Authors' Response to Reviews of

Brief communication: The hidden labyrinth: Deep groundwater in Wright Valley, Antarctica

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Cryosphere

RC: ***Reviewers' Comment***, AR: Authors' Response

1. Reviewer #1

RC: *This manuscript presents a fascinating first look at the electrical conductivity structure beneath Wright Valley, Antarctica, in order to evaluate long-standing predictions that subsurface brine conduits may link several water bodies in the valley. The work is well-argued, clearly presented, and nuanced in its analysis. The manuscript presents a compelling case that subsurface electrical conductivity anomalies are present east and west of Don Juan Pond, but that continuity between DJP and Lake Vanda could not be directly detected. High conductivity regions in the subsurface are clearly demonstrated in the North Fork of Wright Valley, which is strong evidence of conductive porewater solutions in the subsurface on that side of the Dias.*

RC: *One question raised by the paper is the role of sampling geometry in the interpretation of the SkyTEM results. Line 1 in Fig. 1 seems to show highly conductive material extending from Don Quixote pond in the west, nearly all the way to Lake Vanda in the east. The high conductivity horizon in the subsurface is interrupted by the data dropout and by a highly resistive block of material shortly after 5000 m in the along-track direction. Is there any morphological or topographic evidence that could suggest that the high conductivity region could extend continuously from DQP to LV, but that the region of continuity was simply not imaged in the footprint of Line 1? Line 1 seems to have been targeted to intersect with DVDP14 and 4, but is it possible that in doing so, subsurface, high conductivity materials to the north could have been missed? If so, it seems possible that a subsurface connection between salty solutions in pore spaces in North Fork do extend downslope all the way from DQP to LV. Likewise, is it possible that the sampling geometry of Line 3 is what causes the pinch out of the conductive zone in the subsurface west of LV? Some of this could be addressed by mentioning the cross-track sampling width of the SkyTEM.*

AR: The role of sampling geometry in data interpretation is certainly an important concern. It's easy to imagine brine conduits skirting the highly resistive regions that we surveyed. The cross-track sampling width is likely on the order of 60-70 m wide at the shallowest depths and extending to several hundred meters wide at the bottom of our profiles. A recent Groundbased vs Airborne paper has a few nice figs that illustrate this [https://doi.org/10.1016/j.coldregions.2022.103578] (Figs 5 and 6).

AR: Our flight lines were picked to align with the lowest elevation tracks of the valley, where one might assume brine would pool (although we know surface water and groundwater flow fields can be very different). From all of the flight lines, there are indications that there are highly resitive areas as shown in Line 1 and 3. In addition, a handful of ground-based surveys were conducted in 2017 at the far west end of Lake Vanda, as well as in the South Fork. The ground-based data aligns with the airborne data, suggesting that shallow along-valley conduits don't exist. However, we are the first to acknowledge that these data are just one piece of the puzzle and we can't definitively rule out the possibility of conduits that do not follow the valley floor.

AR: For more technical information on data processing, you can find ground-based results from Lake Vanda in: https://www.sciencedirect.com/science/article/pii/S0165232X22000970, and a description of DJP processing in: https://academic.oup.com/gji/article/226/3/1574/6266462

AR: In a revision, we will provide more information on flight line geometry and how it may impact interpretation

RC: *Recognizing that the SkyTEM instrument is insensitive to shallow subsurface processes (i.e., one pixel for the upper 4 m of the soil/water column), the introductory text provides a somwhat facile or dismissive treatment of the role of surface and near-surface waters in affecting DJP chemistry and hydrology. For example, the text suggests that the variability in DJP extent and salinity indicates a hydrological driver beyond surface conditions. But surface conditions strongly control DJP lake level and extent as shown by (Dickson et al., 2013), who found a strong correlation between insolation (hence, snowmelt) and DJP spatial extent. Likewise, (Dickson et al., 2013) show input of water track solutions from the east, which also are associated with high insolation days which drive snowmelt and expansion of the active layer. (Hassinger and Mayewski, 1983) and (Dickson et al., 2013) both report that these near-surface water track solutions have high Ca, low Na, and excess Ca (Ca exceeding that which can be derived from dissolution of gypsum or calcite), which together, represent a potential contributing near-surface source for Ca-rich waters in DJP. The (Toner et al., 2017) modeling work is an important contribution to the understanding of potential subsurface processes in the DJP/Vanda region, but should not be considered an exhaustive analysis of hydrological contributors in the region because it largely considers only regional freshwater systems over the near-surface brines.*

AR: We did not intend to be dismissive of surface hydrological inputs. As you point out, there has been a wealth of strong science that supports surface hydrology playing a role in DJP hydrochemistry. Our language stemmed from the aim of providing well-founded evidence (both empirical and modeling) of a deep groundwater interaction with DJP. Furthermore, we agree with Reviewer 2, that DJP brine chemistry cannot be explained from surface water alone.

AR: In a revision, our aim would be to expand the literature review of DJP hydrology and provide more references to surface processes.

Specific Comments:

RC: *Title: The (real) Labyrinth is a network of bedrock channels. And so, while I love the title, it seems like a network of bedrock and sedimentary fractures or pores in the subsurface really isn't what the manuscript suggests is occurring around DJP, DQP, and LV. In some ways this gets at my general comment above—there may very well be a hidden labyrinth of subsurface brine conduits—but can single TEM lines identify that geometry?*

AR: I agree that we haven't been able to map a network of conduits in the subsurface, but the word labyrinth evokes a complicated maze-like network. The bedrock features on the surface are one such maze, but thus far it seems like the subsurface liquid pathways are still a complicated maze as well... even if we haven't fully solved the mystery. In a revision, we will be more clear about the possibility of "conduits" including the role fractured dolerite might play.

RC: *Line 8. Are brine conduits implied by the observations or brine presence? I'd interpret "conduits" to mean localized zones of high permeability, which does not seem to be implied by the observations.*

AR: Agreed that conduits implies a channel for conveying fluid. This is a important distinction from, say, trapped/isolate brine. We will be more specific in our language when refering to potential "conduits".

RC: *Line 49. Suggest removing the editorial tone of "convincing arguments." It is a really excellent and intriguing* *paper, but a more neutral introduction might help readers weigh the different arguments about water sources for DJP.*

AR: This will be addressed in a revision.

RC: *Line 97. How do you interpret the abrupt stop to the high conductivity zone at depth between DQP and Vanda? Is it a bedrock spur? A cold/dry permafrost pocket? Or evidence of brine diverging off the sensor path (in which case, there really is evidence for a subsurface labyrinth!).*

AR: Unfortunately there's not evidence for brine diverging off the sensor path... unless it's going down. An educated guess would say it's changing geology (Ferrar Dolerite to granite), but that is based off evidence of brine flow through Ferrar Dolerite near Don Juan Pond.

RC: *Line 100. It's really interesting that the low resistivity regions east and west of DJP extent up higher than the modern lake level. That could provide evidence of a perched saline aquifer that provides the hydraulic head observed in the brief artesian discharge episodes from the DJP boreholes, and would suggest that the low-resistivity zones east and west of the pond are at least partially connected to the brine in the ponds. This would be a really important finding because it differs from the classic groundwater interpretation for DJP (which is also invoked in the Toner et al, 2017 paper), which invokes cyclic deep groundwater upwelling. Line 2 seems to show that there is brine adjacent to and higher than the lake, suggesting that DJP solutions may not be exlusively upwelling from deeper sources.*

AR: This is a fascinating aspect that we didn't fully consider in our original submission. This also may align with the Toner et al. 2022 evidence of groundwater beneath VXE-6 pond which is at a higher elevation than DJP.

2. Reviewer #2 response to Reviewer #1

RC: *"...should not be considered an exhaustive analysis of hydrological contributors in the region because it largely considers only regional freshwater systems over the near-surface brines": In the Toner et al. 2017 paper we did model the surface brine evolution, and furthermore we considered all surface waters in Wright Valley as candidates. None of these surface waters can evaporatively evolve to form a DJP brine. Our recent paper Toner et al. 2022 provides an even more comprehensive look at deep, near surface, and surface water compositions in the South Fork of Wright Valley. This more recent paper supports the unique chemistry of DJP.*

RC: *Regarding the comments on surface discharges into DJP, we observed groundwater discharging east of DJP in the field, just as in Dickson et al. 2013. See the timelapse of discharge events over a month in the supplementary part of Toner et al. 2022. However, we also sampled many of these groundwater outflows, even during active outflow events, and analyzed the chemistry (unpublished unfortunately). There is no hint of any surface water contribution; the samples are pure DJP groundwater. Furthermore, these outflows have no observed connectivity to water tracks east of DJP, they simply upwell at the eastern edge the DJP playa. In my opinion, these are just groundwater outflows.*

RC: *Finally, regarding the discharge events and their correlation with insolation and snowfall, the most direct correlation with DJP groundwater levels appears to be air pressure, which is the expected behavior for a confined aquifer. There is data from the DVDP 13 borehole (sorry, again unpublished) that measures air pressure and water levels in the borehole, showing a strong correlation. Harris and Cartwright presented an analysis of the same, although there are many transient features that remain a mystery. We know that surface waters are contributing to DJP from streams on the western end of DJP from the rock glacier, but* *their influence on the chemistry is very slight (possibly, this might explain the small nitrate component of DJP).*

RC: *All this is to say that a deep groundwater interpretation for DJP presented in this paper is well supported by the evidence.*

AR: We agree that the aforementioned modeling studies support the deep groundwater interpretation, and based our introduction around these results. Thank you for your responses.