Antarctic water track hydrology and geochemistry from drone and ground sensors: Active layer wetland processes in a cold desert

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Abstract

We report on drone-borne remote sensing and ground-based geochemical results from water track soils collected in 2022–2023 in the McMurdo Dry Valleys of Antarctica that aim to address how much water is flowing through Antarctic water tracks, what remote sensing reveals about water track melt sources, and what impacts water track flow has on soil biogeochemical processes that may be leading to soil development in the water tracks. Water tracks were measured using drone-borne remote sensing: a Headwall Extended VNIR imaging spectrometer (900–1700 nm spectral range). Soil moisture content was measured during UAV flights using co-located soil moisture probes and was extrapolated beyond probe locations across the water track and adjacent dry soil using a linear fit between in situ measured water content and the depth of the 1.4 µm reflectance spectrum absorption feature associated with water. We report on ground-truth measurements of sediment characteristics, organic matter content, and dissolved silica and clay properties (abundance, soil texture, and exchange chemistry) to evaluate whether Antarctic water tracks are in a positive feedback loop, in which wetting of previously dry ground results in enhancement of soil organic matter, enhanced chemical weathering, and leading to longer wetted periods. This work expands on previous studies by presenting multiple wavelengths of remote sensing data, further refining the water budget for the Antarctic active layer, and by integrating deeper soil sensor and ground-truth measurements to explore the range of biogeochemical processes at work in these Antarctic wetland features.

1 Introduction

Recent observations of accelerating erosion and ground ice thaw in Antarctica's coastal McMurdo Dry Valleys (MDV) suggest that shrinking permafrost extents, thickening active layers, and widespread thermokarst subsidence may be early indicators of imminent, continental-scale change in the state of the Antarctic terrestrial cryosphere (Fountain et al. 2014). Groundwater-mediated thawing of permafrost has been a defining characteristic of Arctic landscapes over the past decade, where changes in drainage, thermokarst pond geometry, and active layer thermal properties have rapidly altered the distribution of soils, ice, and soil carbon (Kanevskiy et al. 2008; Gooseff et al. 2011; Jorgenson 2013; Arp et al. 2015; Strauss et al. 2016). As Antarctic ice-free area grows (Lee et al. 2017) and previously dry soils transition into wetted active layers (Levy and Schmidt 2017), it is not yet clear how Antarctica will participate in global biogeochemical and hydrological processes in a world with dramatically less ice.

"Water tracks" (Figure 1) are the basic unit of the subsurface hydrological system that feeds polar and permafrost wetlands. Water tracks are narrow bands of high soil moisture that route water downslope through soils, in the absence of overland flow (Hastings et al. 1989; McNamara et al. 1999; Levy et al. 2011). In water tracks, moisture moves as shallow groundwater, flowing through the active layer (the seasonally-thawed portion of soil column) along linear depressions in the ice table (the top of the permafrost that remains ice-cemented during summer). Because they are soil landforms, water tracks are notoriously difficult to measure because they cannot be easily gauged like a stream (Gooseff et al. 2016) or bathymetrically surveyed like a lake.

Our working model is that groundwater distribution and duration in MDV soils controls thaw depth, sedimentological composition, and solution chemistry. If groundwater hydropattern controls these near-surface hydrogeological and geomorphic systems, we can predict how changing hydropatterns will alter soil and ground ice in a warmer future (Arblaster and Meehl 2006) by determining how different spatial extents of soil wetting shape soils and ground ice now. We predict that expansion of the extent and duration of wetting, and the enrichment of saline solutions should increase thermokarst subsidence and increase chemical weathering rates. In short, wetting of previously dry active layers will drive the topographic and geological reorganization of the landscape. In particular, we hypothesize that water tracks may be in a positive feedback loop, where enhanced soil moisture for extended periods of the Antarctic summer melt season leads to enhanced chemical weathering of soils to generate clays alongside enhanced growth of soil carbon (through organic and inorganic carbon emplacement). Enrichments in soil organic matter and fine-grained sediments, accompanied by greater soil porewater solute concentrations from weathering reactions and dissolution of soil salts, may lead to increased resistance to active layer freezing, extending the water track thaw period.

To test this hypothesis, we measured water track soil and groundwater properties ("on track") as well as the properties of adjacent, "off track," soils in Taylor, Wright, and Beacon valleys (Figure 1). Here, we focus on active layer soil and

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groundwater conditions at the Howard Glacier (HG) water track in central Taylor Valley.

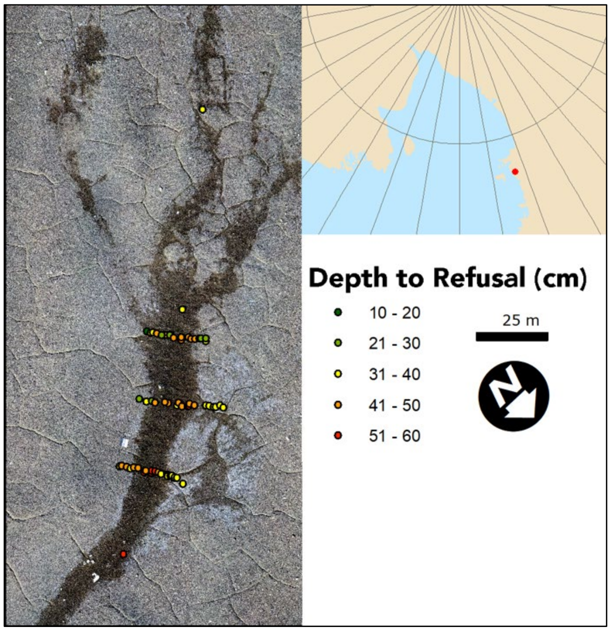

Figure 1. Context map showing the Howard Glacier water track field site, depth to refusal transects and the local of the MDV (red dot) in the Ross Sea region of Antarctica. Downslope to image bottom.

2 METHODS

Field measurements were conducted in Taylor Valley, MDV. The MDV are the largest ice-sheet-free region in Antarctica (Levy 2012) and are located at ~77–78˚S, 160–164˚E. The MDV are a cold desert that experience mean annual temperatures of ~-18˚C (Doran et al. 2002) and little snowfall, typically 3–50 mm water equivalent (Fountain et al. 2009). Field data reported here are primarily from a water track in the Howard Glacier (HG) basin watershed, supported by geochemical measurements from samples collected from across the MDV (including Wright, Beacon, and Garwood valleys).

2.1 Field Methods

In order to determine the spatial distribution of active layer thickness, depth to refusal measurements were collected in transects crossing the water track and along the water track centerline. “On track” sampling sites were selected on the basis of visible darkening of the soil due to the presence of soil moisture. “Off track” samples were dry and bright at the surface and were typically 3–5 m from the light/dark boundary of the water track. Measurements were collected in triplicate and averaged. Where buried rocks, rather than frozen sediment were encountered, measurements were recorded, but were not included in subsequent analyses.

Soil samples were collected from both water track-crossing transects and from vertical soil profiles. Sediments were air-dried to determine water content by mass, and soluble salts were extracted from 1:10 soil extracts made with 18-MΩ deionized water. Soil inorganic carbon content was determined via pressure calcimeter and soil organic carbon content was measured using a Primacs SNC-100 Carbon and Nitrogen Analyzer at the Cornell Soil Health Laboratory.

Pore waters from the water tracks were sampled directly using sterile syringes. Dissolved silica in water tracks was measured using the Heteropoly Blue Method on a Hach DR3900 spectrophotometer. Soil extract and direct water sample major ion concentrations were measured via ion chromatography.

Drone-borne remote sensing was conducted in the field in order to measure the spatial extent and concentration of surface soil moisture. We flew a Headwall Extended VNIR imaging spectrometer (900–1700 nm spectral range) on a Matrice 600 Pro aircraft to generate hyperspectral image cubes with ~4 nm spectral resolution. To support calibration of remote-sensing derived soil moisture estimates, ground-based spectra along soil sampling transects was conducted using a FLAME-NIR spectrometer with a spectral range of 950–1650 nm with 128 spectral channels (~10 nm resolution per channel).

2.2 Remote Sensing and GIS Methods

Ground-based reflectance spectra were used to generate a site-specific continuum-removed water index (CRWI) calibration for the HG water track using the methods of Levy and Johnson (2021). CRWI is calculated by determining the slope of the reflectance spectra continuum between 1.335 μm and 1.63 μm, which brackets the 1.4 μm absorption feature for water. CRWI is the difference between the continuum slope value at 1.5 μm and the measured reflectance at 1.5 μm. Here, we report a normalized CRWI value, which normalizes the measured band depth by the reflectance value of the continuum slope at 1.5 μm in order to scale CRWI to surface brightness. A linear model was then fit between the ground-measured CRWI values and the soil moisture content measured in the lab. This model,

$$\text{Soil Moisture Mass Fraction} = 0.1 \cdot \text{CRWI} + 0.007 \quad [1]$$

was then applied to the airborne hyperspectral data in order to estimate surface soil moisture across the water track surface at the spatial resolution (~5 cm/pixel) of the image cube.

In order to determine the drainage properties of the water tracks, a topographic wetness index (TWI) model was computed for the HG water track, where TWI is defined as:

$$\text{TWI} = \ln(a / \tan(b)) \quad [2]$$

where b is local surface slope and a is the upslope accumulating area for each pixel. Slope was determined from the Fountain et al. (2017) airborne lidar DEM for the MDV. Upslope accumulating area was determined using the lidar DEM to generate downslope routing from source pixels that were identified from a thresholded Worldview-2 image of the study site collected during field operations (WV02_20221202193905, panchromatic DN > 700 to identify snow and ice pixels).

3 Results

Depth to refusal increases towards the center of the water track and downslope along the water track flow direction (Figures 2 and 3). Increased active layer thickness is associated with increased soil moisture at the water track surface, as well as with observations of water-saturated or muddy (unsaturated) conditions in the subsurface, based on observations of the DTR tile probe (Figure 2). Together, this indicates that the deepest parts of the water track are also the wettest, and that surface soil moisture values correlate with soil moisture conditions deeper in the water track.

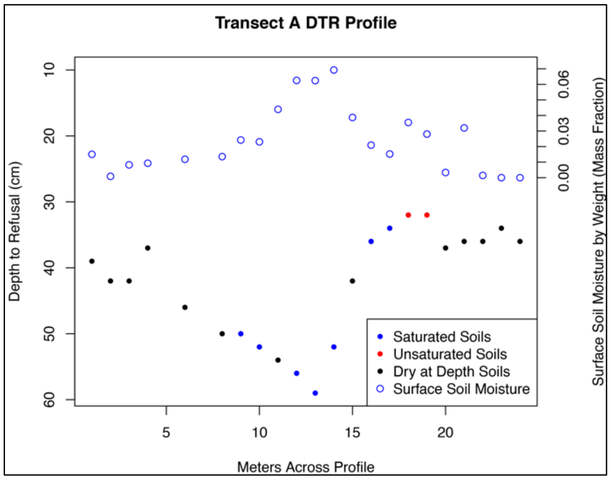

Figure 2. Depth to refusal and surface soil moisture measurements for transect A (downslope-most transect). Surface soil moisture is associated with deep active layers and saturated conditions at the bed.

Soil moisture is higher in water tracks than in adjacent off-track soils (Figure 4) and increases with depth in both on and off-track soils. Soil moisture is typically < 5% by mass for off-track soils, but reaches saturation (20–25% by mass) for water track soils.

Water track location is strongly predicted by the snowbank-initialized topographic wetness index model, and depth to refusal is correlated with TWI (Figure 5). Portions of the water track with low surface slopes lead to ponding of meltwater-derived flow and thaw of the active layer.

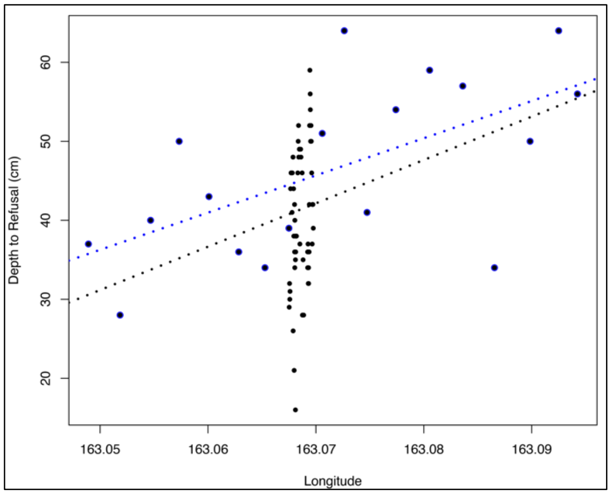

Figure 3. Depth to refusal along the water track. DTR increases along the water track flow path from west to east (left to right). Single, blue points are centerline measurements; grouped black points are transects across (transverse to) the water track. P < 0.001 for both linear fits. R^2 = 0.37 and 0.15 for centerline points and all points, respectively. DTR increases downstream, as well as towards the center of the water track. At the transect locations, there is a wide spread in DTR, but that that spread brackets the downstream tend in increasing DTR.

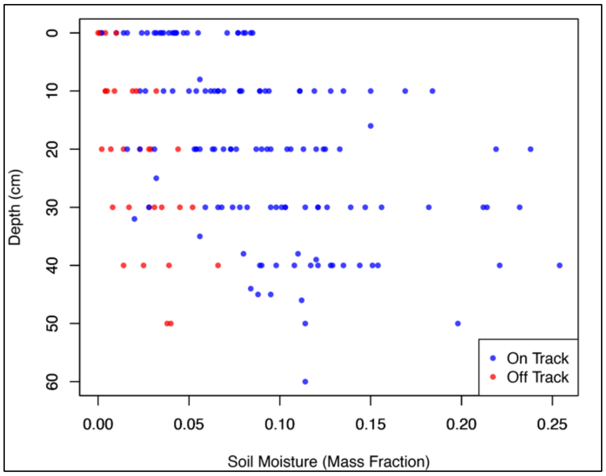

Figure 4. Soil moisture with depth for on-track and off-track soils. Soil moisture increases with depth for both on-and off-track soils, but only exceeds ~10 wt.% soil moisture for on-track soils.

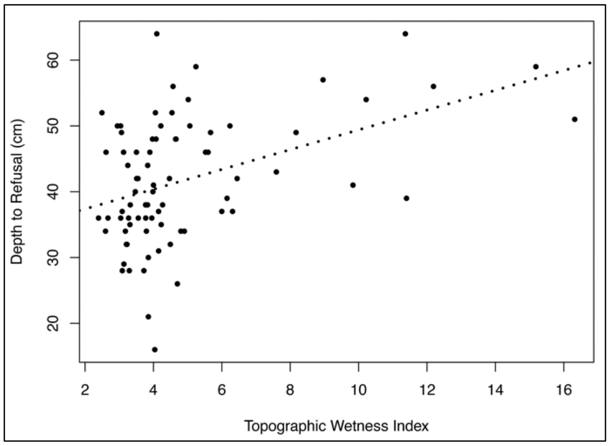

Figure 5. Depth to refusal versus topographic wetness index. Wetter soils show increased depth to refusal in comparison to drier soils. For linear model, $R^2 = 0.18$ and $P < 0.001$.

At the HG water track study site, surface soil moisture content and normalized CRWI are strongly correlated (Figure 6). On the basis of the local CRWI calibration, surface soil moisture along the HG water track spans ~0–3 wt.% (Figure 7), broadly consistent with on and off-track surface soil moisture contents measured in vertical soil profiles in and around the water track (Figure 4). CRWI-derived soil moisture increased towards the water track center and also shows variability associated with water track microtopography (gravel ripples and dunes). Wetted soils outside the water track that are associated with efflorescent salt patches are also detected in the CRWI soil moisture product.

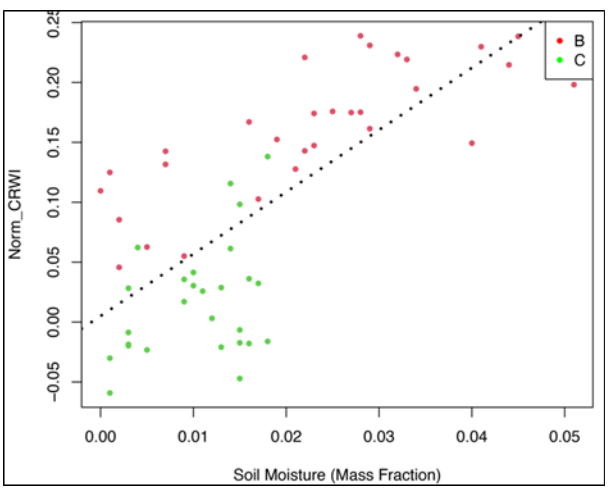

Figure 6. Calibration curve for CRWI soil moisture parameter derived from water track sampling transects sections B and C (left and right green dots in Figure 7). Wetter surface soils show higher normalized CRWI spectroscopic indices. Normalized CRWI is linearly dependent on soil moisture.

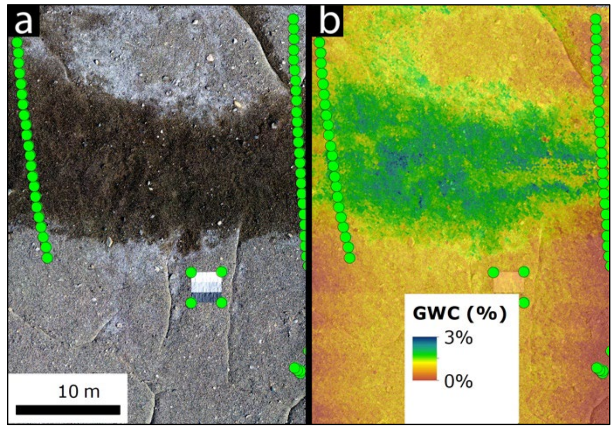

Figure 7. Surface soil moisture estimates across the HG water track using the local normalized CRWI calibration. Soil moisture is variable across water tracks and broadly agrees with surface measurements at transect points. GWC is gravimetric water content, equivalent to soil moisture weight percent.

Soil carbon at the HG sites is in-homogenously distributed. Water tracks typically have higher total carbon than off-track soils (Figure 8), although nearly all HG study site soils have < 1 wt.% total carbon. Neither on-track nor off-track soils have high organic carbon contents, with values almost always < 1 wt.%, and most < 0.2 wt.%, however, the highest organic carbon measurements in the study site are all on-track soils. Water track soil organic carbon increases towards the soil surface (Figure 9).

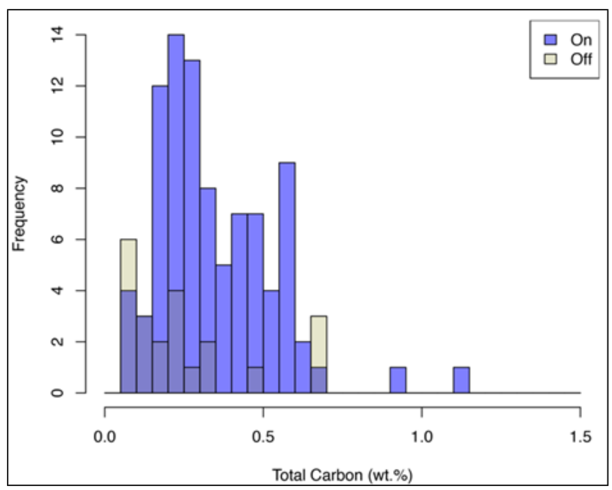

Figure 8. Total carbon on and off water tracks. Water tracks have notably higher soil carbon that off-track soils ($P < 0.02$). Water track carbon is dominated by inorganic carbon, however, the highest organic carbon contents (> 0.2%) are only from on-track samples.

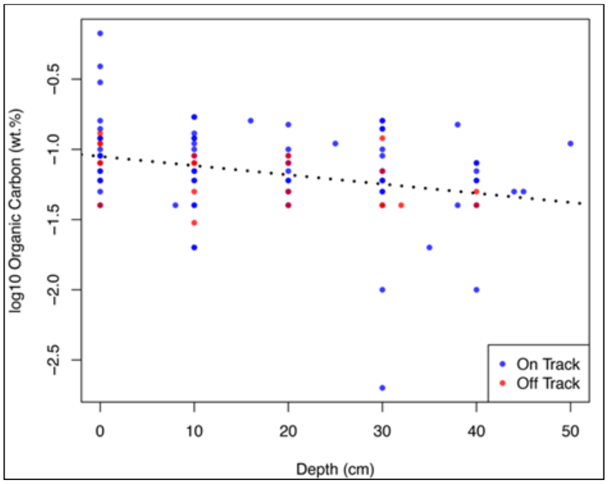

Figure 9. Organic matter with depth. Organic matter increases towards the surface in water tracks, suggesting organic matter is not just advected into water tracks in groundwater flow.

Finally, dissolved silica content is higher in nearly all water track pore waters than in snow or surface streams in the MDV (Figure 10). Silica concentrations in water tracks reach ~1 mM, which greatly exceeds typical fresh snow (< 10 μM) and surface stream water (< 100 μM). Dissolved silica concentration in water tracks increases with increasing total dissolved solids and total chloride (a conservative ion tracer), before reaching saturation between ~10^2 and 10^3 μM.

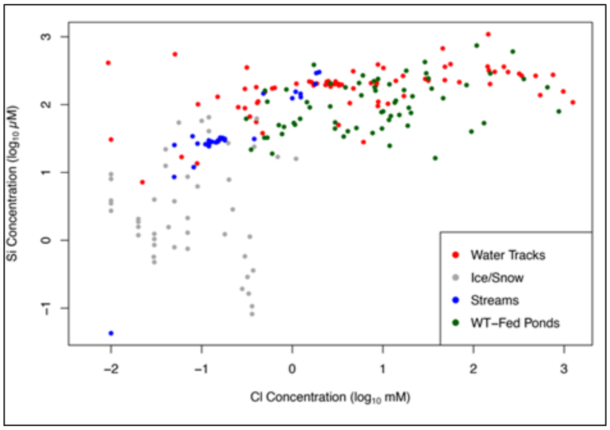

Figure 10. Dissolved silica versus chloride for water tracks and surface water in the MDV. Water tracks have ~10x greater dissolved silica contents than streams and approach silica saturation.

4 Discussion

What do ground-based observations suggest about the spatial distribution of soil moisture in water tracks and the surface energy balance/heat transfer processes that generate active layer flow? Active layer thicknesses on the HG water track increase from the bright, dry, off-track soils to the dark, wetted, on track soils. This is broadly consistent with presence of low albedo wetted soils leading to enhanced shortwave energy flux into the wetted soils, as measured on other water tracks (Linhardt et al. 2019). Thicker active layers on water tracks are also consistent with higher thermal diffusivity for wetted soils than for dry soils, leading to enhanced penetration of the seasonal thermal wave into water tracks (e.g., Levy and Schmidt 2016). Higher thermal diffusivity leads to deepening the ice table below the wettest soils. Together, these changes to surface energy balance and soil thermal regime suggest that water tracks may be self-deepening and self-channelizing systems; wet soils thaw deeply, steepening the subsurface ice table slope, and channelizing any available meltwater into water track drainage pathways. This implies that water tracks are not just persistent features of the MDV hillslope drainage environment, but could expand if additional meltwater became available, either through increases in snow melt or regional ice table thaw.

What do these findings suggest about the range of possible sources of meltwater for water tracks? Can they be used to discriminate between snow melt, ground ice melt, and soil salt deliquescence endmembers? The airborne hyperspectral observations, coupled with the strong dependence of water track darkening on high topographic wetness index, suggest that soil moisture in water tracks is largely sourced from snowmelt, rather than ground ice melt or other meltwater sources. The depth to refusal probing (Figure 2) and the hyperspectral observations both show that water track saturation conditions are heterogenous in the water tracks, and that saturated soils may be present both in the water track thalweg and perched in other channels or pools generated by ice table topography. Water track moisture wicking up from these saturated regions near the base of the water track is spatially heterogenous at the surface owing to both variability in subsurface saturation as well as variability in response to soil surface microtopography, roughness, and likely grain size. That is, moisture may rise higher in wetted in sands and fines, while the surface may be less wet at the surface over gravels and granules.

Finally, to what extent do these observations suggest that water tracks are simply advecting in soil carbon or weathering products versus generating these materials in situ? Organic carbon measured in the water tracks increases towards the surface, suggesting primary production and burial of organic carbon is the main source of water track carbon. Notably, there is no increase in organic carbon at depth in the water tracks where the majority of saturated soil groundwater flow takes place. This suggests that organic matter is not flowing into the water tracks along the ice table. In addition, carbon is enriched in the water track (both inorganic and organic), suggesting that water tracks may be important, and hitherto overlooked components in the carbon dynamics of MDV soils. Water track physical (dissolution/precipitation) and biogeochemical processes (primary production and limited consumption due to high salt contents) may build up carbon in water tracks to concentrations several times those present in adjacent off-track soils. Finally, dissolved silica is reaching saturation in water tracks (Figure 10) but is clearly entering water tracks from dissolution of primary minerals in soils, e.g., feldspar (Lyons et al. 2021). This indicates that even if clays are being advected in groundwater flow through sand pores, those clays are forming in situ in water tracks through hydrolysis reactions that release silica into the groundwater. Together, these measurements of carbon build-up and silicate weathering in the HG water track are consistent with a positive feedback model in which water track biogeochemical reactions, driven by meltwater flow through the water tracks, lead to stronger or more persistent pedogenic processes. Groundwater flow leads to organic carbon build up; organic acids coupled with meltwater interactions with fresh sediment grains lead to enhanced chemical weathering and fines production; decreases in porosity due to the presence of organic matter, precipitated carbonates, and silt/clay particles lead to enhanced capillary rise in water tracks; and enhanced capillary rise leads to greater evaporation from water tracks, concentrating the pore water solutions into freeze-resistant soil brines, which can remain wet late into the spring and fall shoulder seasons (Kuentz et al. 2022).

5 Conclusions

Preliminary analyses of water track ground-measured soil properties and drone-borne remote sensing measurements suggests that water tracks are hydrologically and thermally re-enforcing components of the cold desert hydrological system. Deep seasonal thaw occurs in the wettest soils, and spatial heterogeneity in surface soil moisture content is correlated with differences in active layer thickness and column-integrated active layer soil moisture content. Water tracks are sites where soil biogeochemical processes concentrate soil carbon (both organic and inorganic), raising soil carbon content to levels several times that of adjacent, off-track soils. Chemical weathering of silicate grains in water track soils enriches the water track pore fluids in solutes and also concentrates fine grains in water tracks, decreasing porosity and increasing capillary rise and matric potential. Together, these two mechanisms enhance evaporation and solute concentration in the water tracks. These results suggest water tracks are likely locations where positive feedback mechanisms are generating soil from regolith on Antarctic cold desert hillslopes, which could expand or become more active under warming conditions, additional snowfall, or more widespread thaw.

6 Acknowledgements

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