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

**Ross Maguire et al.**

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We thank Dr. Buffo for his comments and his interest in our work. Below, we give our replies to each comment.

**1) I believe in the current manuscript the geothermal heat flux labels of Figure 6b are mislabeled and need to be switched.**

Our mistake has been corrected.

**2) I do not feel the 1D thermal model of the ice sheet is described in enough detail so as to reproduce or validate the presented results. There is a broad reference to Patankar (1980) but this text focuses on general numerical methods rather than the setup for the specific ice sheet problem discussed here. What**

**is the advection term utilized here? Is it the deposition rate? Accumulation rates are given in 'ice equivalent' form, but are these deposited at the already compacted ice density of 920 kg/m$^3$ or at a lower density and then compacted? I think expanding on the description of the model would help to clarify the utility of the results.**

We agree, and have included a thorough description of the thermal modeling to the Supporting Information section of the manuscript. See also the attached document.

**3) At no point are the reflectivity results gathered over the presumed lake (either GPR or seismic) quantitatively compared to the surrounding bedrock reflectivity values. This seems like a missed opportunity to me. The difference in expected reflectivity between bedrock and an ice-water phase transition is discussed, and hypothetical reflection coefficients are plotted in Figure 4, however it is not demonstrated that this is observed in the current study site. I find results comparing such contrasts in reflectivity crucial to the validity of these types of studies - for example Rutishauser et al (2018) "Discovery of a hypersaline subglacial lake complex beneath Devon Ice Cap, Canadian Arctic" present relative power measurements that show striking contrast between regions with lakes and the surrounding bedrock. I feel a comparable approach could be taken in this manuscript to substantially bolster the evidence for the existence of a lake. I do not feel qualitative inspection of the radargram in Figure 2 is enough evidence to conclude that a lake is present. Why are reflection coefficients for regions not directly over the lake excluded from Figure 4 (when this could validate the claims made in the manuscript)? Without an explicit example of contrasting properties between the purported lake and surrounding terrain I do not feel that the conclusion of a substantial (10-15 m thick) lake existing beneath the ice is a valid one.**

This is a good point that requires further clarification. Firstly, the seismic reflection coefficients were excluded from the region beyond the boundary of the lake simply





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because it is difficult to make clear amplitude measurements of the R2 arrival in this region, which is necessary to compute the reflection coefficient. It can be seen in Figure 2A that reflection R2 is much more difficult to identify, and at some transect distances (e.g., between roughly 1600 km and 1900 km) seems to almost entirely disappear. In the updated manuscript, we attempt to make measurements of $C_R$ in this region. However, given the very low signal strength of R2, it is not clear whether or not we are simply picking noise. If the results are accurate, it suggests that there is no clear change in the reflection coefficient across the boundary. While we choose not to interpret the seismic reflectivity results in the region beyond the lake boundary, we include the results in the updated Figure 4 (see below), so that the reader can decide for themselves. Additionally, we have added some GPR reflectivity results to the manuscript. We find that the reflectivity is approximately 10 dB larger above the lake, which is in good agreement with Palmer et al., (2013) who found a 10 - 20 dB anomaly associated with the lakes.

The results of Rutishauser et al. (2018) are interesting and relevant, but there is not a strong reason to believe that the basal conditions and materials should be similar in the two field regions. In the Devon ice cap, Rutishauser et al. propose that the hypersaline subglacial lakes are present in bedrock troughs. Hence, a strong contrast in reflection coefficient across between the lake and bedrock is expected. However, in our Greenland field site, there is no conclusive evidence that the region surrounding the subglacial lake is bedrock. Indeed, if the basal material is soft and possibly water-saturated sediment, there should not be a large difference between the seismic reflectivity compared with a subglacial lake.

Finally, we disagree with the statement that our interpretation of the presence of a subglacial lake is based solely on "qualitative inspection of the radargram in Figure 2". In Figure 5, we show the results of detailed seismic modeling which provides evidence for our interpretation, by showing that a thin (  12 m ) lake satisfies the traveltime and polarities of the seismic observations. Any interpretation should be able to explain





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i) A flat reflector with a strong seismic reflection coefficient.

ii) Two strong seismic reflections with opposite polarities (i.e., the phases we interpret as the lake top and lake bottom).

iii) The presence of only one single strong reflection present in the GPR data, which likely indicates that the radar energy is strongly attenuated below the surface of the reflector.

In our opinion, a subglacial lake is the simplest explanation for all of these observations. However, if our assumption of the attenuation in the ice is incorrect, it is possible that we could be over estimating the magnitude of the reflection coefficient. In this case, it is plausible that water saturated dilatant till could explain the reflection amplitudes. In the updated manuscript we clarify that our results are not completely conclusive, although we favor the subglacial lake hypothesis.

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## 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, $\rho$ 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$^o$ 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$^o$ 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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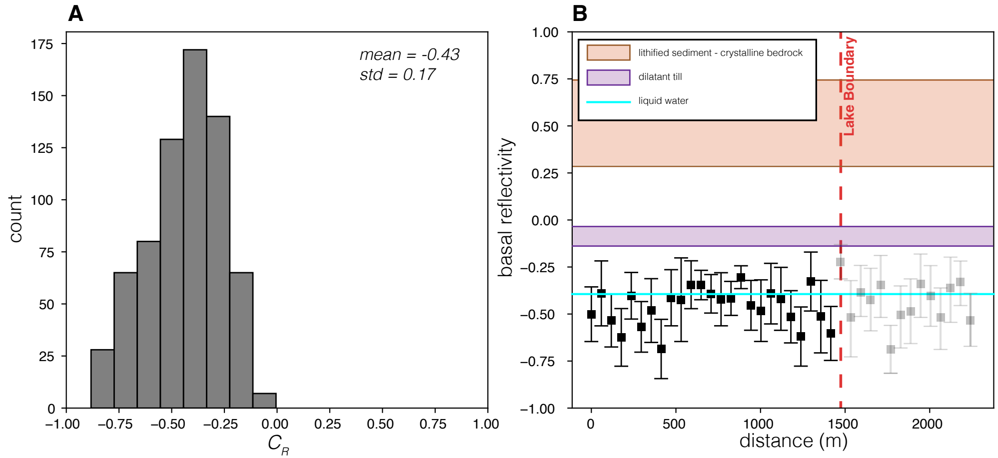
A
mean = -0.43
std = 0.17
count
$C_R$
B
lithified sediment - crystalline bedrock
dilatant till
liquid water
Lake Boundary
basal reflectivity
distance (m)

**Fig. 2.**



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