Reply to Referee #3 Pascal Bohleber

Referee #3 General comments
Festi et al. present chronological information for a 46 m temperate ice core drilled at Pian di Neve, Adamello glacier. The ice core was dated through a novel combination of pollen and refractory black carbon analyses alongside with radiometric dating by 210Pb and already existing 137Cs horizons. By this means, the authors are able to constrain the age of the surface at the time of drilling, which remained unknown due to existing evidence of prolonged negative mass balance at the site. This is addressing an issue of broad relevance to ongoing and future drilling efforts aiming to recover valuable environmental and climatic records at sites that already undergo ice loss at the surface due to persisting warming conditions. I find the manuscript interesting, well-written and suitable for The Cryosphere. I also have a few comments and suggestions on how to improve the manuscript. I find the new approach to constrain the surface age and to derive an average value for the former net snow accumulation to be the key deliverable of the manuscript. This is of interest not only for the dating of ice cores but provides also important overlap with glaciological investigations at the site, in particular regarding the mass balance reconstruction. This latter point certainly provides additional value to the manuscript and should deserve some more emphasis.
Authors: We thank referee #3 Pascal Bohleber for his useful comments and suggestions to improve our manuscript and we hereby address the points of discussion.

Referee #3 Possible additions could be made to the discussion part and in the abstract. For instance, the new evidence for a surface dating to 1995 presented here appears to be nicely consistent with the mass balance investigation by Ranzi et al. (2010), which shows a persistent negative net mass balance since 1995 (one exception 2001).
Authors: Considerations have been added in the discussion (Age of surface) and in the conclusions also including other mass balance records for the region.

Referee #3 In their Table 1, Ranzi et al. (2010) also provide seasonal information on mass balance that may be interesting to take into account with regards to the pollen seasonal signal. It may also be worth pointing out that such point mass balance reconstructions have particular value as they have been shown to reflect changes in climate better than total mass balance or terminus fluctuation (Vincent et al., 2017). Relatedly, it has also been shown that point mass balance changes can reveal clear regional consistencies, which is interesting to note in the framework of the comparison with Ortles and Silvretta (lines 234).
Authors: We thank the reviewer for this valuable input regarding the value of point mass balance data. We included this information in the according section on the "Annual net accumulation rate for the period 1963-1986". Also, we agree that for the interpretation of pollen record information about seasonal mass balance are useful, but unfortunately Ranzi and al (2010) present data from the period 1995-2006 for which we don't have the corresponding layers.

Referee #3 To aid a better comparison with the existing glaciological datasets, Figure 1 should contain a better map of the drilling area, including at least some topographical detail and preferably contour lines. At present, very little can be learned about the position of the drilling site. For instance, it seems like several catchment areas may exist for the deeper ice core sections.
Authors: Figure 1 has been improved following the suggestions provided by all reviewers.

Referee #3 The glaciological setting also concerns another important aspect: It is stated that the core was drilled at the location of greatest ice thickness (line 73). It was not possible for me to verify this statement, however. The seismic campaign of Picotti et al. (2017) focused on one profile. The ground-penetrating radar survey seems to originate in Frassoni et al. (2001), but in spite of making a serious effort, I was unable to retrieve this paper. Ideally an ice thickness map could be added to Figure 1.
Authors: The position of the hole was defined after the survey of Picotti et al., (2017), who selected the seismic line based on the profiles by Frassoni et al. (2001) (file attached). Frassoni et al (2001) define the maximum depth with > 200 m (see fig. 2 therein), with reconstruction of the bedrock contours having a resolution of 25 m. Until now, no final map of the bedrock exists (not yet published) and such a figure can therefore unfortunately not be

included here. For the 46 m of core discussed here, knowledge about the precise ice thickness and bedrock topography is not relevant. It certainly will be for future discussion of results from a potential deep ice core from Adamello.

Referee #3 The ice thickness information could also aid in section 4.1 concerned with an age extrapolation to bedrock. The results are interpreted here basically as reconnaissance for a potential new drilling effort targeting to reach bedrock.
Authors: Knowledge about the total ice thickness is certainly important for the age modelling. At this point we can only rely on the available data (see comment above). However, ice thickness is not the main uncertainty and not crucial to assess the potential of the site. The according section has been reformulated to better portray the main message there and now also more clearly discusses the limitations and uncertainties of these age estimates.

Referee #3 I appreciate that the authors openly state that the use of the Dansgaard-Johnsen (D-J) model serves to make merely a crude estimate (line 259). This is not just due to the constraints located only in the upper third depth range, however. Here the clarification of additional points helps to put the inferred maximum age range into context: First, regarding the assumption that the ice is frozen to bedrock – how likely is this given the present evidence? Second, it is reported that the ice thickness value was determined by ground-penetrating radar, but this could have been via seismics instead? (line 251, citing Picotti et al., 2017). Regardless, the ice thickness value will have considerable uncertainty and the calculated dating function is typically sensitive to this. Therefore, a simple sensitivity study using the maximum vs minimum in ice thickness range would provide a more realistic insight regarding the age range expected from this estimation. This could be added as an illustration to Figure 5, which shows a 95% confidence interval but lacks detail on how this was derived.
Authors: The assumption that the ice is frozen to bedrock is the best we can do based on the present evidence (see Introduction). However, we cannot exclude the possibility for basal sliding. We use the age modelling only to assess the potential of the site. We reformulated the according section, being now more careful about describing the limitations of the modelling and degree of confidence one should assign to these modelled age estimates. The reviewer is correct, the thickness from Picotti et al., 2017 was derived by seismic data. Thank you for making us aware of this error, we corrected accordingly. We included the uncertainty in ice thickness to derive a more accurate estimate of the numerical model uncertainty (to convert the uncertainty contribution from the uncertainty in ice thickness, relative depths were used). The modelled age estimate is now presented as a band only, confined by the upper and lower estimate bounds (instead of the mean and a 95% confidence band). We now describe in more detail how uncertainties were derived. The section with Figure shown below now reads:
"For an estimation of the potential age range accessible by the Adamello ice archive, the one-dimensional Dansgaard-Johnsen ice-flow model was applied (Dansgaard and Johnsen, 1969). For the resulting age-depth relationship estimate shown in Figure 6, model parameters were as follows. Based on the bedrock depth determined by Picotti et al. (2017) using seismic measurements, the value for glacier thickness at the drill site was 265 ± 5 m (238 ± 4.5 m w.e.). The bottom shear zone thickness was assumed to be 15 % of the glacier thickness. This is slightly lower than the ~20 % typically observed for cold and polythermal high-elevation glaciers (e.g. Jenk et al., 2009; Uglietti et al., 2016; Gabrielli et al., 2016; Licciulli et al., 2020) but likely more reasonable for a temperate glacier (e.g. Kaspari et al., 2020). In any case, because constraining information from dated age horizons is lacking for the bottom part, a relatively large uncertainty of ±10 % was assigned. With these parameter settings, the value for the annual accumulation rate was found by tuning for a best model-fit to the dated 1986 and 1963 ^{137}Cs horizons (least squares approach). The dating uncertainty and the uncertainties associated with the pre-set model parameters described above were employed to derive upper and lower bound estimates (to transfer the contribution form uncertainty in ice thickness to uncertainty in age, relative depths were used).
The model - nicely matching the determined bottom age for the ADA16 core and accounting for layer thinning (vertical strain) – provides us a best estimate of the mean annual accumulation rate at the ADA16 drill site for the period ~1946 to 1986 of 0.9 ± 0.03 m w.e. a^{-1}. However, the assumption of steady-state conditions and the complexity of bedrock geometry and glacial flow in the deepest part of high-alpine glaciers strongly limits a realistic modelling of strain rates (and thus age) for the deeper parts, even using the most complex glaciological 3D ice-flow models. In our case, the lack of data for additional constraint in the deeper/older part, the assumption of steady-state conditions in annual accumulation rates (equal to an average value for the entire period contained in the archive) which are further based on a relatively short time range covered by the 46 m core only, the derived model-based age-depth relationship can only yield a current best estimate. Anyhow, this is at least sufficient to

reveal the potential of the site. The Adamello ice archive is very likely to cover the last 1000 years. Being contained in the major part of the total ice thickness (about the upper 240 m of ice; ~220 m w.e.), a millennial-long record should thus be accessible in high resolution. Also, there is reasonable likelihood for a few thousand more years contained in the remaining ~10 % of ice below."

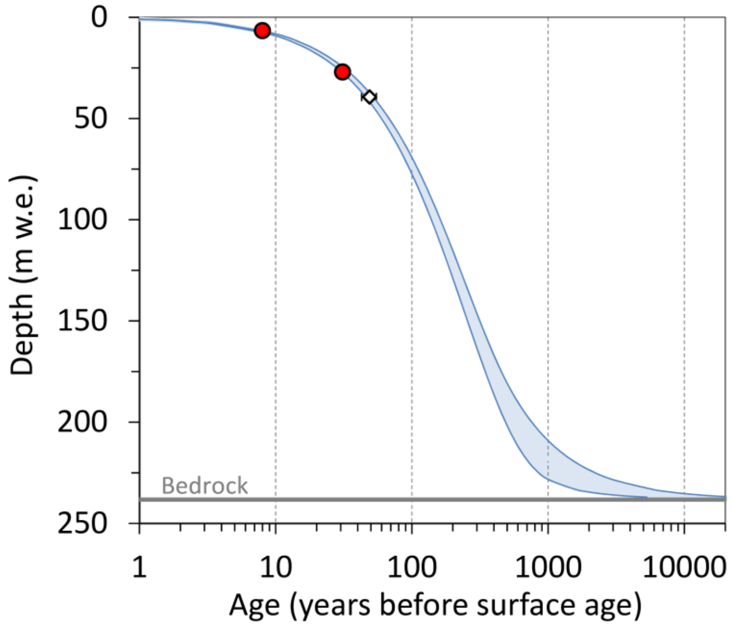

Figure 6. Model based estimate of the age-depth relationship down to bedrock for the ADA16 drill site. Red dots show the 1986 and 1963 ^{137}Cs horizons used to fit the model. The estimated age for the bottom of the 46 m long ADA16 ice core is shown in addition (open diamond, not used for model tuning). The shaded area indicates the range of estimates as confined by the upper and lower uncertainty bounds (thin blue lines).

Technical comments

Referee #3 Line 21: ": : : mass loss affecting this glacier even in the accumulation zone". Since mass loss is persistent today, it might be better to say "former accumulation zone", including at other instances in the text.
Authors: Done

Referee #3 Line 21: "we show that it is possible to obtain a reliable timescale for such a temperate glacier". This has been shown before. I would suggest to emphasize more the novelty of this work in the abstract, specifically regarding the combination of pollen and rBC and the resulting constraints for the surface age.
Authors: Done

Referee #3 Line 27: Maybe say "regional scale"?
Authors: Done.

Referee #3
Line 37: This is of course very important. Maybe use one of the following citations here to back up this statement?
Authors: Done. Reference has been added.

Referee #3 Line 81: "wet conditions" – what do you mean? What kind of problem stopped the drilling?
Authors: Mechanical drilling under wet conditions (percolating surface melt water) causes technical problems, hindering the transport of drilling chips to the "chips barrel" because when becoming wet, they can clog the

transport spiral. We included this information now: "Drilling operations stopped at 46 m of depth due to wet conditions from percolation/inflow of surface melt water causing technical problems for mechanical drilling."

Referee #3 Line 142: Could the striking synchronicity between pollen maxima and rBC be quantified somehow, e.g. through a correlation measure? Out of curiosity, can you make out different regimes if the two datasets are used in a scatterplot? This could help to detect, for instance, anomalously high pollen or rBC values.
Authors: The striking synchronicity in peak maxima is visible in Figure 2 and now very clearly in the newly added Figure 3 (referenced in the manuscript now). Because of different sampling resolution it is not possible to precisely quantify to what degree in terms of timing synchronicity exists, i.e. more precise than annual. In any case, a synchronicity in peak maxima between two parameters does not per se imply that there exists correlation between the two, which is also clearly not something we claim anywhere in the manuscript. Actually, we would not expect (high) correlation because of the different emission sources and processes for Pollen and BC (see comment to reviewer 4). Accordingly, a definition of what should be considered as "anomalously high" is not clear.

Referee #3 Figure 2: Personally I would find a zoom-in into a smaller depth interval of added value here.
Authors: A figure (now figure 3) has been added showing a 5 m zoom into the record.

Referee #3 Line 230: Delete "over the past years"
Authors: Done.

Referee #3 Line 279: I suggest to rephrase this statement considering that the results comprise pollen and rBC and the upper 46 m. It remains to be shown if a climatic and environmental signal, e.g. in the chemical impurities and stable water isotopes is preserved at the site, including the deep ice layers.
Authors: We rephrased.

References

Frassoni A., Rossi G.C., Tamburini A.: Studio del Ghiacciaio dell'Adamello mediante georadar. Suppl. Geogr. Fis. Dinam. Quat. 4: 77-84, 2001.