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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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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: Reviewer 1 comments start with RC1 while author responses start with AR.

RC1. General comments: The paper is interesting and reports worthwhile chronological and elemental data, interpreted in terms of recent intense ablation removing 600 years of ice from MPG (despite the glacier surviving warm times before then). Unfortunately, as presented, I am not convinced the data analysis supports the main

conclusions and I cannot recommend the manuscript be published in its current form.

AR.We appreciate the interest on our manuscript and on the data presented. We provide our answers here to the three main points raised by Reviewer 1 hoping to solve his/her main concerns. Importantly, we think we can approach the chronological issue in a new revised version following his/her advice regarding (1) the translation from lateral surface samples to depth, (2) explanations about the samples that we discarded from the chronology, (3) detailed interpretation of the "debris-rich" layers and (4) relation among the 100 studied samples and the three recovered ice cores. Ideas about the order and organization of the main text are easy to include in a new version of the manuscript and certainly will help to improve its readability.

RC1.First and most importantly, I believe the chronology needs to be addressed with greater structure and formal rigour. For example: - Since this is so central to the paper's message, I find the translation from lateral surface samples to depth too difficult to follow in detail.

AR.We agree with this appreciation. Figure S2 showed a basic scheme of how we sampled the glacier ice and how we translate the surface samples to a depth profile. This figure was probably insufficient and not clear enough to understand our method. We provide an improved version of that figure (Figure 1, see below), which will be included in the main text of the revised manuscript as Figure 2. In that figure the bedding of the glacier ice is included with a downward slope of about 20 degrees. Although such a value has not been derived from local ice-thickness measurements, they are consistent with those derived from neighbouring GPR profiles further to the east (López-Moreno et al., 2019). This figure will qualitatively help the readers to better understand the problem under study and how the sampling was done. A more complete information on this topic will be included in the text of the revised version.

RC1. It appears seven of 17 age samples were dismissed from the analysis; these need detailed comment on each.

AR. This information was already included in lines 309-327 of main text, but at a location within the paper that was not suitable. We greatly value the suggestions by the reviewer regarding restructuring of the manuscript contents, and will follow his/her suggestions. Of course providing the reasons to discard 7 out of 16 dates is one of the most important aspects of our discussion on chronology, so in the revised version we will elaborate on the reasons to discard every sample.

Basically, we keep 8 samples from the first set of 9 bulk samples we dated. Those samples were the ones with more amount of organic material and we expected to get good 14C dates from them. The only one from that set we had to discard was MP46 that was out of order (younger than expected) and attributed to the presence of small pieces of plastic (too small to be removed) contaminating the sample. After obtaining the first 9 dates, we selected some other intervals where the dating information was insufficient but, unfortunately, the samples were not so good in terms of quantity and quality of the organic material. Then, two samples dated by WIOC technique provided too large errors due to the low amount of carbon (still, we included one of them in the age model); three samples from pollen concentrates were too old (several millennia older than the others) likely due to associated problems to concentrate pollen (Kilian et al., 2002) and, finally, two samples from material contained in filters where the mixing among carbonate debris, dust and variable organic matter provided incongruent results. In summary, we constructed the age model from 8 samples from the first set of 9 bulk samples and 1 from WIOC. The other ones were easy to discard following the explained issues.

RC1. The interpretation of debris-rich englacial layers as periods of ablation (concentrating the debris) needs a far more rigorous argument based on physical analysis and exclusion of alternative possibilities. At present, the reader does not know whether these are isochronous, or whether they deform passively or cut-across primary layering/stratification. Could they be basally-derived? How are supply-rate variations excluded?

AR. Although alternative explanations cannot be completely excluded, we have firm reasons to believe that the sequence of debris-rich layers observed along the sampled profile correspond to the primary stratification of debris deposited at the surface of the glacier and are therefore isochronous layers (except for the cases in which the primary layers became merged due e.g. to intense melting episodes and/or low surface accumulation periods). Note, first, that the distribution of layers is rather regular and extends laterally as shown in Fig. 1 and in former Fig. S2, as would be expected for a stratification stemming from the original deposition at surface of snow and debris. Also note that the isochronal layers in a glacier emerge in the ablation area, but this is consistent with our case study, as our sampled profile corresponds entirely to the ablation zone. The reality is more complex, as our glacier has been shrinking and retreating since the end of the LIA, but the situation would be approximately as depicted below (Figure 2).

The reviewer questions whether the observed debris layers could be basally-derived. We believe that they are not. The main reason is that, in general, debris layers transverse to the glacier flow direction correspond to thrust faults developed near the glacier margin due to the compressional stress regime, most often associated to the transition, when we approach the glacier terminus, from warm-based to cold-based ice near the terminus. The warm-based ice slides over its bed, while the cold-based one does not, so strong compressional stresses develop, which cannot be accommodated by creep and thrusts develop. These thrust faults may reach the surface or terminate englacially (blind thrusts; see figure GM-a below). Basal debris is incorporated into these thrusts, sometimes reaching the surface. When they do so, due to surface melting, they often produce large accumulations of debris (often in the form of pinacles or pinnacle ridges along the debris layer; see figs. GM-a and BG below); intense melting episodes can spread this debris over the glacier surface. We believe that the debris layers observed at the surface of MPG are not subglacially-derived, because the hypothetical thrust faults supplying subglacial till to the glacier surface would be limited to the terminal zone, while in MPG the debris layers are observed all-along the sampled profile covering the entire lower glacier. Neither the mentioned large accumulations of debris, nor pinacles, are observed in MPG. Furthermore, if such thrust faults close to the ice margin would form in an advancing glacier (such as MPG during the LIA), they would form progressively in front of each other as the ice margin advances. Upon retreat, they would appear as a moraine-mound complex as shown in figures BG and GM-b below. However, in the proglacial zone of MPG, the only hummocky moraines have been identified as push moraines created by glacier advance before 1850 CE (Serrano and Martín-Moreno, 2018).

Fig. 3: Fig. 7 of Graham and Midgley (2000).

Fig. 4: Fig 9.6 of Bennet and Glasser (1996) – modified from Fig. 2.36 of Hambrey (1994).

Finally, we note that, as indicated in lines 283-287 of the original manuscript, "The debris layers were composed of detrital, silty-sandy size deposits, likely coming from wind-blown particles (e.g. black carbon-rich particles, dust) and from erosive processes of the limestone catchment, including the fall of gravel-sized particles from the surrounding cliffs" and they show no evidences of subglacially-derived glacier till.

Regarding the last concern of the reviewer, on how are supply-rate variations excluded, we note that our hypothesis does not necessarily exclude variations of debris supply-rate. In fact, higher supply rates are expected during warmer periods, in which more exposed rock surface should be available to supply falling debris from adjacent slopes and a larger extent of ice/snow-free terrain would supply a higher amount of wind-blown dust. This is not inconsistent at all with our comment in lines 288-291 of the original manuscript that "the frequency of debris layers increases towards the top of the glacier, where these layers are most abundant. We consider the accumulation of debris layers to be indicative of reduced ice accumulation and dominance of ablation periods."

RC1. How were the three core samples (and two deep samples) combined with theâĹij100 surface samples?

AR. The cores and the two samples from the front belong to a different area of the glacier, more dynamic, and for this reason they have not been combined with the 100 surface samples analysed in the present study. We recognise that, in the first submitted version of the manuscript, our writing could suggest that there was a relation among the cores and the 100 samples. Thus, in the new version, we will focus on explaining the sampling on the slope as the method selected to sample the glacier ice, and will justify the lack of coring by noting that glacier conditions did not allow obtaining a complete ice sequence by coring. Text reads as this: Ice sampling in MPG was carried out in September 2017 along an ordered chrono-stratigraphical sequence covering from the oldest to the newest ice preserved in the glacier (Fig. 2). Unfortunately, coring was not possible since none of the glacio-meteorological and topographical criteria required to obtain a preserved ice-core stratigraphy, such as low temperatures to prevent water percolation, or a large extension and flat surface topography to minimize the influence of glacier flow (Garzonio et al., 2018), are currently met in the glacier.

RC1. Since the annual 0 deg. C contour is at 3,000 m why wasn't snow/firn/ice sampled from the upper glacier. This glacier seems all to lie above this elevation and may therefore be accumulating, providing an undisturbed record of accumulation change?

AR. We could not reach the upper glacier in a safe way for sampling. Thus, up to now, there are no available samples, neither any age information from the upper glacier.

RC1. For me, too much key material seems to be given in the supplementary information rather than forming a central part of the argument of the main paper.

AR. We agree with this appreciation and have included all the supplementary information in the main paper.

RC1. For comparison, what elemental values have been measured in recent ice (not snow/firn)?

AR. Unfortunately, we cannot compare elemental values from current ice in Monte Perdido glacier since ice is not being formed at present, as the glacier has virtually no accumulation zone (the accumulation-area ratio tends to zero). We obtained the same information derived from the lack of 210Pb on the surface ice samples. Neither we have analyses of MPG snow. However, we have several measurements of snow from other zones in the Pyrenees at similar altitude, and found that the variability in elementary values from one site to another, or even from a sampling campaign to another, is enormous (see recently published paper Pey et al. 2020). It would be incorrect to use such values to compare with fossil ice in MPG. On the contrary, sampling atmospheric aerosols in Ordesa National Park station appears better suited to compare with MPG, since we can average over two years to get a more comparable value. Doing this, several elements appear clearly enriched in present-day atmosphere compared with MPG samples.

RC1. Second, substantial relevant material relating to the chronology of MPG appears later in the manuscript when I believe it should be summarised in full in the Introduction, directing the specific aim and objectives of this study. In my view, it's fine to introduce related information in the Discussion (such as the chronology of lakes in the area or of broader Alpine glaciers), but material directly relating to MPG - and particularly the focus of this submission (i.e., its chronology) - should form relevant background material in the Introduction.

AR. The only materials related to the chronology of MPG are the few dates corresponding to the moraines. We include them now in the Introduction as suggested by Rev. 1 and use them to state more clearly our aims.

RC1. Third, I found several of the sections and their contents to be confusing. For example, what I consider to be results are presented in the Field Site and Methods section, and I would separate Results from Discussion.

AR. Following this suggestion, we have separated Results and Discussion and included some dating information that was previously in Methods as Results. We hope that this

new organization of the contents, together with the inclusion of all of the material from the Suppl. Materials in the main text, makes this paper more clear and readable.

RC1. Specific comments Note, the manuscript includes many slight grammatical and typographical errors, as a few stylistic imperfections, which I have mostly not corrected. For me, the meaning was almost always clear, if not grammatically perfect.

AR.We have carefully reviewed the text looking for grammatical and typographical errors and corrected them.

RC1. Line/Location Comment/Suggestion 1 Title is awkward because 'that' is unspecified.

AR. We have changed the title to "The case of a southern European glacier that survived Roman and Medieval warm periods but is disappearing under recent warming". Thus, we better specify that is the glacier the one disappearing today but surviving during other warm periods.

RC1. 47 I'd avoid 'proves' unless the sentence states 'if we assume the chronological model is correct...'.

AR. We do not think that we need to assume that the chronological model is correct… it is based on 14C dates and the uncertainty is also considered. Yet, we can change the word "proves", which is probably too strong, to "evidences".

RC1. 54-55 This claim needs to be supported by a rigorous analysis. AR. We claim that the current warming is unprecedented in the context of last 2 kyr because the loss of ice from MPG in the last decades has been the greatest since we have records. The last sentence was probably not properly placed in the abstract, as it is based on conclusions from previous studies ("We demonstrate that we are facing an unprecedented retreat of the Pyrenean glaciers whose survival is compromised beyond a few decades") and thus we have removed it.

RC1. 94-105 I'd invert this: state the aim of the paper and then state how it was achieved. AR. We think the reviewer was confused by the wrong use of tense of verbs in this paragraph. Now, those explaining previous studies have been changed to past tense, and we state the aim of this paper, and how it was achieved, as suggested by Rev. 1.

RC1. 141 Data need to be presented and analysed to substantiate the claim that '(GPR and modelling)...suggested that the oldest ice could be located in these areas.' This claim is central to the chronology presented in the manuscript.

AR. That section has been removed, since it referred to the three cores which did not cover the whole sequence and thus were not studied.

RC1. 161 1 m of what? A Jacob's staff should be described, or just use 'staff'.

AR.Ok, done

RC1. 175 Which 'uppermost five samples'?

AR. We selected 5 samples towards the top of the sequence to have the most recent ones. In the text we now indicate which are those samples.

RC1.175-6 These are Results

AR. Ok, moved to results

RC1.176-8 This is Interpretation

AR. Ok, moved to discussion

RC1. 186-96 These are a mixture of Results and Interpretation. What values would be expected or have been measured on accumulating glaciers in similar settings?

AR. We moved some sentences to Results and some to Discussion.

RC1. 209 How and where did these samples come from? How were they treated?

AR. They are just two samples in the sequence of 100 samples. They correspond to

samples 67 and 81 and were selected because in that portion of the record the dating obtained by the first 9 samples of bulk material was insufficient. We thought those samples may have more organic material and were easy to date. . .. The pre-treatment is already indicated in the text and the treatment in the 14C lab was similar to any other sample just removing the filter at the first stage.

RC1. 231-2 Why a second-order polynomial/quadratic? If there is a theoretical basis for such a relationship, then that should be presented. If there is not, then what justification is there for this form?

AR. Before explaining the reasoning behind this approach, we note that the model was not built using a second-degree polynomial, and thanks to the referee we have spotted this error. We initially took this model as a quality control for the 7 dates amongst the 16 from which we presumed low quality due to various reasons (discussed in section 4.1 and along this letter). Using a second-degree polynomial approximation, instead of spline or other interpolations, higher degree polynomials, or a Bayesian approach, has been evidenced to be the best approach when there is a low proportion of dates in comparison with the potential changes in sedimentation rate (Telford et al., 2004). In such a way we still account for potential non-linear accumulation, though it rarely happens in nature, while we reduce the number of assumptions when increasing the regression into higher orders. We insist that this approach was used just to double test the quality of the samples that we were discarding.

Our final model was then made with the 9 remaining dates, where we set a hiatus at sample D-AMS 025298 (uncalibrated 14C 1011$\pm$ 25, 2700 cm, equivalent to 73 m depth following a bottom-up sampling strategy, as explained in Figure 2 above). We then run a linear regression that, given our scarce prior knowledge on the record sedimentation and according to the particular nature of our archive, seemed the most reasonable one, reducing the overfitting to noise of splines or higher-order regressions, still not forcing the model though all dates as a piecewise linear interpolation would do.

RC1. 234-8 This argument relating to debris concentration by ablation/low accumulation needs substantial background and argument, including arguments for this interpretation and against alternative interpretations of englacial debris bands. For example, how are supply-rate variations or a source at the glacier bed excluded?

AR. We are referring to the primary ice stratigraphy, which is evidenced by the alternance of layers with more debris (darker layers) and debris-poor cleaner ice (lighter in colour). This alternance occurs at a metric scale and appears all along the ice sequence (Figure 1 above). We interpret that these layers result from periods (summer?) with less ice formation and more "debris" supply. Interestingly, we observe this alternance more clearly between 67 and 72 "meters", where dark layers are thicker and are more closely spaced. From that interval we dated several samples (MP-67, MP-68, MP-69, MP-70, MP-73), obtaining dissimilar results, not in order, and covering a time interval from 600 to 1200 CE. Our hypothesis is that ice was formed at a very low rate during that period (600-1200 CE). Or, even if it was formed at a similar rate as in other periods, at some point it melted. Once most of the ice is melted, the accumulation of the debris particles becomes more evident. Here, the "debris" does not seem to correspond to material eroded at the glacier bed and entrained in the basal ice or transported to the glacier surface through thrust faults near thee terminus, but just to material mostly transported by winds and deposited on the ice surface. Further comments on the debris layers have been included in the answer to the general comments.

RC1. 288-91 These arguments need formalising, expanding and presenting as a logical progression of argument; currently, it is difficult to evaluate the accuracy of the chronology because this logical progression in argument (supported by illustrated data) is missing or split up through the paper and supplementary information.

AR. We agree with this comment about the lack of a logical progression in our argumentation, since the discussion on chronology was indeed split up in various sections of the manuscript. This is now corrected and, after an explanation of the methods

employed, all the discussion concerning the age model is included as Results in the revised version. We have substantially changed the structure and organization of the manuscript, and are confident in that the revised version has improved its readability.

RC1. 281- I find this section difficult to follow since in some places Results have already been presented and they are only referred to here (e.g., 306-8) or Results are mixed with Interpretation, and in some case Methods are included here (318-27). In relating to the last point, I'd discuss sample removal from analysis in Methods and not Results.

AR. Yes, we agree and we have worked on that direction in the new version.

RC1. 328-30 These criteria should be discussed in full and presented in Methods rather than Results.

AR. Yes, we agree and have worked in that direction in the new version.

RC1. 333 I'd bullet or number these three main periods and interpret consistent/repeated data across all three.

AR. Ok, we have indicated the three periods by numbers.

RC1. 361- I'd move much of this into a dedicated Discussion section

AR. We have moved part of this into the Results section (explanation of trace elements values in present-day aerosols and in the glacier ice), and partly into a new section in the Discussion (comparison with another paleoclimate record nearby, the Marboré lake).

RC1. 412-26, 434-7 & 467-70 I'd move this published material relating specifically to the chronology of MPG to the Introduction. That way it would contribute to, and form the framework/rationale for, the aims and objectives of the present study.

AR. Done. That information in the introduction helps to state the objectives of the present study.

RC1. Fig 1 Needs panel letters and I would find it easier to interpret if both had a similar orientation. Precise sample locations are needed. Are the locations of the three cores and the two deep samples noted here?

AR. Panel letters are included and map changed to have the same orientation as the picture. The three cores are not indicated, since we have not studied them, so just the transect with the 100 samples is shown.

RC1. Fig. 2 Y axis states 'h' but caption states 'depth'. 'h' is undefined, but appears to be height above bed. I know this depth scale is determined by translating the surface transect but it needs formal presentation and geometrical-dynamic argument and an error analysis. What flow model was used? If a flow model was not used, then at the very least the 3D surface geometry of the sample profile needs to be presented and the geometrical translation illustrated – in the main text. Is the glacier 100 m deep at present? Where in the glacier does this model relate to?

AR. All these questions posed by Rev1 indicate that the way we translated sample number to depth scale was not clear at all. As indicated in the main point of this letter, more text is added to explain this issue and Fig S2 is now included in the main text and improved with more information about glacier ice bedding (See Figure 1 above).

RC1. Fig. 3 Show uncertainly in elemental ratios. Panels need labelling.

AR. Panels are labelled. Uncertainty is indicated in methods, we do not think that it is necessary to include it in the figures for every sample.

RC1. Recommendations I would combine all that is currently published relating to the chronology of MPG into the Introduction and then recast the aims to address a clear knowledge gap. For example, it is already known that the glacier has lost 40 m of ice since 1980. If so, roughly how many years of accumulation does this cover and, if we are not sure, then can that –along with the existing chronology - form the basis of rationale for a chronological study based on flow-line surface sampling. Why

here and not in the upper glacier? An age-depth model derived on the basis of the analysis of samples from the ablation area of an ablating glacier is not a trivial glaciological advance. I think this should form the main aim of the paper and be presented and argued in a logical and formal way, with relevant data presented in the main text and not supplementary information. Having done this, I would like to see a rigorous assessment and inclusion of all un-certainties involved in the age and depth scales, included in Figures such as current Fig. 2. I realise this cannot be achieved with great confidence, but I imagine it can be approximated.(i) Methods, (ii) Results, and (iii) Interpretation/Discussion/Conclusions need to be separated clearly. As a minimum, Results need to be separated from Interpretation and Discussion.

AR. We really appreciate this final summary from Rev1 and are sure that we can follow his/her advice in a new revised version of the manuscript. The most problematic point regarding age-depth relationships is improved by including Fig S2 in the main text (in fact, all information in the Supp. Materials is now in the main text) and by more detailed explanations. However, we cannot present a rigorous assessment of uncertainties in depth scale since we do not know the inclination angle of the glacier ice layers to translate our sample numbers to real depth. We can approximately calculate the bedding tilt to finally have 30 m of ice sequence as happens in the easternmost section of the glacier. But still it would be unprecise and speculative. Therefore, we do not use the term "depth" anymore in the age model construction but "sample number" or "sample ID", which is more accurate. Regarding age uncertainties, they are included in the age-depth model. The organization separating methods / results / discussion really helps to understand the ideas and outcomes of this study. Similarly, including in the introduction more information about what we know about this glacier helps to better state our aims.

AR. References cited:

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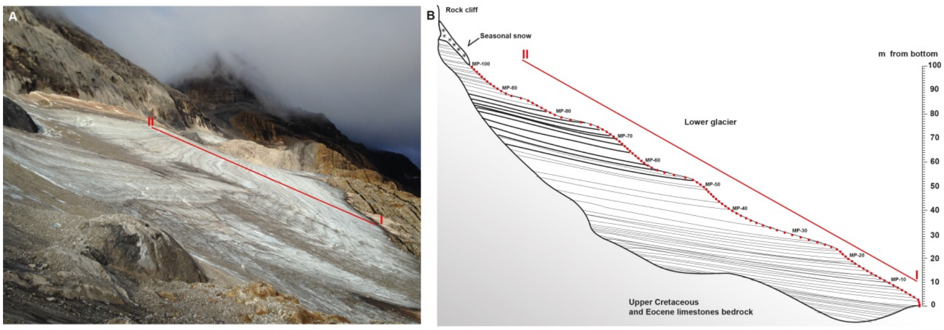

Fig. 1. This would be the new Figure 2 in the revised version, with an image of the glacier surface where we conducted the sampling and a scheme with the position of the 100 samples taken along the slope.

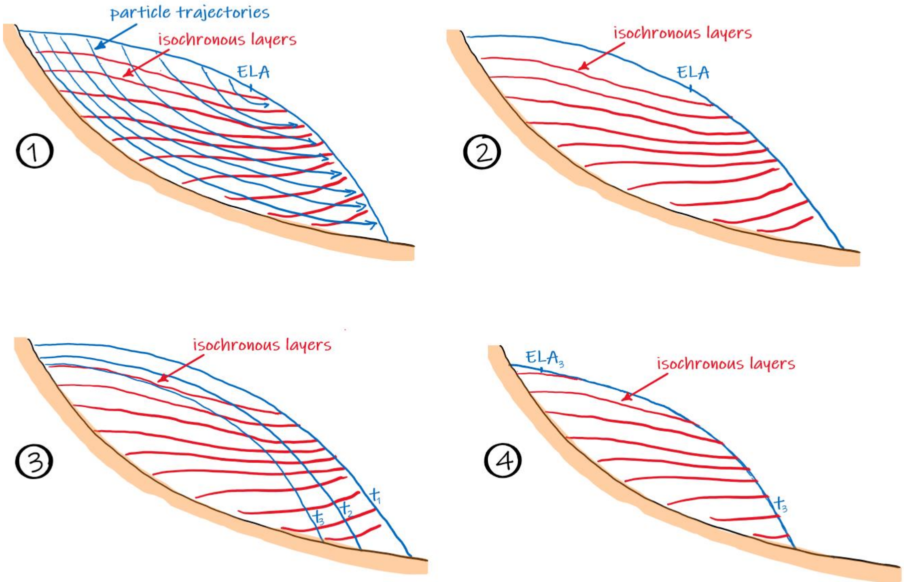

Fig. 2. In (1) we see the particle trajectories (blue) and the associated isochrones (red), emerging below the ELA; in (2) the trajectories have been removed to show only the isochrones; (3) shows subsequent

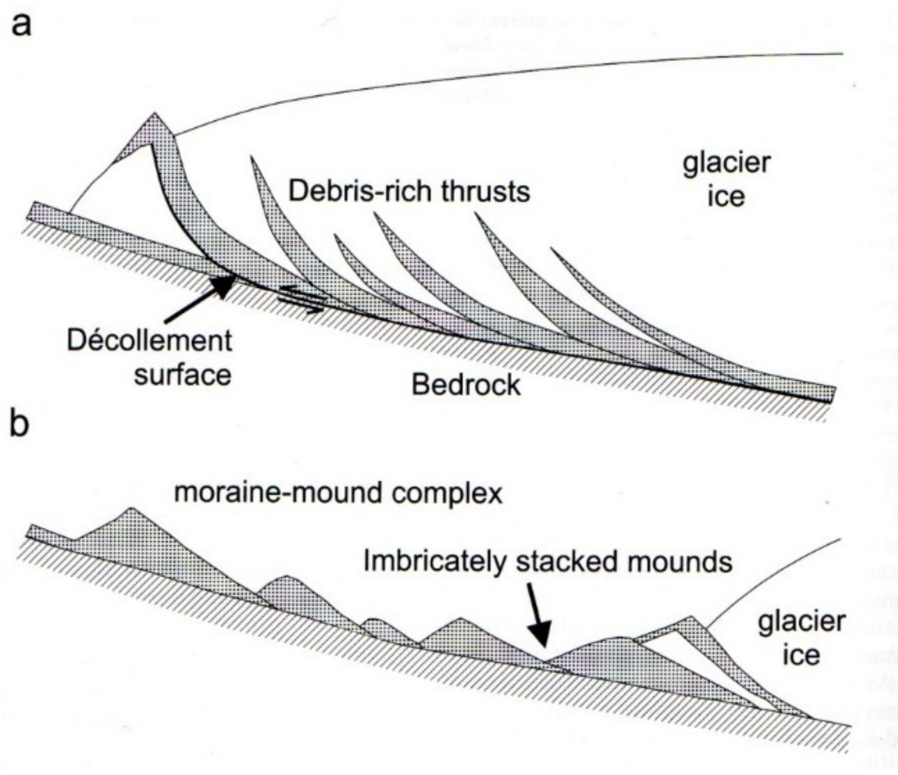

Fig. 3. Fig. 7 of Graham and Midgley (2000).

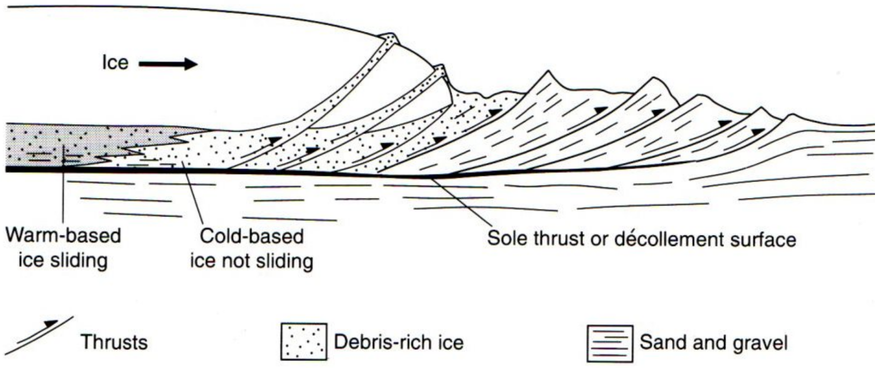

Fig. 4. Fig 9.6 of Bennet and Glasser (1996) – modified from Fig. 2.36 of Hambrey (1994).