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Interactive comment on "Geophysical constraints on the properties of a subglacial lake in northwest Greenland" *by* Ross Maguire et al.

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We thank the reviewer for their thorough review, and will respond to their comments point by point below. Comments by the reviewer are bolded.

(1) Presentation of methodology Some essential information is missing about the measurements and analysis used in this study. For example, radar device is described only by "a 10 MHz monopulse radar system". Information of the manufacturer, type of antenna, receiver-transmitter distance, the way of data acquisition and dragging the device (sledge?) should be described. Another example is ice temperature analysis. Only available information for this computation is "1D steady state advection-diffusion heat transfer model solved using the control

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Discussion paper

volume method". How do you compute vertical strain rate? What is spatial resolution? Any influence of neglected firn layer and horizontal advection? Please describe all these details in the Method section.

We have added a more detailed description of the GPR data acquisition and processing to the Methods section (see also our response to Reviewer 1). Additionally, we have added a new section to the Supporting Information that provides a detailed description of the thermal modeling, along with its assumptions. See the attached document for more details.

(2) Presentation of data Results of the seismic and radar survey are presented in a limited way (Figs 2, 3 and 5). They are given only by plotting amplitude or power in a grey scale on a time-space domain. I wonder how the authors determine reflections at ice-water and water-bottom reflections. Fig. 2B and Fig 3A show important boundaries, but it gives me an impression that they were drawn only by visual inspection. Further, the authors discuss the phase of the seismic signals to identify the material under the ice. Nevertheless, there is no plot clearly showing such an important observation. I think more details, particularly plots of amplitude/power against time, are necessary to convince the readers of the interpretations and discussions.

The seismic reflections analyzed here (i.e., from either the ice or lake bottom) are clearly distinguishable from other phases based on their moveout; reflected energy arrives at all geophones in the line nearly simultaneously due to the near vertical incidence. In other words, there is no ambiguity of whether or not the phases we are interpreting are subsurface reflections. The reviewer states that it appears that the ice bottom and lake bottom reflections appear to have been drawn based only on visual inspection, yet this is common practice and well accepted. Additionally, we are not certain what is meant by “results of the seismic and radar survey are presented in a limited way”, since the cross sections shown in Figures 2A and 3 show all of the relevant data collected from the seismic and GPR surveys, respectively. The presentation style (i.e., using grey scale colormaps) is a very common way of displaying reflection results, and to us, seems to be a matter of personal preference. However, we do agree that the phase of the seismic reflections (particularly the opposite polarity of R1 with respect to the seismic source), was not clearly demonstrated. Thus, we have added a new section to the supplement that outlines the polarity analysis, and we include a new figure that more clearly demonstrates the opposite polarity of the source and reflection. The figure, which will be our new Fig. S4, is attached below. The waveforms shown in black in panels B and C are the first arrival and R1 reflection, respectively. In panel C, we have rescaled and reversed the polarity of the first arrival, and aligned it with R1 (shown in grey).

(3) Comparison with previous studies Seismic survey on a glacial lake is new in Greenland, but available for lakes beneath the Antarctic ice sheet. Interpretation of the seismic signals should be carried out based on the knowledge obtained in Antarctica. Such studies in Antarctica include those reported in Whillans Ice Stream and Lake Ellsworth. Important previous work exists also in Devon Ice Cap in the Canadian Antarctica. Considering the proximity of the sites and possible similarity in water property, closer comparison of the thermal conditions, geographical and geological settings should be performed. Please also introduce these previous studies more in detail in the Introduction section. I would like to read what are known about water depth, lake–bed constitution, water properties in subglacial lakes in Antarctica and other regions.

We have included a more thorough summary of previous active source seismic surveys conducted in Antarctica, which provides more context for the present study. However, we point out that many of these regions have fundamentally different geological histories and properties, and there is no strong reason to expect any similarity in subglacial water properties. Therefore, direct comparisons are challenging.

(4) Construction of the sections The paper suffers from mixing of method, results and discussion in the text, particularly in the Methods section. The Meth-

ods section begins with study site, and a little of methodology of seismic and GPR measurements (2.1 Field experiment). Then, it explains a bit more about the seismic measurement and directly goes into data and interpretation (2.2 Seismic and GPR imaging). Next subsection explains the analysis of the reflection power, which is followed by interpretation of the data (2.3 Basal reflectivity). This is not usual as a journal article and not convenient for readers. Please consider reconstruction of the text. The best for readers is to explain all the methodology in the Method section, which is followed by presentation of data in detail but without interpretation in the Results section, and finally interpretation and discussion in the Discussion section. I also find the last paragraph of the Introduction section includes too much results and conclusion. I would expect this kind of summary of the study in Abstract, which is currently rather weak.

We agree that a restructuring of the paper was warranted. In the new version the results are clearly separated from the methods in a new section titled Results. Additionally, we have removed the last paragraph of the introduction and moved the main points to the abstract.

Line 15–20: This abstract can be improved by incorporating the essential results of the measurements and conclusion described in the last paragraph of Introduction (Line 68–77).

See response above.

Line 32: "Bentley et al., 2011" > Missing in the reference list (or the publication year is wrong).

The publication year was wrong in the references and we have corrected it.

Line 36–37: "airborne radio-echo sounding"> "airborne" is not a necessary condition. Snow vehicle or snow mobile are also used for surveying lakes.

We have deleted the word "airborne".

Line 51: "approximately 40% of ..." > This is not consistent with 124 out of 400 as described in Line 40.

The discrepancy likely comes from different author determinations of "active" subglacial lakes. We have removed the inconsistency, and prefer to reference Smith et al. (2009), who found evidence of 124 active subglacial lakes in Antarctica.

Line 81: Please provide coordinates and elevation of the lake.

We have added a table with the latitudes, longitudes, and elevations of our seismic shot locations to the Supporting Information (new Table S1).

Line 82: Can you indicate the 980 km2 drainage basin on Figure 1B?

We refer the reader to Figure 1 of Palmer et al. (2013), who provide a plot of regional bed topography.

Line 86: "24 40 Hz" > Hyphen is missing.

Fixed.

Line 96: "longitudinal seismic reflection image" > Here and other places, the authors use "longitudinal" and "across", which are not clear to explain settings. Here, for example, "seismic reflection image along the survey route" is better if I understand it correctly.

We agree that “longitudinal” was unnecessary, and have removed it.

Line 107-108: "An additional reflection with opposite polarity of R1" is not clearly shown by Fig. 2B. Also not clear why you think "which is consistent with a lake bottom reflection".

The opposite polarities of R1 (i.e., the "lake top" reflection) and the secondary reflection we identify as “the lake bottom” reflection is more clearly demonstrated in Figure 5A, which shows a close up view of the lake reflection sequence on a single shot gather collected above the lake (shot gather number 12). It is expected that lake top and lake bottom reflections will have opposite polarities because of the opposite reflection coefficients between a layer of ice over water (negative reflection coefficient), and a layer of water over sediment (positive reflection coefficient). This is indeed supported by our modeling results shown in Figure 5B and 5C.

Line 110: What do you mean by "across the seismic section"?

We have replaced "across the seismic section" with "as a function of distance along the transect".

Line 111–112: Uncertainty due to wave velocity is evaluated, but I wonder if there is additional uncertainty due to signal peak determination. How do you define the reflection boundaries in Figure 2B?

This is a good point. There is likely to be variation between different analysts in terms of how they preprocess their data and how they determine phase arrivals and amplitudes, which would introduce some uncertainty. However, this uncertainty is difficult to quantify, and is always prevalent in any such seismic analysis. In this study, we do not believe that the travel time uncertainty would have a large impact on our lake depth results because a difference of several ms in travel time picks would translate to only small changes in the inferred lake depth (less than 5 m or so). When determining the lake thickness, we prefer to pick the first breaks (of R1 and the subsequent 'lake bottom' reflection) in the processed seismic image.

Line 116: "across the majority of the transect" > "across" is confusing.

Replaced "across" with "along".

Line 117-118: "lake is slightly deeper" > Do you mean "ice is slightly thicker"?

Yes. We have added clarification.

Line 118: Please define "transect distance".

The transect distance is the distance along the profiles shown in Fig 1C. We have added labels W, X, ,Y, and Z to the map in Fig 1C and to our cross sections, which should make this clear.

Line 126: "A_{R1} and A_{R2}" > The variable "A" should be in italic?

We have replaced all instances of A_{R1} and A_{R2} to be formatted consistently with how they are presented in Equation 1.

Line 160: "IMBIE Team Report" > The author name is inconsistent with the reference list.

Fixed.

Line 160: Can you provide an estimate of "net storage capacity of all of Greenland's subglacial lakes"?

I think that the uncertainties on such an estimate would be too large to make a useful addition. The first–order assumption that would need to be made is that all of the high reflectivity regions identified in airborne radar surveys (e.g., Bowling et al. 2020) represent subglacial lakes with similar depth than the one we identify in this study, which does not seem justifiable.

Line 180: How do you know the surface temperature in the region?

The surface temperature is determined from RACMO2 modeling. This has been made explicit in the text (see below).

"Using RACMO2 1-km resolution modeling of Greenland's near surface climate and surface mass balance (Noel et al., 2018), we estimate the mean annual air temperature to be -22 C. "

Line 181–182: "the basal temperature ... be well below the pressure dependent melting point" > Why do you think so?

Our estimates of basal temperature are determined through the thermal modeling results summarized in Figure 6.

Line 185: "1D steady state advection–diffusion heat transfer model" > Please describe more details with equations to be solved.

We have added a new section to the Supporting Information that fully describes the thermal modeling, including the equations that are solved and the assumptions that we make (also see attached document below).

Line 190: "When advection is ignored" > I understand that you ignore vertical ice motion. It is confusing because you also neglect horizontal advection of ice. Ice flow is small near the divide and down glacier advection of cold ice does not influence the conclusion about basal temperature below melting point, but mentioning the horizontal ice flow helps the readers.

By "when advection is ignored", we are referring to cases in which ice does not accumulate. When accumulation is considered (i.e., when we consider 'advection'), the thermal profiles are altered because the near surface isotherms are moved to deeper depths. We clarified this in the manuscript.

Line 199: Do you have estimate of the salinity from the computed basal temperature? Can you discuss your results with the study at Devon Ice Cap?

Based on our thermal modeling that suggests a basal temperature of between -12 C and -14 C, we estimate that the salinity required to keep the lake liquid would need to be between 160 and 180 ppt. This is comparable to the results of Rutishauser, who suggested a salinity of 140 – 160 ppt for the Devon Ice Cap region. We have added this discussion to the manuscript.

Line 199-200: "ice surrounding the lake would be frozen" > Do you think the hypersaline condition is limited with in the lake area? Such condition may extend to the surrounding area and cause basal melting outside of the lake.

This is a good point and we agree that the hypersaline condition may not be limited to the lake. Discussion has been added to Section 3.1 of the manuscript.

Line 210-219: I agree that continuous supply of surface meltwater to the bed is not likely because meltwater production is limited in this elevation range. Near the study site, a Japanese research group has been running an automatic weather station (e.g. Aoki et la., 2014), performed in-situ snow observations and ice core studies (e.g. Niwano et al., 2015; Kurosaki et al., 2020). I suggest the author to discuss water availability in the region based on the climatic conditions and the previous studies. - Aoki, T. et al. (2014). Field activities of the "Snow Impurity and Glacial Microbe effects on abrupt warming in the Arctic" (SIGMA) Project in Greenland in 2011-2013. Bulletin of Glaciological Research. 32. 3-20. 10.5331/bgr.32.3. - Niwano, M. et al. (2015). Numerical simulation of extreme snowmelt observed at the SIGMA-A site, northwest Greenland, during summer 2012. The Cryosphere. 9. 2015. 10.5194/tc9-971-2015. - Kurosaki, Y. et al. (2020). Reconstruction of Sea Ice Concentration in Northern Baffin Bay Using Deuterium Excess in a Coastal Ice Core From the Northwestern Greenland Ice Sheet. Journal of Geophysical Research: Atmospheres. 125. 10.1029/2019JD031668.

While it is important to consider water availability, there are no obvious pathways for surface meltwater to recharge the subglacial lake (e.g., moulins / crevasses), even if it were available.

Line 235: "cryoconcentration" > Is this a right word to explain lake formation due to "latent heat from freezing".

We agree that this was confusing. We have clarified our meaning. The new text is below.

"For the isolated lake of actively freezing brine (as in Hypothesis 1), the hydrologically connected continuous flow (Hypothesis 2), or if the lake is a relic of a larger freshwater body that is slowly freezing, the thermal profile of the ice would show a curvature

change at depth due to a latent heat source at the bottom boundary. Given a latent heat of freezing of 334 J/g, freezing a layer 1 m thick to the bottom of the ice over one year is roughly equivalent to increasing the geothermal flux by 10 mW/m2."

Line 235-239: It is odd to read this conclusion within the same paragraph explaining "Latent heat from freezing". Please consider to change the paragraph, or merge these sentences with the next paragraph.

Done.

Line 266: "Peters et al., 2013" > Missing in the reference list (or the publication year is wrong).

Thank you for catching this. The correct citation is "Palmer et al. 2013".

Line 272: "hydropotential modeling" > "hydropotential analysis"?

Done.

Figure 1c: Please label the ends of the GPR and seismic survey profiles (e.g. "X" and "Y") so that you can use the labels on Figures 2 and 3.

We have added labels W,X,Y and Z to the map in Figure 1c and the corresponding cross sections.

Figure 6B: There is something wrong with the line colors. I would expect warmer temperature for the higher geothermal heat flux.

We thank the reviewer for catching our mistake. It has been corrected.

Figure S2B: The vertical axis label "Ice Sheet Velocity" is odd. It's seismic wave velocity, right?

Yes, we have changed the label to "seismic velocity" as to not confuse it at the speed at which the ice is flowing.

Figure S4: Please enlarge the study site and consider drawing contour lines.

Otherwise, the color scale map does not tell a lot about the hydraulic potential distributions around the lake.

We prefer to show a broader regional context because the hydraulic potential does not vary perceptibly in the subglacial region since it is dominated by the surface topography of the ice.

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-321, 2020.

Model description for Greenland Paper

In order to estimate the temperature in the ice above the lake, we use the steady state conservation of energy:

$$\rho c \frac{\partial T}{\partial t} = 0 = \underbrace{\frac{\partial}{\partial x_i} k_{ij} \frac{\partial T}{\partial x_j}}_{\text{diffusion}} - \underbrace{\rho c \dot{u}_k \cdot \frac{\partial T}{\partial x_k}}_{\text{advection}} - \underbrace{\dot{Q}}_{\text{sources}} \tag{1}$$

where T is the temperature, ρ is density, c is the specific heat capacity, and $\dot{u}$ is the velocity. Tensor indices i, j, k are defined as 1 and 2 being in the horizontal along and across flow directions and 3 as the vertical. The conductivity, k. The sources are combined into $\dot{Q}$ and for this case they include both the geothermal flux and that due to latent heat of melting or freezing at the lake ice boundary: $\dot{Q}_{\text{freeze}} = -L\dot{m}$ where L is the latent heat for ice and $\dot{m}$ is the melt rate. Freezing of ice (negative $\dot{n}$) generates heat at the lake interface.

In order to apply this to the ice over the lake, we make several simplifying assumptions:

1. We assume one dimensional geometry. For our low-sloping icefield, this is a reasonable assumption for several reasons. Considering a typical lapse rate of 7°K per kilometer, $\frac{\partial T}{\partial x_1} \sim \frac{\partial T}{\partial x_2} \ll \frac{\partial T}{\partial x_3}$; therefore, even though we have a non-zero horizontal along-flow velocity, the effect of the advection of temperature from upstream is negligible compared to the vertical temperature gradient.
2. We assume that the vertical velocity linearly decreases from the surface (Cuffey and Paterson, 2010)
3. We assume that ice density is constant and equal to 920 kg/m^3. This assumption is weak for a compacting firn column, however our firn column is small compared to the full ice depth and we estimate an uncertainty due to this assumption of less than 0.1° C. We could however, we can estimate the effect of differing densities by varying the diffusivity (conductivity and specific heat).
4. We assume the conductivity (2.3 W/m/K) and specific heat (2000 J/kg/K) are uniform. This assumption results in an uncertainty of similarly less than 0.1° C.
5. We assume that the melt or freezing rates at the lake/ice boundary are small enough that the ice thickness is not changing significantly and we can assume steady state.
6. We assume that there is no convection or other currents within the lake and therefore that the bottom boundary condition is the heat flux at lake/ice boundary which is a combination of geothermal flux and melting or freezing.

We vary the surface temperature, the geothermal flux, the freezing rate, and the surface vertical velocity (the accumulation rate in ice equivalent) over a range of values to test hypotheses for lake water temperature.

$$\frac{k}{\rho c} \frac{\partial^2 T}{\partial x_3^2} - \dot{u}_3 \frac{\partial T}{\partial x_3} = \dot{Q}_{\text{geo}} + \dot{Q}_{\text{freeze}} \tag{2}$$

We solve this using a control volume method (e.g. Patankar, 1980).

1

Fig. 1.

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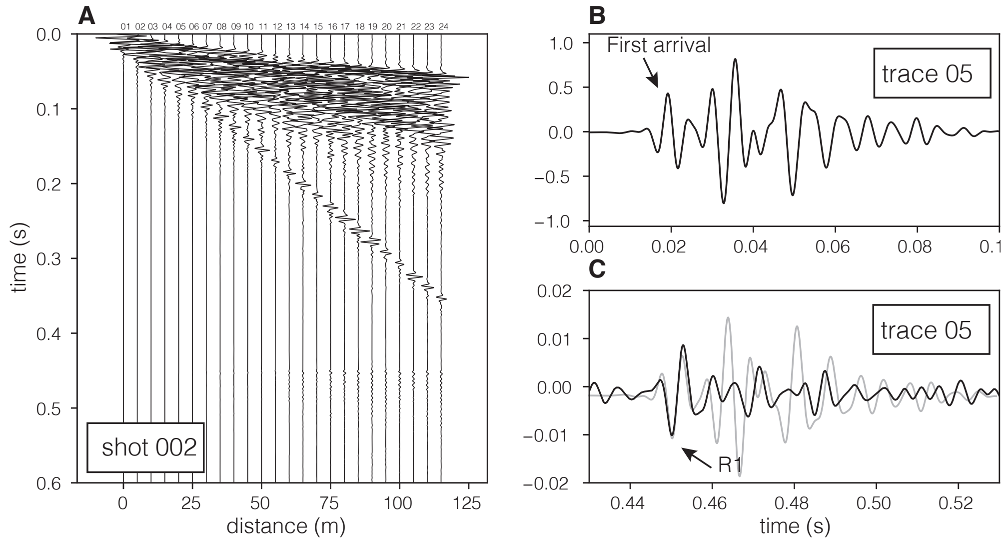
A
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
shot 002
time (s)
distance (m)
B
First arrival
trace 05
C
trace 05
R1
time (s)

Fig. 2.