Comment on "Ground-penetrating radar imaging reveals glacier's drainage network in 3D"

12 May 2021

Summary

The manuscript presents a 3D ground-penetrating radar (GPR) survey near the termini of Rhonegletscher, Switzerland. The goals of the study are to characterize the englacial/subglacial drainage system, as well as highlight the advantages of 3D GPR over glaciers, which this study is the first of its kind. Based on manual inspection of the radargrams an englacial drainage network is outlined with high resolution. The authors then use the amplitude of the picked network reflection, as well as the bed return to derive locations of englacial/subglacial water. The results are in agreement with two main theoretical frameworks - i) the englacial drainage network leads around an overdeepening rather than water flowing directly across it, and ii) the drainage conduit is likely flat and non-circular shaped.

General minor comments

According to the authors-, and my knowledge, this is the first 3D GPR study over a glacier, resulting in detailed characterization of the Rhonegletscher's englacial/subglacial hydrological drainage system. The methodologies and results are mostly well explained, and the manuscript is well structured, while the writing could be improved with some minor changes. I believe that the observations bring a valuable contribution to the glaciology and radioglaciology community and is well within the scope of The Cryosphere. However, I find that the main weak point of the manuscript is the lack of a discussion of possible implications of the findings for glacier dynamics and hydrology, especially as this is the motivation for studying such drainage networks (as outlined in the manuscripts introduction). Additionally, the manuscript could be improved in several aspects outlined below:

Introduction: The introduction provides a decent overview of the topic, stating the importance of a glaciers subglacial hydrological system for mass loss, and the difficulties/lack of observations using 2D GPR measurements. However, there are a few minor points that could be improved:

1) The differences between 2D and 3D GPR is not entirely clear and could be introduced in a bit more detail (i.e. both datasets are collected as line-by-line surveys, but with different survey setups/line spacing and processing techniques)
2) I think that the research goals could be formulated more clearly and more closely tied to the current knowledge gaps. For example, the manuscript mentions the study is motivated by previous findings (Line 57). I therefore suggest including a brief overview of these previous observations regarding the glacier hydrology on the Rhonegletscher, and what aspects of these findings (i.e. unknown extent of drainage system, improved resolution?) motivated this study. A brief introduction to the current knowledge on the Rhonegletscher drainage system would also help the reader to better understand the results from this study.

3) The introduction would greatly benefit from a brief overview of the theory of englacial drainage flow around overdeepenings, rather than simply mentioning it as a "long-standing glacier hydraulic theory (L45)".

Methods: The description of the methods is generally good, but I think the interpretation of the drainage network would benefit from a bit more detailed explanation on how the drainage network was picked (i.e. manual picking of visually strong, coherent reflections, added knowledge from previous GPR/seismic/boreholes data (Church et al., 2019, 2020)). I find it particularly difficult to follow how the drainage network was identified at the glacier bed. For example, on Figure 2c there is no obvious visual difference between the picked subglacial drainage network (dark blue arrows) and the ice-bed interface at profile locations 1850 and 1900. Additionally, in Section 4.3, the manuscript states that high basal reflectivity regions may also represent a subglacial water/drainage system, but these were not identified as drainage network in the manual picking. This leaves me wondering why these areas were not picked in the first place, and whether the identification of *subglacial water* should be done via interpreting bed amplitudes rather than visually identifying/picking a drainage network.

Additionally, Church et al., (2020) note the importance of calibrating reflectivities using borehole data. Was this attempted in this study? Or could it be done via comparing the 3D grid from this study to the previous GPR data?

Results: In general, the results are well described, however, there are two main points that could improve the manuscript:

1) Rather than stating that water is pooling where the bed is flat, it should be stated in terms of subglacial hydraulic flatness. I suggest calculating the subglacial hydraulic head/gradient, and determine whether the areas of high basal reflectivity occur in local hydraulic minima (which would allow pooling). Additionally, I wonder whether the high bed reflectivities could be caused by saturated sediments (or clay, see (Tulaczyk & Foley, 2020)) rather than ponded water.
2) The comparison of the 2D vs. 3D processing is based on a single profile. Because there is so much data available, I think the argument for 3D processing would be stronger if more data is shown (i.e. more profiles in a supplement, and/or statistics showing the difference between bed/englacial reflections identified in the 2D vs. 3D data). I also think that there would be an opportunity to compare results from this study's 3D data to the (already picked) 2D data in Church et al., (2020). Considering the manuscripts goal "to demonstrate the feasibility and opportunities of 3D GPR", I think that a more sophisticated comparison between 2D and 3D data would better highlight the advantages of 3D GPR.

Discussion: Overall, the discussion is well structured, however, is a bit vague regarding some findings:

1) I think the manuscript would benefit from a more detailed discussion on the configurations of the drainage system and its implications for glacier hydraulics, possible seasonal evolution and ice dynamics. For example, the results show a channelized water system

upstream, and a more dispersed system downstream. What causes this and what are the implications for ice dynamics? What are the implications of the englacial drainage network connecting to the basal drainage network and vice versa? And what implications could be derived from the study's results regarding future glacier retreat and the formation of the proglacial lake?

2) The results appear to agree with the theory of non-circular channel shapes, however, there is no discussion about the implications of this agreement. What does this mean for the water pressure, channel evolution, ice dynamics?
3) Finally, the manuscript would benefit from a discussion of the findings with respect to previous observations on the Rhonegletscher. For example, does the 3D data agree with the previous 2D survey in the upstream part? What knowledge is gained from the 3D survey compared to the 2D survey from Church et al. (2020)?

Figures/Movies: Most figures are very well prepared and are easy to read/understand. I also highly appreciate the movies which helped to understand the results. I have a few small suggestions for the figures:

Figure 2b: Maybe I am seeing this wrong, but it looks like the bed contour lines are different than in the following figures. It appears that the overdeepening minima is west of profile line C, whereas in the following figures the overdeepening minima is east of profile line C.

Figure 4a: The dark blue outline in conduit region C is difficult to see, I suggest using a different color.

Figure 5: I wonder if it would be beneficial to mark the hydraulic head contour lines instead of the bed contour lines. Additionally, it might be useful to mark the outline of the picked drainage network to highlight the difference in englacial/subglacial water pathways.

Line-by-line minor comments:

L33-34: "2D data sets are typically unable to image complex subsurface structures, …" I'm not sure if it is the *complexity* of subsurface structures that is difficult to image with 2D radar datasets, or rather the *size/scale* of subsurface structures relative to the radar surveys.

L36: Suggest replacing "option" with "tool"

L39: "…, because 3D GPR provides subsurface images that can be viewed from arbitrary directions,…" I agree that being able to view/visually inspect subsurface images in 3D provides an advantage, but results from 2D survey grids could be interpolated to generate (lower resolution) 3D images as well. I believe that the main advantage, and thus the argument for 3D surveys (or simply closely-spaced survey grids) is the high data coverage allowing to image the target at high spatial resolution. The "high resolution" is also noted as the motivating factor on Line 46. I suggest adding the high resolution aspect to this sentence.

L43-46: I think this paragraph would benefit from some re-structuring. It is not clear whether the 3D GPR survey was performed to demonstrate the feasibility of such surveys, to further characterize the drainage network previously identified in (Church et al., 2019, 2020), or to

investigate the hypothesis that englacial drainage flows around overdeepenings (or all of the above).

L45: "… to confirm long-standing glacier hydraulic theory." I think confirm is a strong word, and I am not sure if a theory can be confirmed with just one observation. I suggest changing this to "our hydrological observations are in agreement with a long-standing glacier hydraulic theory". Additionally, I think it would be helpful to spell out what the theory is.

L49: Replace 'It is representative…" with "The Rhonegletscher is representative…"

L70-71: "The 3D GPR data were collected …" I'm a bit hesitant to call this 3D GPR data, as the data was collected along 2D profile lines, just with close line spacing. Maybe this could be specified by something along "The GPR data for our 3D processing flow were collected in dense (2m spaced) survey lines perpendicular to the ice flow direction."

L93: "performed using an EM wave propagation velocity" (insert an)

L93: I suggest replacing "stretched" with "converted"

L95: I am not familiar with Q compensation for attenuation, but is it possible to state the attenuation rates used in the study (typically expressed as dB/km)? And what are the uncertainties from this attenuation correction?

L99: "…, the drainage network was picked …", it is unclear on what basis the drainage network was identified, i.e. manual picking of visually strong, coherent reflections, added knowledge from previous GPR/seismic/boreholes data (Church et al., 2019, 2020)?

L121-123: The sentences are a bit longwinded and repetitive. Also, rather than just stating that the drainage network was identified from the GPR data, I suggest clarifying based on which GPR attributes the network was interpreted from (i.e. based on the high amplitudes, manual inspection, the spatial pattern, the agreement with previous observations, see comment above). Additionally, how are the low amplitudes towards the edges and southern part of the outlined drainage network interpreted? Are these areas of past water flow, channel filled with air/sediments?

L123: "red" should be "yellow"

L125&L126: replace "overdeepen" with "overdeepening"

L126: "flowing alongside", a conduit doesn't really flow itself, replace with "follows" or "runs"

L128/130/134: "flows into a subglacial drainage system" / "flows into another englacial conduit", same as above, I suggest changing this to "connects with", or "transitions to …"

L132: replace "the conduit is expected to flow" with "water in the conduit is expected to flow"

L145: add "local basal hydrological conditions" to be more specific

L145-147: "… thereby indicating this area is positioned along the main drainage network identified in Figure 4.". The message of this sentence is not clear. What does "along the main drainage network" mean? I assume the argument is that the high reflectivities suggest the presence of water

at the glacier bed, with the upstream and downstream boundaries of this area spatially coinciding with the location of the englacial drainage network identified in Figure 4.

L148: Delete s in "amplitudes"

L154: Delete "today's"

L155: In my opinion, 2D surveys can provide 3D subsurface images via interpolation, but the distinct advantage of 3D surveys is the image resolution. I suggest changing to "unable to provide high resolution 3D subsurface images, …"

L157-161: I think "ambiguities" or "off-nadir reflections" would be a better description than "distortions".

L158: Figure 6 refers to an example geometry that can lead to off-nadir reflections in 2D GPR surveys, but it does not show the "distortion"/ambiguity itself.

L163: Delete "improved"

L167: I suggest changing "more unambiguous" to "less ambiguous"

L174: "In our case, it has a meandering nature …" I suggest changing this sentence to: "The Rhonegletscher drainage network identified in this study has a meandering nature throughout the survey area, with an increasing network width towards the glacier terminus."

L182-183: "The 3D GPR imaging results…" this sentence is a repetition from above (L175), I suggest merging them.

L185: I think it would be great to include a bit more detail on how exactly the Rhonegletscher results are in agreement with Hooke et al. (1990).

L194-197: There is no figure in the results section that shows the hydraulic potential/gradient. I suggest adding hydraulic potential contour lines to one of the maps (e.g. on Figure 5a, replacing bed elevation contours). This would also take care of the argument about high reflectivity in areas where water has the potential to pool. Alternatively, I suggest adding a figure to show the hydraulic head/gradient (possibly as supplement).

L202: "This is in contrast to our 3D GPR data set,…" I suggest removing or re-wording this sentence, as the GPR dataset in the study is not over a subglacial lake, but the sentence refers to the delineation of subglacial lake outlines.

L207-210: Here, the water accumulations are interpreted as isolated cavities, but in the results section (L150), it is noted that in the southern area there is likely a connected water system. If there is a different interpretation of the hydraulic system in the north and south, this should be stated more clearly.

L218: Not clear what is meant by "rate of acquisition". Time-consuming dense survey grids required for 3D surveys?

L218: I am not sure if the "accessibility" of the field site is more difficult for 3D surveys than 2D surveys. When conducting a 2D profile across an ice cap/glacier, I would expect the glacier to be

similarly accessible a few meters upstream/downstream of this profile line (with the exception of heavily crevassed areas). I think another argument for UAVs would be safety (i.e. less time spent on the glacier, no need to cross crevasses etc.).

L227: "… confirming long-standing…", in my opinion, confirming is a strong word here (see comment above).

L233-234: "… which is in contrast to theory. However, these observations are in line with further conduit geometry developments…". This is a bit vague, I suggest clarifying and spelling out that the results agree with the theory of broad and low shaped channels rather than circular channels.

L235: delete "as"

References

Church, G., Bauder, A., Grab, M., Rabenstein, L., Singh, S., & Maurer, H. (2019). Detecting and characterising an englacial conduit network within a temperate Swiss glacier using active seismic, ground penetrating radar and borehole analysis. *Annals of Glaciology*, *60*(79), 193–205. https://doi.org/10.1017/aog.2019.19

Church, G., Grab, M., Schmelzbach, C., Bauder, A., & Maurer, H. (2020). Monitoring the seasonal changes of an englacial conduit network using repeated ground-penetrating radar measurements. *Cryosphere*, *14*(10), 3269–3286. https://doi.org/10.5194/tc-14-3269-2020

Tulaczyk, S. M., & Foley, N. T. (2020). The role of electrical conductivity in radar wave reflection from glacier beds. *Cryosphere*, *14*(12), 4495–4506. https://doi.org/10.5194/tc-14-4495-2020