Reviewer 2

Review of the manuscript cp-2024-75 "Geochronological reconstruction of the glacial evolution in the Ésera valley (Central Pyrenees) during the last deglaciation" by Vidaller et al.

This manuscript deals with the reconstruction of different stages of glacier retreat and readvances (here called last deglaciation) in northern Spain. The authors use cosmo nuclide dating, as well as isotope ratios to constrain the glaciation history. The methods are robust, even though paleoELA is subject to quite some uncertainties in terms of interpretation of impacts of temperature versus precipitation changes. It would be good to defend this point in a more convincing manner – with this being said, it is a standard practice in the geomorphological community and is thus acceptable. One very interesting discovery is the subglacial paleolake that existed under the glacier during the glacier readvance prior to its final, relatively smooth retreat.

I enjoyed reading the manuscript – it is relatively well written, presents a nice story and new, previously non-existent data that are high quality and well-aligned in chronology as opposed to earlier studies in the same area characterized by a large scattering. I particularly liked the discussion in light of existing proxy data in the region and globally. Nicely done. I recommend publication after minor revisions that are listed below.

We greatly appreciate this constructive remark and concur on the significance of examining lacustrine records linked to glacier evolution, as they provide crucial evidence for understanding the timing and patterns of glacial retreat. The Pllan d'Están sequence constitutes an exemplary case study illustrating the potential of this research approach.

General comments

Please, edit for typos. There are quite many of them. I will pass the file with some typos marked through the editorial system.

Answer (hereinafter A): Thank you, we have reviewed all the typos.

The title with "last deglaciation" is a bit misleading because the authors also discuss the PLGM conditions at 75 ka and MIS3 evidence of glacier shrinking. I understand that it could be inferred that the last deglaciation actually started at 75 ka and continued until now but this is not commonplace to state something like this and besides the choice of a journal (CP, which is focusing on the climate reconstructions, not on paleoglaciology or glacial geomorphology as such) requires that the authors make their messages very clear and use generic language. I therefore suggest that the authors simplify their narrative for the cross-discipline communities.

A: It is true that some terms are too specific. We have tried to simplify the nomenclature using more generic language, including in the title, to make it understandable for cross-disciplinary communities.

The snow shielding effect is parameterized using quite an old methodology. I am not an expert in this subject, so I am asking whether there are any other recent publications that would introduce

a more up-to-date parameterization and how the choice of methodology impacts your conclusions. Please, elaborate and include a comparison in the appendix.

The equation from Gosse and Phillips (2001), used in this study to correct for snow cover, remains a standard approach for adjusting cosmogenic nuclide production via high-energy neutron spallation (e.g., Palacios et al., 2019; Ye et al., 2023). Recently, it has been suggested that the mass attenuation length for high-energy neutrons should be adjusted for snow, as neutron modulation by hydrogen makes difference in attenuation lengths from that in other media (Zweck et al., 2013; Delunel et al., 2014). Zweck et al. (2013) used Monte Carlo simulations to derive a lower mass attenuation length of 109 g/cm² for high-energy neutrons (100-200 MeV) in snow, which is much lower than the values for lithological media (140–170 g/cm²; Cerling and Craig, 1994).

We have included a Supplementary Table (Table S4) with age calculations for our samples, using the lower attenuation length (109 g/cm²) and comparing the results to those in the main text (Table 1). Using a lower attenuation length reduces cosmic-ray flux, leading to lower production rates and older exposure ages for a given nuclide concentration. The alternative ages calculated with the lower attenuation length are only slightly older (<1%-6%) and remain within 1-sigma errors (internal and external). The only exceptions are Samples PDE-1 and PDE-2 from valley-bottom locations, where ignoring boulder height causes an offset slightly exceeding the 1-sigma internal error but still within the 2-sigma error.

Table S4. Cosmogenic ^{10}Be exposure ages from Ésera valley calculated using the lower attenuation length for high-energy neutrons in snow

Field ID [a]	Best ^{10}Be age (ka) [a]	Int. Err	Ext. err	Comparison to the Best ^{10}Be age in Table 1
PDE-1	14.49	0.56	1.05	1.06
PDE-2	13.94	0.50	0.99	1.06
PDE-3	14.02	1.17	1.45	1.06
PDE-4	14.34	0.52	1.02	1.00
PDE-5	13.28	0.50	0.95	1.01
PDE-6	12.66	0.45	0.90	1.01
PDE-7	13.58	0.49	0.96	1.00
PDE-8	0.433	0.037	0.045	1.01
PDE-9	0.405	0.052	0.057	1.01
PDE-10	11.14	0.55	0.88	1.01
PDE-11	10.81	0.40	0.77	1.00
PDE-12	13.64	0.51	0.98	1.02
PDE-13	17.10	0.63	1.23	1.03
PDE-14	16.45	0.68	1.22	1.01

Uncertainties are in one sigma: Internal (Int.) errors include only analytical errors and external (Ext.) errors include also systematic errors (such as errors associated with production rate and half-life). When compared to other geochronological data, external errors must be considered.

[a] Calculated assuming erosion rates at 3 mm/ka and using mass attenuation length of 109 g/cm^2 (Zweck et al. 2013) for high-energy neutrons in snow for correcting for snow cover effect considering respective boulder heights, where for PDE1 and PDE2, which are located in the valley bottom, no boulder heights was considered (see text).

In conclusion, the choice of mass attenuation length for high-energy neutrons does not significantly affect our conclusions. To clarify this minor variation, we added the following sentences at the end of Section 3.1 (now in lines 186-190): "*It is noted that the mass attenuation length for high-energy neutrons responsible for spallation reactions producing cosmogenic ^{10}Be may be shorter in snow (109 g/cm²) than the conventional value assumed here (160 g/cm²), due to hydrogen moderation (Zweck et al., 2013). Calculating exposure ages with this lower value shows minimal differences for most samples (within 1-sigma errors) and only slight differences for Samples PDE-1 and PDE-2 (within 2-sigma errors; see Table S4 in the Supplementary Information).*"

References:

• Cerling, T.E., Craig, H. (1994) Geomorphology and in-situ cosmogenic isotopes. Annual Review of Earth and Planetary Sciences, 22, 273–317.

• Delunel, R., Bourlès, D.L., van der Beek, P.A., Schlunegger, F., Leya, I., Masarik, J., Paquet, E. (2014) Snow shielding factors for cosmogenic nuclide dating inferred from long-term neutron detector monitoring. Quaternary Geochronology, 24, 16-26.

• Gosse, J., Phillips, F. (2001) Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Science Reviews, 20, 1475–1560.

• Palacios, D., Gómez-Ortiz, A., Alcalá-Reygosa, J., Andrés, N., Oliva, M., Tanarro, L.M., Salvador-Franch, F., Schimmelpfennig, I., Fernández-Fernández, J.M., Léanni, L., ASTER Team (2019) The challenging application of cosmogenic dating methods in residual glacial landforms: The case of Sierra Nevada (Spain). Geomorphology, 325, 103-118.

• Ye, S. Cuzzone, J.K., Marcott, S.A., Licciardi, J.M., Ward, D.J., Heyman, J., Quinn, D.P. (2023) A quantitative assessment of snow shielding effects on surface exposure dating from a western North American 10Be data compilation. Quaternary Geochronology, 76, 101440.

• Zweck, C., Zreda, M., Desilets, D. (2013) Snow shielding factors for cosmogenic nuclide dating inferred from Monte Carlo neutron transport simulations. Earth and Planetary Science Letters, 379, 64-71.

Again, for PaleoELA calculations – a very old publication. I understand that everyone is using ELA approach but the authors could at least add a discussion of how alternative methods could differ in terms of climate interpretation and how robust it is.

A: It is true that the references mentioned in the text are a bit old, but there are not any recent study defending the use of a new method, all the recent investigations use the same method (AABR), considering its limitations. In this sense, a new paragraph was added in order to clarify this issue (lines 54-59 in the revised manuscript): "*There are several methods to determine the ELA for a glacier, but the most accurate method is the Area x Altitude Balance Ratio (AABR; Benn et al., 2005), although this method presents challenges associated with the reconstruction of past glacier extensions, particularly the identification and dating of geomorphological features that are not always well preserved to reconstruct the surface of glaciers, overthought this*

approach remains a valuable method for understanding past thermal changes in mountainous environments (Pellitero et al., 2019)."

The glacier has been retreating since the LIA. Why didn´t you use more robust, recent observations to validate your ELA calculations? There are plenty of remote-sensed studies, aerial surveys, and maybe even some repeat photography. Besides, there are climate reanalysis data and observations to validate your choices of parameters.

A: Since there are no remote-sense studies or aerial surveys for the LIA, only some pictures and old photos from the first alpinists are available. Even thought, there are very well conserved moraines for this cold period, so the best option is to reconstruct the glacier surface using the glacial geomorphology feature. A sentence was added (now in lines 217-219): "*Unfortunately, drawings or photographs of enough quality for the LIA period to better constrain the ELA are not available, so the best option was to use the glacial geomorphology features to reconstruct the glacier surface.*" For the current situation, we have used more robust analyses and observations published in our previous papers that are referenced in the main text (Vidaller et al., 2021, 2023).

In the line 255 you mention equations. What equations are we talking about? There are no eq. numbers, neither do I find many equations in this work. Namely it is just one it seems. Please, clarify.

A: This sentence has been changed as (now in lines 298-299): "*This has been achieved considering the ELA obtained with the AABR method for each moment and the TLR calculated with eq. 1*"

Temperature lapse rate does not only depend on elevation but also on the season (can go from 4.5C/km in summer to 10C/km in winter) and even on the background climate. Please, add it in your discussion of limitations. I think such a section might need to be introduced in the appendix. Since this is part of a PhD study, such section is anyway needed in the thesis.

A: For this study mean annual temperature has been used, but as R1 and R2 the temperature lapse could vary between different periods. A new sentence has been added in the review manuscript to mark the limitations of the method (now in lines 481-486): "*PaleoELAs have been demonstrated to serve as effective proxies in the determination of temperature variations during periods for which instrumental records are unavailable. However, it should be noted that the method is not without its limitations. In certain instances, such as the present case, the temperature variation values obtained through the utilisation of paleoELAs do not exactly correspond with those obtained through the application of alternative proxies. Among other limitations in the method, we are aware of the likely changes in the temperature lapse rate with elevation and with the season throughout the different considered periods.*"

Minor comments:

Line 260: Not obvious that the formation of moraines is marking the onset of glacier retreat. Aren´t they accumulate during stillstands? Also, "ablation zone" seems out of context here. Further discussion/explanations are needed here.

A: This sentence has been removed.

Line 272: I don´t understand these calculations. Please, explain in a better way.

A: The variation of temperature is based on the variation of the paleoELA. Considering a stable AGT throughout time, the difference of temperature is based on the difference of the elevation of the paleoELAs. This sentence has been changed as (now in lines 298-299): "*This has been achieved considering the ELA obtained with the AABR method for each moment and the TLR calculated with eq. 1*"

Table 2: Correct "Period - 2023". It is the other way around. Clarify if it is a summer temperature difference or mean annual?

A: This sentence has been added to the table description (lines 326-328 in the revised manuscript): "*Each dated age corresponds to a specific moment during a climatic period, which does not imply that there were other situations during that period that were not recorded. The TLR was calculated considering the mean annual temperature of 2020 and 2022.*"

In section 5.1 you use a sediment core record dated by the OSL method. Was it not possible to cross-correlate temperature anomalies?

A: If we understand correctly, you ask to correlate temperature obtained with paleoELAs and with sediment data. In this case we did not inferred temperature data of the sediment core, only the type of ambient (e.g. a forest surrounding the lake or cold climate that avoid the development of organic matter correctly). Obtaining quantitative temperatures from the Pllan d'Están sediments would have implied a more detailed palynological study or the application of biomarkers proxies.

The statements about the early PLGM in section 5.1 are not inclusive. For example, the Barents-Kara Sea ice sheet reached its local LGM during MIS5. A lot of glaciers in Asia did too. The Patagonian ice sheet did so during MIS3, as well as glaciers in New Zealand.

A: It is right, this statement refers to a European context. This has been clarified in the reviewed text (now in lines 351-354): "*Therefore, the last glacial maximum extent in the Pyrenees does not correspond in time with the global Last Glacial Maximum (LGM) considering a European context, which is estimated to have occurred between 23 and 18 ka, implying the greatest advance in European glaciers, erasing the glaciological record of previous periods (Cutler et al., 2003; Toucanne et al., 2023).*"

Line 325: Misleading sentence – In many parts of the world glaciers during the Penultimate LGM were more extensive. Indicate that this is only for the last glacial period.

A: Change as suggested.

Lines 356-357: Why is that? How do you justify that your choice of parameters is more reliable? Uncertainties in delta T estimates should be explicitly discussed.

A: Because our margin of error in dating is smaller and because in almost all locations we take samples from two nearby blocks and the results are very similar. In previous studies, not only is

the margin of error in dating greater, but also, in some cases, the dates of nearby blocks are very different.

Line 403: I am not sure I understand this sentence. Rock or debris-covered glaciers or both?

A: Both, this has been clarified.

Lines 408 – 411: How do you explain such a disparity? What about the role of precipitation change?

A: As in a previous comment we have answered, the method of the proxy has limitations, this is discussed in lines 353-357 of the revised manuscript.

Line 420: The formulation is weird.

A: This sentence has been rewritten as (now in lines 493-495): "*Thus, some polished bedrocks at an elevation of 2549-2719 m a.s.l in the Gállego valley (Central Pyrenees), were dated with ^{10}Be and ^{36}Cl exposure ages, resulting in a date of 10.6±1.3 ka (Palacios et al., 2017a).*"

Line 431: I agree regarding biological indicators but isn´t it the same for ELA to some extent?

A: I agree with you, the ELA determines the elevation of the iso 0ºC during the ablation period, so during summer. In this sense this discussion has been deleted.

Lines 439-440: Why so?

A: These values were determined in other studies.

Line 462: What mechanism can explain such an early local LGM?

A: In this sense, in the rest of Europe, there was also a glaciation around 70-60 ka, but there during the LGM (23-18 ka) glacier advanced more than during the 70-60 ka expansion. In the Pyrenees, during the LGM the weather was cold but arid, avoiding large accumulations of snow, and consequently limiting the expansion of glaciers. This is up to now the more accepted hypothesis but the lack of LGM advances in Central and Western Pyrenees is still a matter of debate in our community.

How reliable are reconstructions of glacier retreat followed by a readvance? What makes your methodology trustworthy? Explain for paleoclimatologists.

The main strength of this study is the combination of a continuous paleoclimate record, the lacustrine sequence in Pllan d'Estàn, and the discontinuous information obtained throughout the cosmo dating. Such an approach allows us to infer different episodes of glacier advances and retreats based on the combination of different type of information. For example, for the LGM we can infer that the glacier covered Pllan d'Estàn using the type of sediments accumulated during that time period in spite we don't have any moraine associated to that age. On the other hand, we can infer a glacier readvance at 16 ka BP using the Llanos del Hospital moraine dated at the Oldest

Dryas period. Ideally, the complementary study of other continuous sedimentary sequences along the Ésera valley would provide additional information to support our interpretations.