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

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Abstract. Since the 1960s, a deep groundwater system in Wright Valley, Antarctica, has been the hypothesized source of brines to hypersaline Don Juan Pond and Lake Vanda, both of which are rich in calcium and chloride. Modeling studies do not support other possible mechanisms, such as evaporative processes, that could have led to the current suite of ions present in both waterbodies. In 2011 and 2018, an airborne electromagnetic survey was flown over the Wright valley to map subsurface resistivity (down to 600 m) in exploration of liquid water. The surveys revealed widespread unfrozen brine in the subsurface near Lake Vanda, Don Juan Pond, and in the North Fork of Wright Valley. While our geophysical survey can neither confirm nor deny deep groundwater connectivity between Lake Vanda and Don Juan Pond, it does point to the potential for deep valley-wide brine conduits.

1 Introduction

Wright Valley in the McMurdo Dry Valleys of East Antarctica is notable for being home to the Onyx River, the longest river in Antarctica; Lake Vanda, the deepest and warmest lake in Antarctica; and Don Juan Pond, one of the saltiest bodies of water on Earth. It is also notable for having a long-standing debate as to the origin and connectivity of groundwater brines in the valley. Both Don Juan Pond and Lake Vanda hold salty calcium-chloride rich brines, distinct from the sodium-chloride brines seen to the south in Taylor Valley (e.g., Blood Falls, Mikucki et al. 2009) and to the north in Victoria Valley (e.g., Lake Vida, Dugan et al. 2014).

The earliest limnological investigations of Wright Valley in the 1960s revealed saline waters in both closed-basin Don Juan Pond and the hypolimnion of closed-basin Lake Vanda (Wilson and Wellman, 1962; Armitage and House, 1962; Meyer et al., 1962), but it was not until the summers of 1973/4 and 1974/5 with the undertaking of the Dry Valleys Drilling Project (DVDP) that subsurface hydrology was able to be investigated. Importantly for our investigation, were three boreholes. DVDP4 was drilled in the center of Lake Vanda, DVDP13 was drilled immediately to the west of Don Juan Pond, and DVDP14 was drilled, at the time, to the west of Lake Vanda in the North Fork of Wright Valley (under the surface of Lake Vanda at present).

In 1973-74, DVDP4a penetrated 17.4 m beneath the sediment/water interface of the bottom of Lake Vanda, and found 3.5 m of lacustrine sediments, underlain by 2.2 m of glacial sediments, 6.7 m of marine sediments, and eventually basement rock (Cartwright et al., 1974). Cartwright et al. (1974) hypothesized the presence of a groundwater system flowing from Lake Vanda to the west. They later invalidated this hypothesis based on fluid potentials measured in the sediments. They found that there was no change in total head between the lake bottom and the underlying sand and gravel, indicating that groundwater was flowing laterally at the borehole location, and if there was an area of groundwater discharge into the lake, the borehole did not intersect it (Cartwright and Harris, 1981).

The following summer, DVDP14 was drilled 1.5 km west of Lake Vanda. Total penetration depth was 78 m, with basement rock reached at 27.94 m depth (Mudrey Jr. et al., 1975). All water and sediments in the borehole were found solidly frozen, which, at the time, was thought to negate the previous summer's hypothesis that water flowed westward from Lake Vanda into the North Fork. Water was later squeezed from the 28 m of sediments and found to be hypersaline (50-180 ppt) (McGinnis et al., 1981).

That same summer, at Don Juan Pond, DVDP13 was drilled 75 m deep, reaching highly fractured basement rock at 12.7 m depth (Chapman-Smith, 1975). Water was encountered in the borehole, and consistently rose to a level 0.65-0.80 m higher than the surface of the pond, which indicated the pond was receiving groundwater discharge. The borehole water was saline, but less so than Don Juan Pond itself. In Dec 1978, the borehole was revisited. Once cleared of ice, -15.5°C water flowed from the hole for three days as an artesian well before being shut off (McGinnis, 1979). It was hypothesized that the fractured and highly mineralized Ferrar dolerite might be a confined aquifer, sourcing water from the base of the Antarctic Ice Sheet (McGinnis, 1979; Harris and Cartwright, 1981). The water levels and salinity of the pond itself vary as well, which suggests a hydrological driver beyond surface conditions (Harris et al., 1979). Geophysical resistivity logs of the DVDP13 borehole showed higher resistivity in the Ferrar dolerite from 23-33 m depth. McGinnis suggested that this may be a zone of high permeability and high flow, and therefore have less diffusion of salts (McGinnis et al., 1981).

Since the DVDP era, a number of scientists investigated the origin of salts in these lacustrine systems. Most mixing models predict that for Lake Vanda and Don Juan Pond, the salts could not have originated solely from surface inputs from the Onyx River, and must be derived in part, from a deep groundwater source (Green and Canfield, 1984; Green and Lyons, 2009; Carlson et al., 1990). Furthermore, if a regional groundwater system did exist that connected both waterbodies, water should recharge from higher elevation Don Juan Pond (113 m asl) and discharge to lower elevation Lake Vanda (90 m asl).

A convincing argument is made by Toner and colleagues (2017), who present a model of brine evolution in Don Juan Pond, and find that the ionic ratios in Don Juan Pond are explained by the upwelling and evaporation of deep groundwater, and that the turnover time is relatively short (<1 year). They too conclude the presence of a regional groundwater flow system, but note their investigation is equivocal on whether a groundwater connection exists between Don Juan Pond and Lake Vanda. Lake Vanda has much higher Mg:Cl and K:Cl ratios than Don Juan Pond, which suggests the lake undergoes closed-basin evaporation without a significant outflow, unlike Don Juan Pond where they hypothesize groundwater flows both into and out of the pond (Toner et al., 2017).

2 Wright Valley AEM survey

Here, we present data from airborne electromagnetic (AEM) surveys flown in Wright Valley in 2011 and 2018 (Foley et al., 2015). Previous examinations of these data in Victoria Valley and Taylor Valley have revealed both the existence of confined brine pockets (e.g., under Lake Vida, Dugan et al. 2015), and expansive groundwater connectivity (e.g., lower Taylor Valley, Mikucki et al. 2015; Foley et al. 2020), and have transformed our understanding of hydrological connectivity in this polar desert ecosystem.

Comprehensive methodology on our AEM survey can be found in Grombacher et al. (2021). Briefly, a transient electromagnetic (TEM) measurement involves a current in a transmitter loop being turned on and off, which generates a time-varying magnetic field in the subsurface, subsequently leading to electrical eddy currents in the subsurface that generate a secondary time-varying magnetic field. These secondary fields are measured by a receiver coil. Highly conductive regions produce larger amplitude, slowly decaying eddy currents, whereas highly resistive regions give rise to smaller amplitude, quickly decaying currents. Our AEM surveys were conducted by suspending a TEM system beneath a helicopter. Inversion is used to estimate the underlying electrical resistivity structures consistent with observed TEM signals. Here, standard 1D TEM forward modelling approaches are employed (Auken et al., 2015), except in the case of Don Juan Pond where a more complex forward response is required to account for strong induced polarization effects (Fiandaca et al., 2018). Inversion results are presented as cross-sectional images of resistivity (Ω-m) to infer subsurface properties (i.e. highly resistive ice or bedrock, or highly conductive water and brines). The depth of investigation (DOI), where the signal to noise ratio is too low for accurate interpretation, was several hundreds of meters in many areas.

We focus on three flight lines: Line 1, along the North Fork and Lake Vanda; Line 2, along the south fork over Don Juan Pond; and Line 3, along the southern edge of Lake Vanda (Fig. 1a). Additional flight lines were flown N-S across Lake Vanda, but many appear to display 3D effects where measured signals are sensitive to features not beneath the sensor (i.e. to the side/front/or rear). In these cases, forward modelling employing 1D assumption may introduce spurious features in an attempt to attribute observed signals to structures directly beneath the sensor. These spurious features, that sometimes manifest as “pantlegs" where a shallow feature is stretched deeper to the sides, can render interpretation of connectivity difficult. In addition, any gaps between or within a flight line were areas where no earth signal could be reliably detected that exceeded instrumental noise levels. This does not negate the presence of a deeper conductive unit, only that it is not present within the DOI of the employed AEM system.

The returns from the three along-valley flight lines are intriguing (Fig. 1b-d). Firstly, the surface conductors of Lake Vanda and Don Juan Pond are clear. The top 20 m of Lake Vanda have a resistivity of ∼20 Ω-m (a typical value for freshwater). At 60 m depth, resistivity drops to 3.9 Ω-m, and further drops to 0.2 Ω-m at 70 m depth. This is consistent with electrical conductivity (EC) of lake water in Vanda, which shows low EC (< 5 mS cm^{-1}) from the surface to 63.6 m depth (in 2014), followed by a rapid increase to 120 mS cm^{-1} between the depths of 63.6 and 78 m (Castendyk et al., 2016). The minimum resistivity of 0.14 Ω-m is recorded from 80-92 m, a depth within the lake sediments, the overlaps with the highly saline water (> than lake water) found in the sediments of DVDP4.

Similarly, the surface of Don Juan Pond, from 0-4 m had a resistivity of 1 Ω-m in Line 2. This might appear high for the second saltiest body of water on Earth, but the pond itself is only 20-30 cm deep, and the AEM inversions are averaged over the top 4 m. The second area of low resistivites (12-14 Ω-m) is seen from 23-36 m. This depth overlaps with the hypothesized aquifer in the Ferrar Dolerite (Harris and Cartwright, 1981). The surface of saline Don Quixote pond is also evident at the very western edge of Line 1 (Englert et al., 2014).

Beneath the surface, any connectivity is obscure. To the east of Lake Vanda, there is little evidence of subsurface conductors and it is unlikely there is deep groundwater. From Lake Vanda to the west, there is no obvious shallow (<100 m) connectivity between the Lake and the North or South Forks. There is evidence for a layer of shallow brines in the North Fork, possibly a remnant of paleolakes. DVDP14 did not penetrate the permafrost, and it may be that it did not extend deep enough, or the spatial heterogenity is such that it did not intersect an unfrozen brine layer.

3 Conclusions

From Lake Vanda towards Don Juan Pond in the South Fork, we cannot establish a direct subsurface connection from our data, however, a deep (>200 m) connection may be present. Certainly, resistivities <100 Ω-m to either side of Don Juan Pond support this speculation. This depth is in the range at which liquid brines were inferred in Taylor Valley from AEM (Mikucki et al., 2015), and also similar to the frozen-unfrozen transition of 183 m found in DVDP10 at New Harbor, Taylor Valley and the speculated frozen-unfrozen transition of 243 m in DVDP11 in front of Commonwealth Glacier, Taylor Valley (Cartwright and Harris, 1981). DVDP geological data establish that any deep groundwater connectivity in Wright Valley would be through fractured bedrock (possibly the Ferrar dolerite) and not sediments, as in Taylor Valley.

These findings do not resolve the potential for deep groundwater connectivity in Wright Valley, Antarctica, but do confirm the presence of unfrozen brine saturated regions in the subsurface, and importantly, do not rule out deep valley-wide groundwater connectivity.

Code availability. R code to reproduce the figures in this manuscript is available at: github.com/hdugan/WrightValley_AEM

Data availability. Data for the three flight lines presented in this manuscript are available at: github.com/hdugan/WrightValley_AEM Data for the project is available via the US Antarctic Program Data Center: usap-dc.org/view/dataset/601373

Author contributions. HD led manuscript preparation. DG, EA, NF, TB oversaw data collection, data processing, inversion, and interpretation. All authors contributed to field campaigns, and intellectual development of the manuscript.

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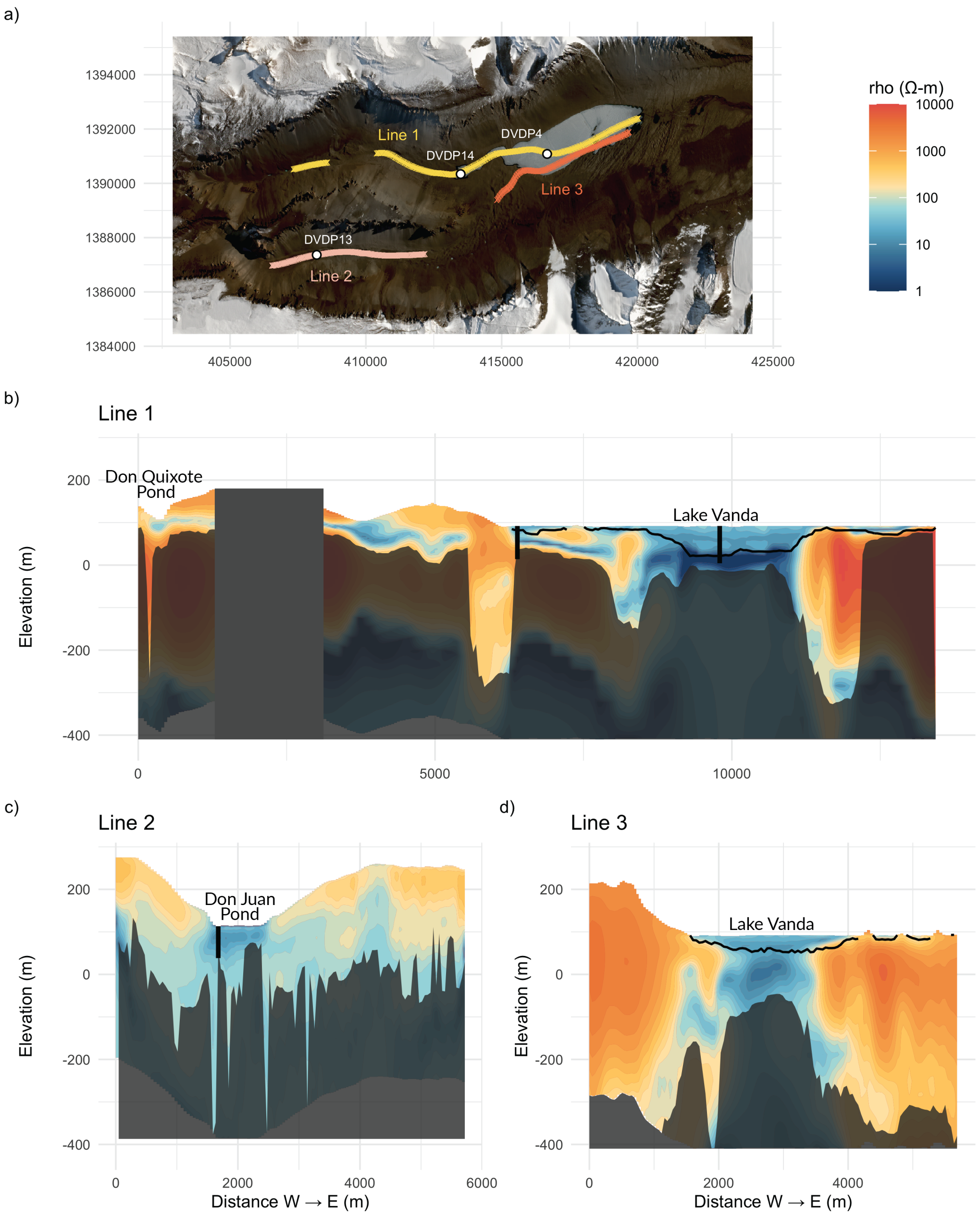

Figure 1. a) AEM flight lines over the North Fork of Wright Valley and Lake Vanda (Line 1), over Don Juan Pond (Line 2), and Lake Vanda towards the South Fork (Line 3). White circles show the location of the DVDP boreholes. Coordinates are in UTM-58S. Satellite imagery from Copernicus Sentinel data 2020, processed by ESA. b-d) Resistivity profiles of the three flight lines. The black line represents the sediment/water interface (bathymetry) of the Lake Vanda basin. Lower data are shaded beyond the depth of investigation. Black vertical rectangles show the approximate location and depth of the DVDP boreholes crossed by Line 1 and 3.