and ^{14}C dating, indicating that the record spans the last ~7000 years (Gabrielli et al., 2016). The present work improves this preliminary dating based on additional information. First, ^{14}C dating of a fragment of a charred spruce needle present in the basal ice provided an age (232 ± 126 BCE) which agrees with previous ^{14}C dates in the oldest part of the record. Second, novel seasonally resolved pollen records from the upper firn/ice portion of the Alto dell'Ortles cores were combined with $\delta^{18}O$ and dust annual variations to refine the dating for the 20th century. Finally, the Pb Ortles records were used to match the depth scale of two of the Ortles cores and with a Pb record from an Arctic ice core (AN), well-dated (±5 years) for the ~200 BCE to ~2000 CE period.

Summary (for details see overall and specific comments below) of aspects accounted for

- Does the paper address relevant scientific questions within the scope of CP?
  If geochemically discussion of Pb records will be addressed in a revised version (see comments below), yes, if not, no.
- Does the paper present novel concepts, ideas, tools, or data?
  No, except for Pollen analysis
- Are substantial conclusions reached?
  Not really, but already existing ice core dating was improved.
- Are the scientific methods and assumptions valid and clearly outlined?
  No, see comments below
- Are the results sufficient to support the interpretations and conclusions?
  No, see comment below
- Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)?
  No, see comments below
- Do the authors give proper credit to related work and clearly indicate their own new/original contribution?
  Yes, but some references are missed
- Does the title clearly reflect the contents of the paper?
  No since comparison with Arctic is not geochemically discussed
- Is the overall presentation well structured and clear?
  Yes, but analytical section is missing
- Is the language fluent and precise?
  Yes
- Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?
  Yes, see comments below

Overall comment:

Whereas the improvements of the preliminary dating of the Ortles records based on the new ^{14}C dating, the pollen records, and the use of a 1-D ice flow model used to test steady state conditions of the glacier, are adequately presented and surely merit to be published, the

presentation of the Pb records from the Ortles ice cores is made rather poorly: There is a) an absence of analytical details, b) a not very serious discussion on the difference between the Pb records of Ortles core 1 and core 3, and c) an absence of a geochemical reasoning for the validity of the comparison between the Ortles and the AN Pb record. On this last point, on the one hand, the authors argue that the geochemical discussion of the Ortles Pb records are out of the scope of this paper, but on the other hand they adjust two Ortles Pb peaks (dated by Ortles ^{14}C to environ 400 and 230 BC) on the two AN peaks attributed by Mc Connell et al. (2019) to the roman Republic and Empire (70 BC and 100 CE), without clearly specifying in the text that this fit is based on the assumption that Ortles ice has recorded the Roman antiquity, and without discussion on the geochemical reason for this assumption, respectively. This is incomprehensible and incoherent already (see further comments below) because there is a potential alternative interpretation of this two peaks in the Ortles Pb record which leaves them at the age attributed by the ^{14}C and which is not presented in the manuscript. Also, there are major differences between the Ortles and AN Pb records (see Figure 6 and 8), e.g. from 400 to 700 CE and after 1400 CE to recent times, which strongly require geochemical comments. Given also numerous errors, the very poor quality of Figures reporting on Pb (some are completely unreadable), the non-convincing explanation for differences of the Pb records in core 1 and 3, and finally the quasi-absence of a plus value of the comparison between Ortles and AN (if correct), I strongly recommend to refocus the paper on the other dating improvements only and skip the whole presentation of Pb. If the authors decide to maintain the Pb part of the manuscript, they have to provide a complete geochemical discussion (and revise the text with respect to several problems that will be detailed below).

Specific comments:

1) Abstract:
Whereas at the time of submission, the authors could not have known about recent findings made in the French Alps at the ice core drill site of Dome du Goutier (DDG) showing undisturbed continuous climate and aerosol ice records spanning the last 12,000 years (Legrand et al., 2025), however this new finding should be referenced and the wording in the text adequately updated.
For instance, the first sentence of the abstract (line 20) is not true anymore: please change to "provided evidence that the record spans the last 7,000 years" (remove the oldest Alpine ice core records).

In the same sentence, please remove "back to the last northern hemisphere climatic optimum": Indeed, as discussed in their review, Heiri et al. (2014), a number of climate records imply a Holocene Climate Optimum in the Alps during the 10 to 5 ky BP period but often with different timing. On the other hand, the discussion of the DDG record (Legrand et al., 2025) revealed that as for some other European records no evidence of a Holocene Climate Optimum is observed in the DDG ice record, opposed to Greenland records that show a well-marked Climate Optimum. Anyway, having mentioned the climatic optimum in the abstract, you do not come back to this point when presenting the $\delta^{18}O$ record (Figure 1) in the manuscript. If this discussion is foreseen as the geochemical discussion of Pb, for another paper, I wonder whether the actual manuscript should rather go to The Cryosphere journal than to Climate of the Past.

Heiri, O. *et al.* Palaeoclimate records 60–8 ka in the Austrian and Swiss Alps and their forelands. *Quaternary Science Reviews* 106, 186-205 (2014). https://doi.org/10.1016/j.quascirev.2014.05.021
Legrand, M., McConnell, J. R., Preunkert, S., Wachs, D., Chellman, N. J., Rehfeld, K., Bergametti, G., Wensman, S. M., Aeschbach, W., Oberthaler, M., & Friedrich, R. (2025), Alpine ice core record of large changes in dust, sea-

salt, and biogenic aerosol over Europe during deglaciation. PNAS Nexus, Vol. 4 (6), doi: https://doi.org/10.1093/pnasnexus/pgaf186

2) Question and comments concerning the Ortles Pb records:

- Page 3 Line 30: The wording “crustal excess Pb concentration” sounds strange: you mean the non-crustal Pb (ncPb) ?

- An additional section is needed before section 2 (ice core realignment) reporting on the different analytical approaches for Pb measurements applied to Ortles core 1 and 2, and compared to the one applied for the AN core. Also specify in this section how ncPb was calculated (which crustal reference species is used and what is assumed Pb/crust ratio?). Please give blanks and detection limits and introduce a discussion on the effect (or not) of the online acidification (there are numerous papers on the literature on that) (see also next comment).

- Page 4 Lines 22-25 (section 2): the leaching time.
The authors seem to ignore numerous publication that examine the recovery of species using the online acidification of the CFA systems. For instance, previous assessment of measurement recovery during continuous measurements with the DRI system indicated that recovery was 100% and 60% for Pb and Ce, respectively (McConnell et al., 2018). That is because Ce is mainly present in relatively large dust particles and so remains in the particle phase longer than other elements associated with pollution that are adsorbed onto smaller particles and so readily washed off during on-line acidification. Other studies on this topic include Arienzo et al. 2019 (and references therein). Generally, these studies indicated a good recovery for Pb (in contrary to Al or Fe for instance). One of the reasons is that Pb is one of the trace elements that have very weak crustal contribution. For instance, Preunkert et al. (2019) indicated (in their Figure 2) that at the Col du Dome Alpine site the crustal lead contribution is negligible even during the pre-roman antiquity when the Pb level was as low as 0.015 ng g^{-1}.

With that in mind, let’s have a look on Figure 2 of the manuscript and the comparison of the Pb magnitudes between core 1 and core 3. However before doing so, note that the y axis title is wrong, “pg/g^{-1}“ makes no sense, and compared with Figure 8 obviously it should not be pg g^{-1} but ng g^{-1}.
At 59-60 m depth in core 1 there are ~0.44 ng g^{-1} instead of ~0.13 ng g^{-1} in core 3, at 65-65.5 m depth in core 1 there are ~ 4.5 ng g^{-1} instead of ~ 1.8 ng g^{-1} in core 3, at 68-69 m depth in core 1 there are ~ 2.2 ng g^{-1} instead of ~ 1.0 ng g^{-1} in core 3, and at 69.5-70 m in core 1 there are ~ 0.8 ng g^{-1} instead of ~ 0.02 ng g^{-1} in core 3. These differences are significant with respect to absolute Pb fluctuations over time (of course they are less visible on the log scale shown in Figure 2). Why do this differences between the two cores suddenly disappear at certain depths? If attributed to a problem of leaching (as suggested in the manuscript) one would expect an increase of crustal species at depths for which the differences between the two cores are important. Checking the Rb data provided following a question from a reviewer during the CP2022 review process, I saw however no large enough changes being able to disturb the Pb data gained with the online acidification. From that I conclude that the reason which is invoked to explain the Pb record differences between core 1 and core 3 is not related to leaching time but rather suggests that core 1 might data have suffered from contamination.

McConnell, J. R., Wilson, A. I., Stohl, A., Arienzo, M. M., Chellman, N. J., Eckhardt, S., et al. (2018). Lead pollution recorded in Greenland ice indicates European emissions tracked plagues, wars, and imperial expansion

during antiquity. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(22), 5726–5731. https://doi.org/10.1073/pnas.1721818115
Arienzo, M. M., McConnell, J. R., Chellman, N., & Kipfstuhl, S. (2019). Method for correcting continuous ice-core elemental measurements for under-recovery. *Environmental Science & Technology*, *53*(10), 5887–5894. https://doi.org/10.1021/acs.est.9b00199

3) Questions and comments concerning the comparison between Ortles, AN and CG

- Figure 6: In spite of several recommendations during the CP2022 review process, to provide a better Figure 6, the present version is still unreadable even with the linear scale for AN. It is a pity since this Figure illustrates how you propose to adjust peaks by comparing AN and Ortles. You propose to shift the oldest peak in Ortles from 400 BCE (dated with Ortles ^{14}C) to 180 BCE to become the roman Republic peak, and the wide peak dated with Ortles ^{14}C to 350 BCE to 510 CE to 70 BCE to 230 CE, to become the roman Empire perturbation. Thus, between the oldest peak and the end of roman Empire perturbation initially covering 860 years is reduced to 300 years. That is almost a factor of 3 and would require more comments.

- Also, there are other major differences between the Ortles and AN Pb record (see Figure 6 and 8), i.e. from 400 to 700 CE and after 1400 CE to recent times) that strongly require geochemical comments. In addition, the peaks dated with Ortles 14C to 600 CE and 1400 CE are higher than the industrial Pb increase at Ortles. This is in contrary to all published Pb ice core trends from Greenland and the Alpes (CG and CDD). Again, a geochemical discussion would be needed here.

- Why do you compare the Pb records between Ortles and the remote site of AN? On the one hand, I agree that it is legitimate given the accuracy of the AN dating, on the other hand you missed to check other relevant records such as the peatbog record from Tyrol (70 km away from your site, von Scheffer et al., 2024) that shows in its Figure 5 a large increase of Pb from 400 BCE to ~500 CE, i.e. quite similar to your record (without the scaling on AN). Again, if you do not want to discuss the geochemistry of Pb, I am not convinced by the reliability of the applied peak matching between Ortles and AN. Also note that, the applied Pearson Correlation is not an adequate measure to assess the goodness of the peak matching, since it is unsensitive against whether in reality same or different dated peaks are matched together.

- Whereas I agree that a comparison between the Roman Pb perturbation shown at the Col du Dome (CDD) site by Preunkert et al. (2019) and recently at DDG (Legrand et al., 20325) is not evident since the published Pb records are not as continuous as at AN, a direct comparison of Pb concentrations observed over the Roman perturbation with other Alpine ice records is more than welcome over the time prior and during the roman antiquity, and more relevant that a comparison of ice concentrations between Ortles and AN.

- In Fig S2 the Ortles Pb record is compared with the Pb CG03 record from CG but unfortunately the roman perturbation is not present in this latter record. What is the reason the comparison with CDD and DDG records have not been conducted?

Von Scheffer, C.; De Vleeschouwer, F.; Le Roux, G.; Unkel, I. Mineral dust and lead deposition from land use and metallurgy in a 4800-year-old peat record from the Central Alps (Tyrol, Austria). *Quater. Inter.* **2024**, *700–701*, 68–79.

4) Conclusion:
Rephrase conclusion, depending whether the Pb record is kept and its alignment to AN is discussed geochemically. If it is kept, add the fact that the very reliable ^{14}C age assignments based on larch and charred spruce needles, were shifted for more than 1-sigma in the lower part of the core to match the Pb peaks. And rephrase the last sentence of the conclusion in view of the now existing western Alpes CDD record including ^{14}C, ^{39}Ar, the Pb roman antiquity perturbation and the drop of $\delta^{18}O$ when entering the end or mid Younger Dryas period.

5) Other comments:

- Different depth units are used within the manuscript: depth in meter with 0 m at the glacier surface, depth in m w.e. with 0 m we at the glacier surface, ice thickness in m w.e. with 0 at glacier bedrock. No conversion in given between the different scales even not from m to m w.e.. With that, the reader cannot compare data between the different figures and Tables. Use only one single depth unit (m w.e. would be probably the most adequate) within the whole manuscript.

- Supplementary Text S2: The first sentence is very misleading: “The Colle Gnifetti ice core (Mt. Rosa, Western Alps) is currently the oldest record from the Alps, dating back >15000 5 years (Jenk et al., 2009)”. This sentence gives the impression that the CG ice recorded environments (and/or climate) back to more than 15,000 years. This is however not correct: as argued by Jenk et al. (2009), while radiocarbon analyses of particulate organic carbon have indicated that Pleistocene ice is sometimes present in the bottom layers at CG, it is shown that prior to 3,000 years the climate $\delta^{18}O$ record was strongly disturbed by post-deposition liquid migration of ^{18}O at the grain boundary of ice located in zones of strong strain-rate gradients above the inclined bedrock.

- The captions of figures are often not well completed. For instance, in Figure 6, 8, Fig S2, where you report the AN record of Pb, you have to specify in the caption that the AN record is from Mc Connell et al. (2019) (the citation only in the text is not enough). Please check also for CG.

- Figure 6, 8, S2 and S3: Records on linear scale are still unreadable, again please change the scales. For example, you could increase the height of the graphs and cut the y axis scale at 3 ng g^{-1} for Ortles and CG03 and at 0.3 ng g^{-1} for AN (indicating the maximum of the industrialization with a flesh to the top and a number). This would put the 10-year averages in the focus. Anyway, the annual lines indicated are too thin to be visible.

- Fig S2, As for Ortles and AN (see Figure 6 and 8), the discrepancy between CG03 and AN after 1600 CE is huge (even on a log scale). That requires a comment in the text. Also, in Fig S3 the comparison between Ortles and CG03 requires a discussion.

- Tables: in all tables the type sizes are too small

- no data were provided to the reviewer for the review process. Please, detail which data will be made available in the World Data Center. If the Pb data are kept in the manuscript they need to be made available.