PAST AND PRESENT SOIL MOISTURE CONDITIONS IN ANTARCTIC RSL-ANALOG SOILS: MEASURING AQUEOUS PROCESSES WITH HYPERSPECTRAL VNIR REMOTE SENSING, MICROWAVE RADIOMETRY, AND SOIL GEOCHEMISTRY

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Introduction: The annual warm-season elongation and winter disappearance of recurring slope lineae (RSL) [1] coupled with their mean elongation rate and persistent growth on slopes shallower than the angle of repose [2,3] have suggested the possibility that groundwater or intergranular brines play a role in RSL formation. Such "wet" mechanisms for RSL formation should produce detectable signatures of soil moisture, as moisture derived from subsurface aquifers [4], atmospheric recharge through deliquescence and/or dehydration [5,6,7], or top-down melt [8] must be present in the soil during RSL expansion for these mechanisms to operate, with evidence of liquid water potentially disappearing during RSL brightening. Past efforts to detect soil moisture present in RSL during low-albedo growth periods include the use of visible and near-infrared (VNIR) reflectance spectroscopy [9], mid-infrared (MIR) thermal imaging [10], and quantitative analysis of visible albedo [11,12,13].

Past efforts to directly detect hydrated salts at RSL sites have been inconclusive [9,14], and nearly all RSL investigations are limited to surface observations of the upper microns of the soil column that are sensible by high-resolution imaging spectrometers. Further, studies of active RSL cannot directly determine the extent to which past water/brine flows may have occurred at an RSL site, leading to the deposition of soil salts sufficient to undergo modern hydration or dehydration in order to trigger potential "dry" mechanism to trigger modern surface change [e.g., 6,7].

In order to better understand the relationships between surface-detectable water absorption features (at ~1.4 µm), near-surface soil moisture (in the upper 5-10 cm of the soil column), and past water flow, we report on combined investigations of water tracks (active layer groundwater conduits) in the McMurdo Dry Valleys (MDV), Antarctica. Our goal is to determine how soil moisture detections at visible to near-IR wavelengths [e.g., 15] compare to soil moisture detections via L-band microwave radiometry [16], and in turn, the extent to which underlying, seasonally wetted sediments record evidence of past water flow through brine-mediated changes in exchangeable cation composition [17] on water track clays.

Methods: We report on geochemical results from water track soils collected in 2012-2013 and 2015-2016 as well as new remote sensing observations collected during the 2022-2023 field season. To determine active (low-albedo) flow season soil moisture properties, snow- and ground-ice fed water tracks were measured using drone-borne remote sensing instruments: a Headwall Extended VNIR imaging spectrometer (900 – 1700 nm spectral range, ~1.7 nm spectral resolution, and ~4 cm ground resolution at 100 m AGL), a FLAME NIR point spectrometer (940-1646 nm, ~12 nm FWHM optical resolution, and ~2 m spot size from 17 m AGL), a TerraRad Tech PoLRa 3.1 L-band radiometer. Volumetric soil moisture content was measured during UAV flight operations using co-located METER Environmental 5-TE soil moisture probes placed in the upper 2 cm of the soil profile, and was extrapolated beyond probe locations across the water track and adjacent dry soil using a linear fit between in situ measured volumetric water content and the depth of the shoulder of the 1.4 µm water absorption measured in the spectroscopic data [after 15].

To evaluate the past presence of hypersaline brine flows (NaCl and $CaCl_2$ saturated flows), we use the cation exchange mechanism from [17]. By measuring exchanged Na^+ and Ca^{2+} ratios from cation exchange reaction solutions (1 M NH_4Cl), it may be possible to infer if soils have been exposed to concentrated NaCl brines during winter freeze-up of water tracks. Exchangeable cations from water track soils were extracted and concentrations of Na^+, Ca^{2+}, Mg^{2+}, and K^+ were measured via ICP-OES. Exchangeable Ca^{2+}/Na^+ ratios were evaluated to determine if Ca^{2+} has been preferentially exchanged out from soils and been replaced with Na^+ during freeze-concentration of soil solutions. Sediments are mostly near-surface samples (upper 10 cm of the soil column), however, some samples from deeper in the active layer were also analyzed.

Results and Discussion: Preliminary cation exchange results show that in near-surface sediments, exchangeable Ca^{2+}/Na^+ ratios do not show enhancement of Na^+ and depletion of Ca^{2+} (low Ca^{2+}/Na^+ ratios) on seasonally wetted water tracks and high Ca^{2+}/Na^+ ratios in adjacent, dry off-track sites where no exchange was predicted to occur (Fig. 1). It is notable that in one water track depth profile (Fig. 2), however, which was collected from the same watershed from which the [17] borehole samples were collected, Ca^{2+}/Na^+ ratios reach a minimum value at ~20 cm depth, bracketed by higher values above and below. We interpret this depth profile to reflect preferential exchange of bound calcium for pore water sodium at this depth, which experiences passage solute-rich solutions during both early-season thaw and late-season freeze-up. We suggest that exchangeable cation distribution in water track analog RSL sediments could also serve as a proxy for prior potential brine flow at RSL sites on Mars.

Inhomogeneous distributions of exchangeable cations within the RSL sediment column could be interpreted as markers of past flow of concentrated chloride solutions through RSL sediments, even if no brines are moving under current environmental conditions.

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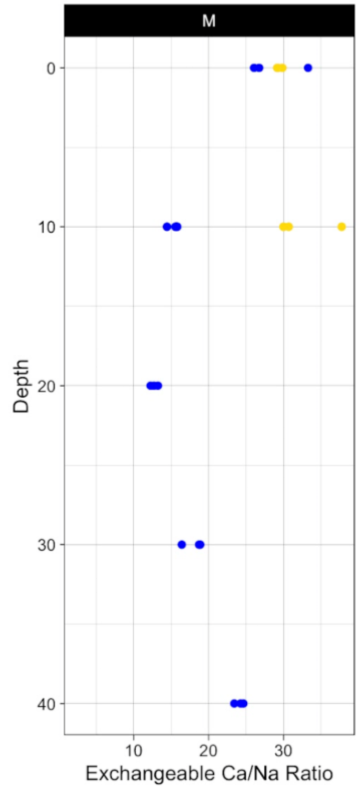

Figure 2. Ca^{2+}/Na^{+} ratio in MWVT as a function of depth. Blue is on-track wetted sediment, yellow is off-track dry sediment. The minimum in Ca^{2+}/Na^{+} ratio at 20 cm depth suggests enhanced flow of seasonally concentrated fluids at that depth, leading to depletion of bound Ca^{2+} due to cation exchange.

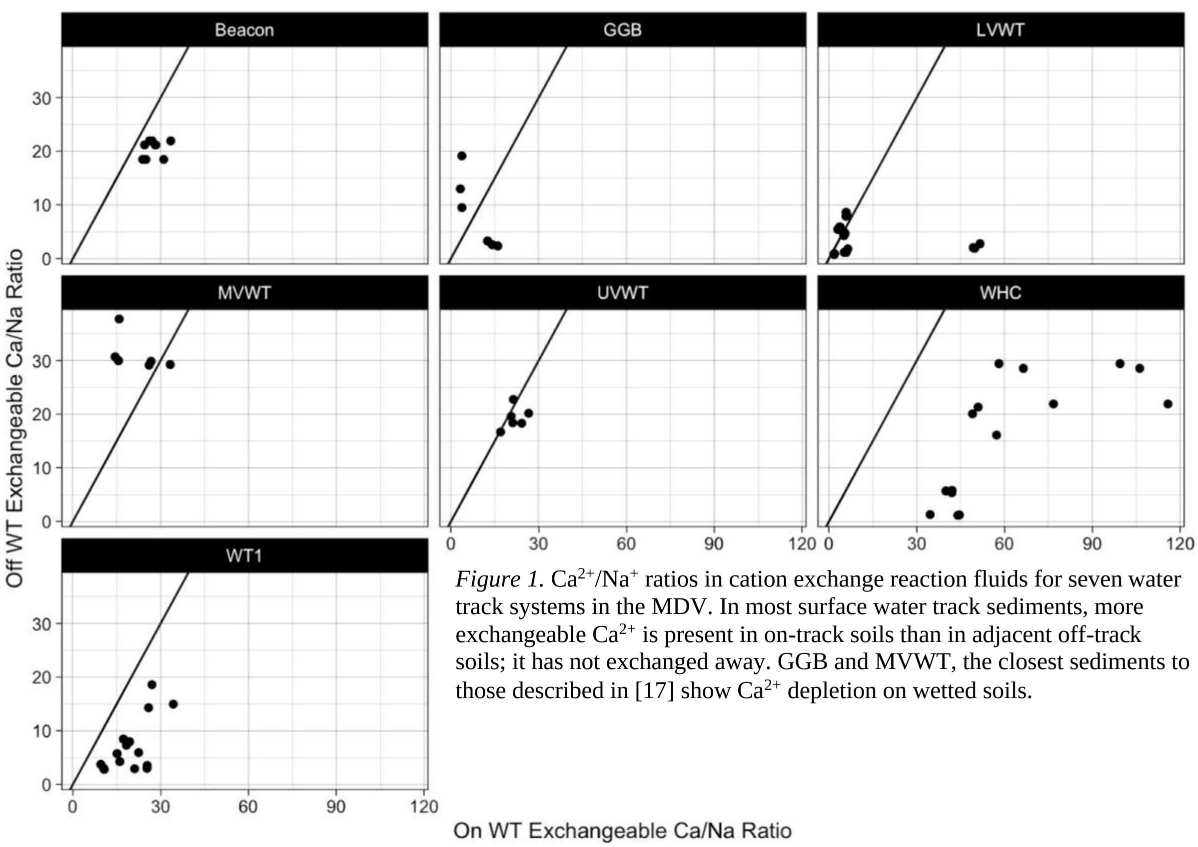

Figure 1. Ca^{2+}/Na^{+} ratios in cation exchange reaction fluids for seven water track systems in the MDV. In most surface water track sediments, more exchangeable Ca^{2+} is present in on-track soils than in adjacent off-track soils; it has not exchanged away. GGB and MVWT, the closest sediments to those described in [17] show Ca^{2+} depletion on wetted soils.