Water tracks and permafrost in Taylor Valley, Antarctica: Extensive and shallow groundwater connectivity in a cold desert ecosystem

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ABSTRACT

Water tracks are zones of high soil moisture that route water downslope over the ice table in polar environments. We present physical, hydrological, and geochemical evidence collected in Taylor Valley, McMurdo Dry Valleys, Antarctica, which suggests that previously unexplored water tracks are a significant component of this cold desert land system and constitute the major flow path in a cryptic hydrological system. Geological, geochemical, and hydrological analyses show that the water tracks are generated by a combination of infiltration from melting snowpacks, melting of pore ice at the ice table beneath the water tracks, and melting of buried segregation ice formed during winter freezing. The water tracks are enriched in solutes derived from chemical weathering of sediments as well as from dissolution of soil salts. The water tracks empty into ice-covered lakes, such as Lake Hoare, resulting in the interfingering of shallow groundwater solutions and glacier-derived stream water, adding complexity to the geochemical profile. Approximately four orders of magnitude less water is delivered to Lake Hoare by any given water track than is delivered by surface runoff from stream flow; however, the solute delivery to Lake Hoare by water tracks equals or may exceed the mass of solutes delivered from stream flow, making water tracks significant geochemical pathways. Additionally, solute transport is two orders of magnitude faster in water tracks than in adjacent dry or damp soil, making water tracks "salt superhighways" in the Antarctic cold desert. Accordingly, water tracks represent a new geological pathway that distributes water, energy, and nutrients in Antarctic Dry Valley, cold desert, soil ecosystems, providing hydrological and geochemical connectivity at the hillslope scale.

INTRODUCTION

The polar desert of the McMurdo Dry Valleys, the largest ice-free region in Antarctica, is a matrix of deep permafrost, soils, glaciers, streams, and lakes that together form the geological context for the southernmost functioning terrestrial ecosystem (Kennedy, 1993; Lyons et al., 2000). Recent observations in Taylor Valley (Fig. 1) of shallow groundwater discharge from the active layer (the seasonally thawed portion of the permafrost) as seeps during peak summer warming have generated new interest in examining permafrost-related groundwater processes (Harris et al., 2007; Lyons et al., 2005). These new observations revive early reports of groundwater activity in nearby Wright Valley (Cartwright and Harris, 1981; Wilson, 1981).

These seeps appear to be supplied by melting snow and ground ice, suggesting that they may be similar to "slope streaks" and gully landforms observed in neighboring Wright Valley (Head et al., 2007; Levy et al., 2008), and may be morphologically or genetically similar to slope streaks or transient slope lineae on Mars (Mushkin et al., 2010; McEwen et al., 2011). Linear or downslope-branching zones of enhanced soil moisture and downslope water transport, often occurring in the absence of well-defined channels, are hallmarks of "hillslope water tracks"—features that route much of the water and nutrient flux through Arctic, permafrost-dominated soils (Hastings et al., 1989; McNamara et al., 1999). The goal of this paper is to integrate permafrost processes that route water through active-layer soils into the Antarctic cold desert hydrogeological paradigm.

Do Antarctic water tracks represent isolated hydrological features, or are they part of the larger hydrological system in Taylor Valley? How does water track discharge compare to Dry Valleys stream discharge, and what roles do water tracks play in the Dry Valleys salt budget? What influence do water tracks have on Antarctic ice-covered lakes?

In this paper, we present the case that, during summer months, the shallow permafrost/soil environment of Taylor Valley supports a spatially extensive system of interconnected water tracks that result in the appearance of linear and sublinear dark soil patches at the ground surface. We test the hypotheses that (1) these water tracks are part of a morphological and hydrological continuum that includes previously described seeps and streams; (2) water tracks contribute an ecologically significant volume of water to Taylor Valley soils that originates from snow and ground-ice melt, rather than from glacier melt; and (3) water tracks are a major pathway for solute transport through Dry Valleys soils and are an important component of the Lake Hoare (a closed-basin lake) salt budget.

SITE DESCRIPTION

The McMurdo Dry Valleys span an ice-sheet–free region between the Trans-Antarctic Mountains of southern Victoria Land and the Ross Sea. Taylor Valley, one of the McMurdo Dry Valleys, is an ~50-km-long valley centered on 77.7°S, 162.6°E (Fig. 1). Taylor Valley

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has been the focus of the McMurdo Dry Valleys Long-Term Ecological Research project (MCM-LTER) since 1993. The valley is filled to the west by the Taylor glacier, a polythermal outlet glacier of the East Antarctic Ice Sheet, and it opens to the east into McMurdo Sound in the Ross Sea.

An extremely simple, nematode-dominated soil ecosystem (Priscu, 1998) persists in Taylor Valley, despite mean annual temperatures of ~–18 °C (Doran et al., 2002a), 3–50 mm water-equivalent annual precipitation (Fountain et al., 2009), and extreme aridity produced by desiccating winds (Clow et al., 1988). Liquid water availability is thought to be the primary limiting factor in Antarctic soil ecosystems (Fountain et al., 1999; Kennedy, 1993). Accordingly, the simplicity of the ecological processes in Dry Valleys soils has been shown to reflect the limited geohydrological pathways that distribute liquid water to organisms during the brief summer season when surface temperatures exceed 0 °C (Conovitz et al., 1998; Courtright et al., 2001; Gooseff et al., 2003a, 2007; McKnight et al., 1999; Virginia and Wall, 1999). Liquid water in Dry Valleys soils is largely limited to the upper ~1 m—the active layer of the permafrost column that thaws during warm summer conditions.

Taylor Valley Hydrological Setting

The dominant hydrological pathway in the McMurdo Dry Valleys connects glaciers to perennially ice-covered lakes via a network of stream channels in which hyporheic exchange moves water, salts, and nutrients into and out of the stream- and lake-proximal soils (Barrett et al., 2009; Cartwright and Harris, 1981; Doran et al., 2008; Gooseff et al., 2002, 2007; Green et al., 1988; Lyons and Mayewski, 1993; Matsubaya et al., 1979; McKnight et al., 1999; Nezat et al., 2001). Neither infiltration of snowmelt nor groundwater movement (shallow or deep) has been considered to be a major hydrological process (Cartwright and Harris, 1981; Chinn, 1993; Hunt et al., 2010). This limited hydrological activity results from the extreme aridity of the McMurdo Dry Valleys and the persistence of continuous, ice-cemented permafrost that extends from the surface to depths of hundreds of meters (Bockheim et al., 2007; Campbell et al., 1997; Clow et al., 1988; Decker and Bucher, 1980). The paucity of shallow groundwater in Dry Valleys permafrost has been inferred to result in minimal transport of salts and nutrients through soils (Claridge et al., 1997).

Three large, ice-covered, closed-basin lakes are located in Taylor Valley (from west to east, Lakes Bonney, Hoare, and Fryxell) (Fig. 1) that are fed principally from glacier melt (Lyons et al., 1998a). Thirty named streams route glacier meltwater to the lakes (Alger et al., 1997), although more than 60 channels wider than ~6 m across (and thus, clearly resolvable in *IKONOS* satellite and airphoto data) are present along the valley walls (McKnight et al., 1999).

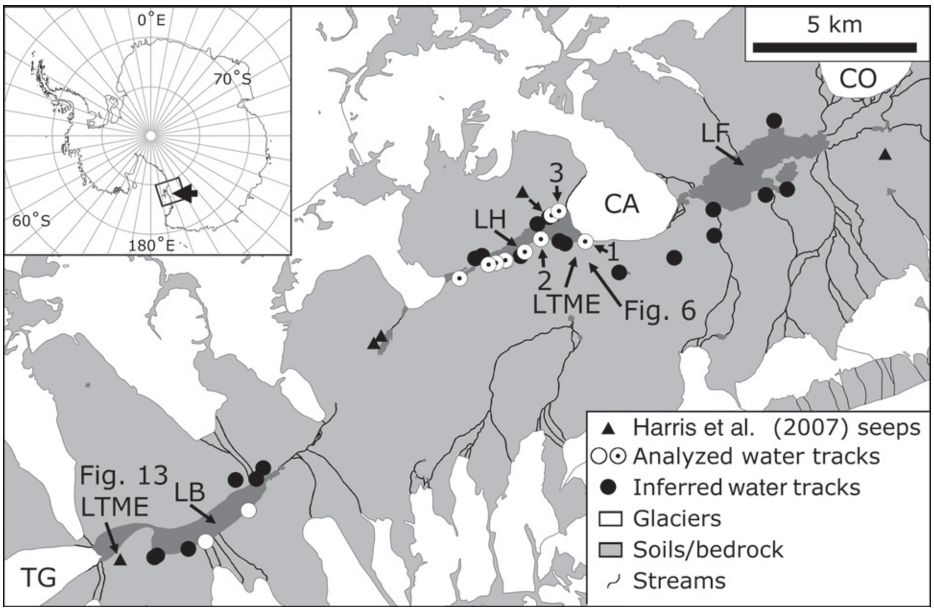

Figure 1. Location map of Taylor Valley. TG—Taylor glacier, LB—Lake Bonney, LH—Lake Hoare, CA—Canada glacier, and CO—Commonwealth glacier. LTME—Long-Term Manipulation Experiments (described in the ecological implications section). Numbers 1–3 indicate the locations of water tracks considered in the water budgets section. Water tracks with internal dots are included in the geomorphic analysis. Inset shows location of the McMurdo Dry Valleys (MDV), with box indicating the vicinity of Southern Victoria Land, and the arrow indicating the location of the McMurdo Dry Valleys. Latitude and longitude are demarcated in 10° increments. Taylor Valley is located at 77.7°S, 162.6°E.

Taylor Valley Soils and Permafrost

The portions of the surface of Taylor Valley that are not characterized by lakes, glaciers, or bedrock are covered by a heterogeneous soil composed of glacial drift, valley-wall colluvium, marine sediments, and paleo–lake beds (Bockheim et al., 2008). With a mean annual temperature of ~–18 °C (Doran et al., 2002a), Taylor Valley soils are perennially frozen, forming continuous permafrost to a depth of ~200–600 m (Decker and Bucher, 1980; McGinnis and Jensen, 1971). Much of this permafrost is ice-cemented; however, the low atmospheric water vapor pressure in Taylor Valley (Clow et al., 1988) results in the removal of shallow ground ice by vapor diffusion (Hagedorn et al., 2007). Accordingly, based on observations of the upper ~1 m of Taylor Valley soils, approximately half have been mapped as dry frozen, while half are shallowly ice-cemented (Bockheim et al., 2007). Summer warming of the soil surface results in thawing of the upper ~10–60 cm of the permafrost, resulting in the formation of an active layer (Bockheim et al., 2007). In some locations, the active layer is meltwater-saturated, while in other locations, it is nearly dry (Campbell et al., 1997; Marchant and Head, 2007).

The presence of both water-rich and water-poor permafrost in Taylor Valley results from the fact that it spans a microclimate transition between the relatively warm and wet coastal thaw zone and the cooler and drier intermediate mixed zone (Marchant and Head, 2007). Across this microclimate transition, precipitation drops from ~40–50 mm water-equivalent per year to <10 mm water-equivalent per year (Fountain et al., 2009). Accordingly, the hydrogeological landforms present in Taylor Valley, along with other permafrost features such as sand- and ice-wedge polygons and solifluction lobes, represent important examples of climate-controlled "equilibrium landforms" that are diagnostic of these transitional climate conditions (Marchant and Head, 2007).

Water tracks analyzed in this study are located in the Lake Hoare, Lake Fryxell, and Lake Bonney basins. Most are located on the south sides of the basins (Fig. 1). The north sides of the basins are characterized by steep slopes (20°–25°), with thin colluvial soil covers resulting from debris flows and/or exposed bedrock. The south sides of the basins have more gentle slopes (5°–10°) with thicker soils and do not show evidence of energetic mass wasting. Taylor Valley soils below ~300 m elevation (in which the water tracks are located) are predominantly sandy skeletal calcic haplorthels (typically 75%–80% sand by mass), and there is a surface of desert pavement of coarse cobbles and pebbles (Campbell, 2003).

FIELD OBSERVATIONS: METHODS AND RESULTS

During the 2009–2010 austral summer, we observed and measured the properties of Antarctic water tracks. The morphological, sedimentological, hydrological, and in situ geochemical properties of the water tracks are described here. Laboratory geochemical analyses are described in a subsequent section.

Water Track Surface Characteristics

Several dark, linear, or downslope-branching surface features (water tracks) were observed during reconnaissance of Taylor Valley. These darkened soil surfaces extend downslope, typically oriented along the steepest local gradient, over lengths of ~200–1900 m (Figs. 2 and 3). The dark soil surfaces range from ~1 to 3 m in width and are commonly observed in sublinear depressions, or in local low ground between knobby terrain composed of ice-cemented, degraded moraines (Figs. 2 and 3). In situ measurements were collected along the length of several water tracks and from adjacent, light-toned soils. Measurements included: soil volumetric water content (VWC), electrical conductivity (EC, a measure of salinity), and depth to the ice-cement table (measured as the depth to refusal of a 1-cm-diameter steel rod inserted manually into the soil). VWC and EC were measured using a Decagon Devices 5TE probe with a Taylor Valley soil-specific calibration. During December–January 2009–2010, water track surface soils had surface volumetric water contents three times higher than adjacent, light-toned soils (15% ± 2% VWC vs. 5% ± 2% VWC; standard deviations: 9.0% and 1.0%, respectively). Water track surface soils had electrical conductivities approximately ten times higher than adjacent soils (0.53 dS/m vs. 0.05 dS/m ± 10%; standard deviations 0.9 and 0.1, respectively). Light-toned salt-efflorescences on the fringes of some water tracks are inferred to result from desiccation of brine-bearing surface soils along the margins of the water tracks. Surface darkening is inferred to result from reduction in visible wavelength surface albedo with increasing water content (e.g., Liu et al., 2002). The depth to the ice-cement table in water tracks was more than twice the depth of refusal for adjacent light-toned soils (45 ± 1 cm versus 19 ± 1 cm; standard deviations 11 cm and 9 cm, respectively). These comparisons are summarized in Table 1.

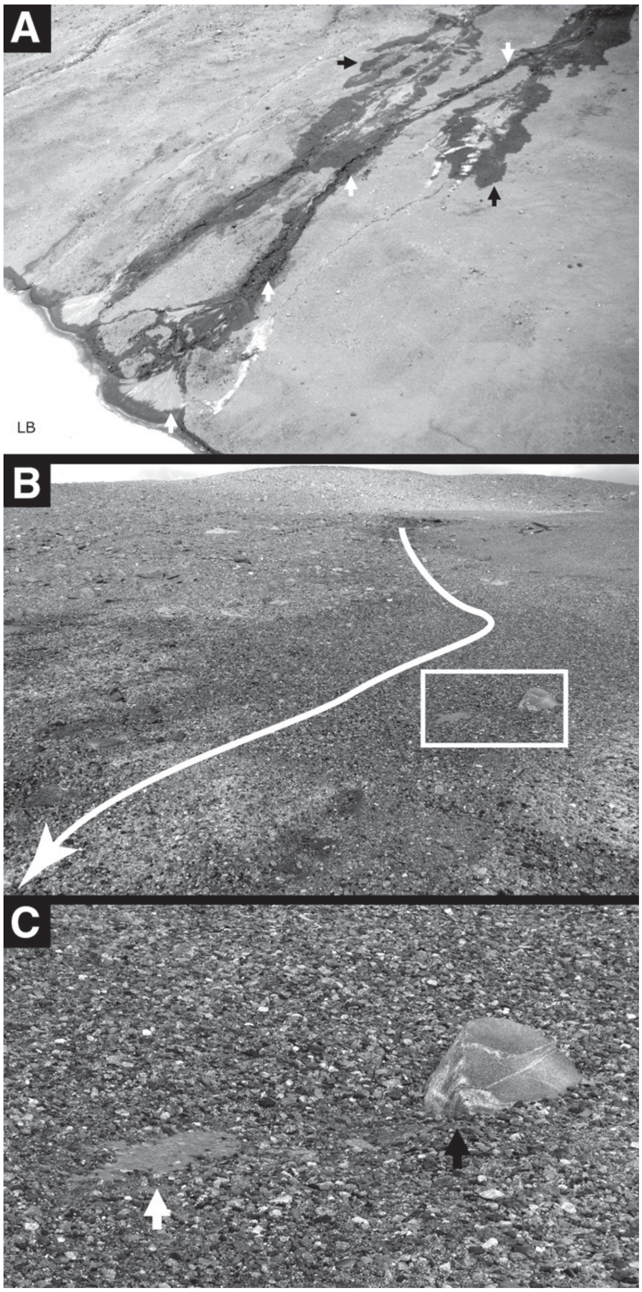

Figure 2. Spatial relationships among seeps, fluvial channels, and water tracks. (A) Glacier-fed channel (white arrows) on the north shore of Lake Bonney (LB). Black arrows show dark, linear patches of soil adjacent to the incised channel. Image is ~150 m across. (B) Water track on the south shore of Lake Hoare. Arrow shows water track downslope flow direction. Box indicates the extent of part C. Image is ~5 m across. (C) Surface seep (white arrow) downslope of a boulder (black arrow). The seep emerges from the water track. Image is ~1 m across. Images have been stretched to enhance contrast.

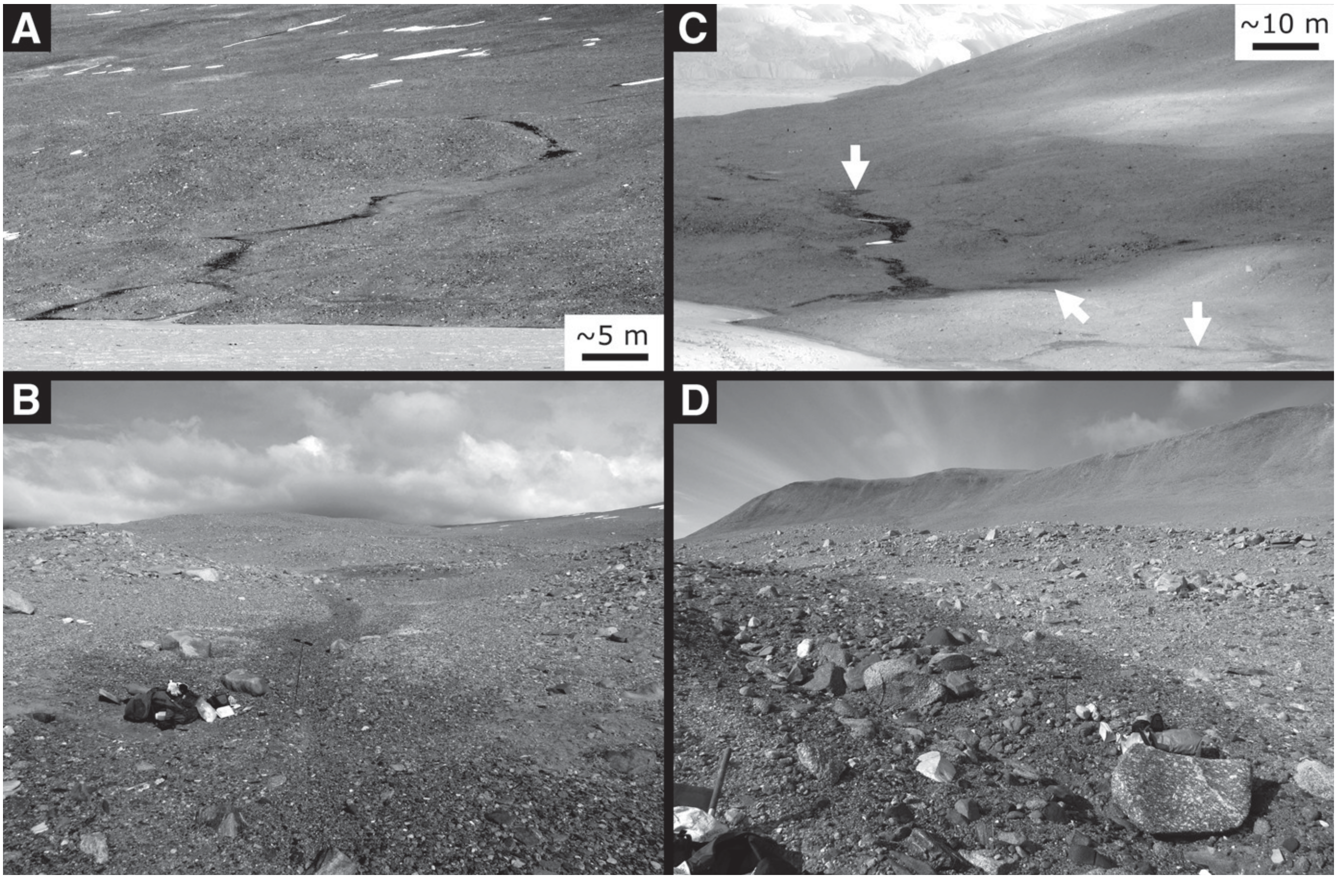

Figure 3. Taylor Valley water tracks. (A) Water track 1 (Fig. 1) extends downslope from snowpack sources to ice-covered Lake Hoare. (B) Close-up view of the water track surface shown in part A. Backpack and 1 m tile probe are shown for scale. (C) Water track 2 (Fig. 1) on the south shore of Lake Hoare. Several linear, dark patches (water tracks) are visible (white arrows), which integrate into a higher-order water track that empties into Lake Hoare. (D) Close-up view of the water track shown in part C. Pick at lower left is for scale. Images have been stretched to enhance contrast.

Water Track Profile Characteristics

Water track soils are predominantly classified as sandy skeletal calcic haplorthels (Campbell, 2003), and they are composed largely of unsorted silt, sand, and pebbles, although clay-sized particles can constitute several weight percent in some samples (Levy et al., 2008). Like most Antarctic gelisols, water track soils lack well-defined soil horizons (Bockheim et al., 2008).

Excavations into the water tracks revealed increasing soil moisture with increasing depth (Fig. 4). This is typical of active-layer soils in Taylor Valley (Campbell, 2003; Campbell et al., 1997). Saturated horizons were absent in soil pits into light-toned, dry (off-track) soils. Water-saturated soil was typically encountered above the ice table in soil pits excavated into water tracks. Saturated layer thicknesses ranged from <1 mm (surface dampness) to ~20 cm (Fig. 5). Removal of wet soil down to the ice table resulted in the flow of water out of the lower portion of the upslope face of the pit. Water slowly filled the excavation to the height of the saturated level, entering the pit from the upslope face, and draining from the downslope face of the excavation. The thickest saturated horizons were observed where concavities existed in the ice table and where ice table slopes were low. These observations suggest transport of water track melt solutions over the ice table and ponding at local lows. As noted in Table 1, wet surface soils are most common along water tracks where the saturated horizon is thick (~10 cm) and where active-layer thaw is deep (~40–50 cm).

TABLE 1. WATER TRACK VERSUS NON-WATER-TRACK SOILS

Parameter	On-track	Off-track	*N*
VWC (%)	15 ± 2	5 ± 2	34, 20
EC (dS/m)	0.53 ± 10%	0.05 ± 10%	31, 16
DTR (cm)	45 ± 1	19 ± 1	28, 20

Note: Comparison of surface soil volumetric water content (VWC), surface soil electrical conductivity (EC), and depth to refusal (DTR) for water tracks (on-track) and adjacent soils (off-track). *N*—number of samples for on-track, and off-track, respectively. Errors indicate actual measurement experimental uncertainties.

Water Track Landscape Position: Channels and Seeps

Water tracks in Taylor Valley are present in association with several landforms related to water transport. In some locations, water tracks were located within incised stream channels in which no overland flow was present at the time of observation (Fig. 2). This distinguishes water track–related water transport from hyporheic

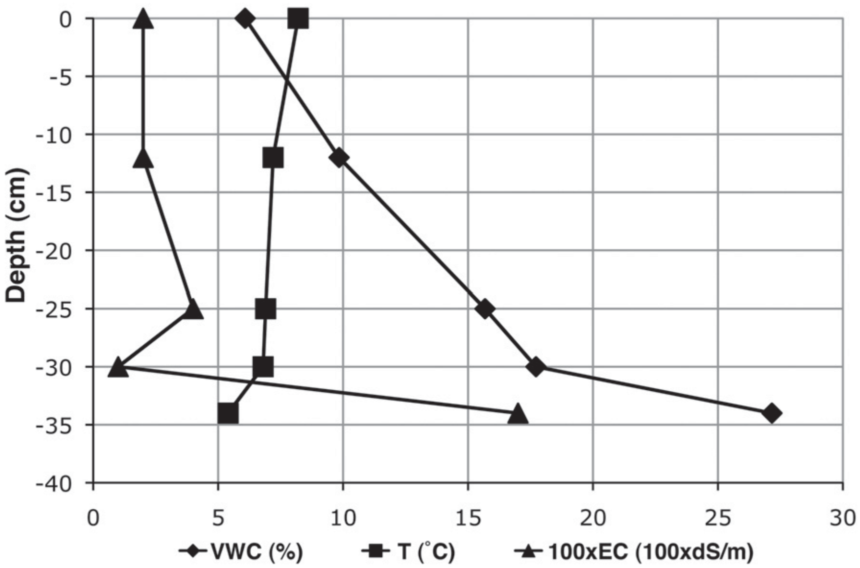

Figure 4. Plot showing volumetric water content (VWC), temperature (T), and electrical conductivity (EC) with depth in a water track soil column.

transport, in which water is exchanged between a flowing stream and the streambed (Gooseff et al., 2002; McKnight et al., 1999). In addition, liquid water seeps with identical morphological characteristics (i.e., dark, damp soil not associated with a glacial runoff channel, through which small volumes of groundwater discharge occurred through gentled channelized topography) to those described by Lyons et al. (2005) and Harris et al. (2007) were present within some water tracks (Fig. 2). Taylor Valley seeps are commonly associated with linear or downslope-branching patches of darkened, damp surface soil, and they can be extremely salt-rich (resulting in seasonal bright salt efflorescences), making it possible to map seep locations from air-photo and satellite image data (Fig. 2) (Harris et al., 2007). In fact, water tracks can be observed in their present locations in aerial photographs extending back to 1959, suggesting that they are not a "new" feature of the McMurdo Dry Valleys.

Seeps typically discharge at the water track surface at points where boulders produce a local break in slope, resulting from upslope damming of colluvium (e.g., Putkonen et al., 2007). In such locations, the thickness of saturated soil above the ice table is greater than the available soil column height in the downslope lee of the boulder, resulting in the percolation of water from the active layer as a seep (similar to familiar spring processes).

Water Track Soil Hydraulic Conductivities

The hydraulic conductivity of wet and dry soil was measured in Taylor Valley using a Decagon Devices Minidisk Infiltrometer. Mean hydraulic conductivity was 0.02 cm/s ($N = 6$). Hydraulic conductivity was strongly dependent on soil grain size (spanning cobbles to silt) and on the thermal conditions of the soil. Hydraulic conductivity was found to be low for muddy soils (0.002 cm/s), as well as for hard-frozen soils (0.005 cm/s), and to be greatest for dry, unfrozen soils (up to 0.06 cm/s). The observed differences in hydraulic conductivity between frozen and unfrozen, nonsaturated surface soils are consistent with the 1–2 orders of magnitude reduction in hydraulic conductivity predicted by Kleinberg and Griffin (2005) for frozen soils that are 40%–60% saturated.

Hydraulic conductivities in water tracks are also likely to be temporally variable due to changes in volumetric water content during the summer season. Permeability of water track soils will increase as soil moisture increases during thaw and snowmelt addition periods, and it will decrease as water drains prior to winter freezing (although the presence of ice-saturated and excess ice permafrost suggests that drainage

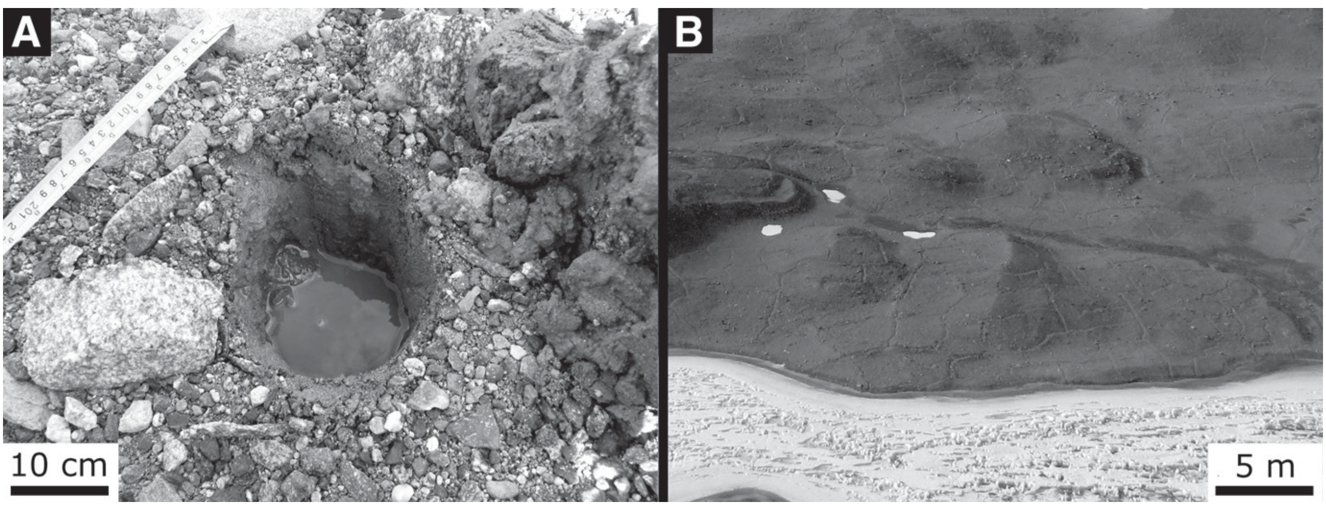

Figure 5. (A) A thick saturated horizon filling the pit from the ice table (~35 cm depth) to ~15 cm depth on a water track. (B) Snowbanks commonly accumulate in water track troughs (windblown snow) at several locations along water tracks. The water track (water track 2) is ~500 m from left to right. Images have been stretched to enhance contrast.

of water track soils in summer is minimal). To capture these complexities, we assume an average water track hydraulic conductivity of 0.02 cm/s. Future analyses will focus on seasonal changes in Antarctic permafrost hydrological characteristics.

Water Track Melt Sources

Most water tracks are clearly associated with surface ice in the form of snow. Seasonal snowbanks commonly accumulate in topographic troughs or depressions associated with water tracks (Fig. 5)—similar to observations of snow accumulation in polygon troughs and gully channels in neighboring Wright Valley (Levy et al., 2008; Morgan, 2009). During summer, snowbanks contribute water to the water tracks as snowmelt infiltrates into the soil. Surface soil moisture in the vicinity of snowbanks typically exceeds 10% VWC, and the depth to the ice table is typically 5–10 cm (likely owing to insulation of the ice-cement by the overlying snowbank), even when nearby water track active-layer thicknesses are greater. This source of meltwater, coupled with a thin active layer (limited capacity to store or transport the snow runoff), accounts for the high soil moisture and relatively low EC associated with water track soils in the vicinity of snowbanks (see geochemistry section).

Water tracks are also associated with ground ice, raising the possibility of nonsnow contributions to water track flow. Pore ice (commonly called "ice-cement") is the dominant form of ground ice in Taylor Valley, based on 62 soil pits excavated during 2009–2010. Ice content in the upper ~10 cm of the ice table averages 29% by volume (n = 20, 16% by mass, assuming 1.8 g/cm^3 sediment bulk density, i.e., the mean for 58 Taylor Valley soils collected during 2009–2010). Mean skeleton density for Taylor Valley samples is 2.73 g/cm^3 (n = 26), suggesting an average porosity for Taylor Valley soils of 36%.

Excavations within water tracks also provided examples of excess ice (ice exceeding pore space) (French, 2007). Excess ice in water track excavations was present as ice lenses with and without laminations, suggesting ice segregation processes during autumn freezing. Excess ice was also present as friable, granular, poorly consolidated wedges 1–2 cm in width, suggesting localized ice-wedge formation (Leffingwell, 1915). For comparison, sand-wedge polygons are the dominant thermal-contraction-crack polygon variety in Taylor Valley, consistent with generally dry soil conditions outside of water tracks (Marchant and Head, 2007; Pewe, 1959). At the margin of one water track excavation, an ~10-cm-wide wedge of foliated ice and sand grains was located several centimeters off the axis of the current sand wedge, suggesting the relict formation of composite-wedge polygons in some Taylor Valley water tracks (Ghysels and Heyse, 2006; Marchant and Head, 2007; Murton, 1996). Buried massive ice deposits have also been observed in Taylor Valley in some locations, and these could serve as additional sources of water track meltwater (Bockheim et al., 2008; Prentice et al., 2008).

Water Track Thermal Properties

Given the importance of soil moisture in determining the thermal properties of soils (Baver et al., 1972; Ikard et al., 2009), measurements of soil apparent thermal diffusivity (ATD) were collected. Two strings of Campbell Scientific 107-L thermistors were buried in Taylor Valley soils starting in December 2009 (four probes per string, spaced 10 cm apart, recording hourly). One string was buried in a wet soil patch (mean soil moisture = 21% by volume), while the second string was buried in a dry soil patch (mean soil moisture = 7% by volume). ATD was determined by the graphical finite difference method (Pringle et al., 2003) using temperature data from the thermistor strings, and a moving 48 h calculation window (i.e., the ATD for a given time was calculated using the change of temperature with depth for the preceding and subsequent 24 h relative to a data point). ATD calculations are summarized in Table 2. ATD is highly variable in Taylor Valley. Taylor Valley soils show diverse thermal characteristics, but they are consistent with sandy soils with moderate porosity containing <40% water by volume (Baver et al., 1972; Ikard et al., 2009).

DEM AND SATELLITE IMAGE ANALYSIS

A light detection and ranging (LiDAR) digital elevation model and coregistered *Quickbird* satellite image data were used to test whether the geochemical linkages among water tracks, seeps, and the other surface hydrological features in Taylor Valley outlined here resulted from hydrological linkages at the hillslope scale. Water tracks in Taylor Valley were identified in *Quickbird* satellite image data for comparison with spatial and hydrological analyses conducted using a 2 m/pixel digital elevation model (DEM). The DEM was produced from airborne LiDAR scanning in 2001–2002 (Schenk et al., 2004). Surface darkening of soils along water tracks (e.g., Fig. 3) and surface brightening due to salt efflorescence are visible in panchromatic 60 cm/pixel *Quickbird* images (Fig. 6). Satellite image analysis was used to identify the inferred water track locations marked on Figure 1.

DEM analysis of water track topography was conducted using methods typically applied to Arctic hillslope watersheds (e.g., McNamara et al., 1999). DEMs for eastern and western portions of Taylor Valley were first mosaicked in ArcMap 9.3 to produce a seamless DEM covering the full extent of Taylor Valley (the DEM covers Taylor Valley from the valley floor to 1306 m and extends from the coast to Taylor glacier). The mosaicked DEM was then processed using the ArcToolbox Fill function to remove sinks in the DEM (sinks are DEM pixels that have no downslope outlet). Although the maximum fill depth was left unconstrained, 46% of sinks identified in the DEM were <10 cm deep, and 99% were less than 70 cm deep (Fig. 7). Many of the sinks were located within dark water track surfaces visible in *IKONOS* image data, suggesting that they were not artifacts in the data but, rather, represent sites of localized internal drainage, consistent with observations of ponding along water tracks. The presence of sinks and pond sites along water tracks may indicate the existence of a critical active-layer saturation depth required to achieve water track hillslope connectivity (e.g., Stieglitz et al., 2003). A flow direction raster was then computed using the ArcToolbox Flow Direction function (to produce a raster showing the maximum downslope drainage direction from each DEM pixel). From the flow direction raster, the Flow Accumulation and Flow Length ArcToolbox tools were used to create rasters cataloging the number of upslope DEM pixels that contributed flow to each point in the DEM, and the maximum upslope distance from which flow could be traced to each DEM pixel.

Inspection of flow accumulation rasters coupled with satellite image data shows the presence

TABLE 2. WATER TRACK SOIL SUMMERTIME APPARENT THERMAL DIFFUSIVITY

Soil type	Mean apparent thermal diffusivity (mm^2/s)	Apparent thermal diffusivity range (mm^2/s)
0–20 cm depth wet soil	0.46% ± 10%	0.38–0.51
0–20 cm depth dry soil	0.71% ± 10%	0.56–0.87
20–40 cm depth wet soil	0.78% ± 10%	0.68–0.92
20–40 cm depth dry soil	0.49% ± 10%	0.31–0.61

Note: Calculations of apparent thermal diffusivity (ATD) for water track (wet) and off-track (dry) soils as a function of depth in Taylor Valley.

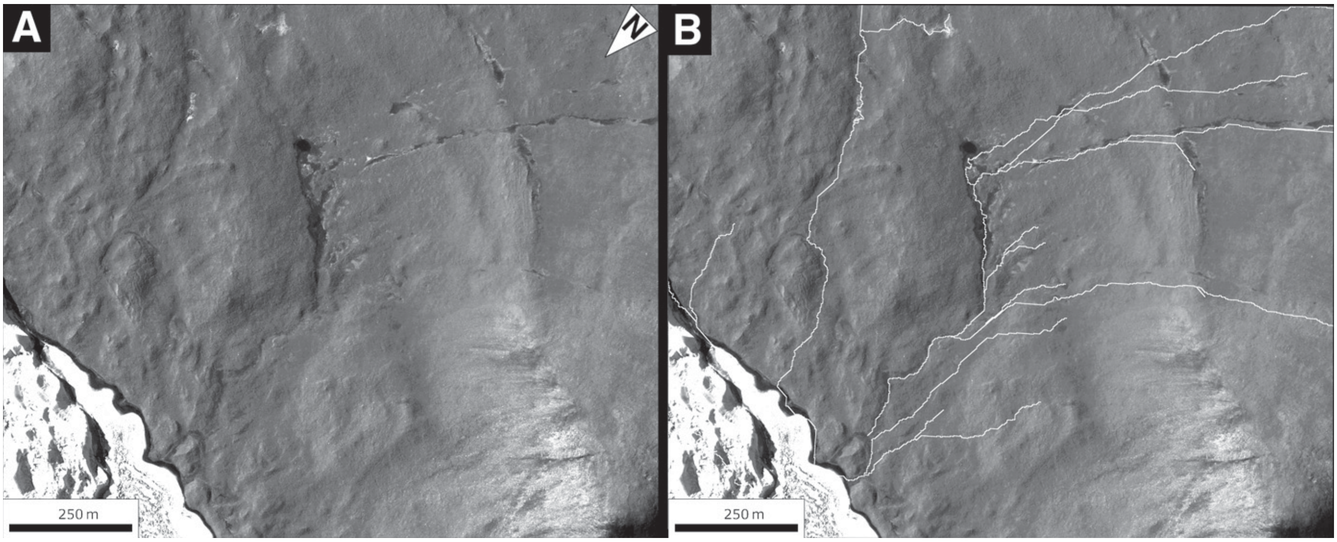

Figure 6. Dark water track soils are spatially correlated with locations of enhanced, topography-driven, potential water accumulation. Water track 1 traverses the south wall of Taylor Valley, downslope toward Canada glacier and Lake Hoare. (A) Panchromatic *Quickbird* image data showing darkened soil with bright salt efflorescences. (B) Image data with overlay showing digital elevation model pixels with >0.04 km² upslope accumulation area. Portion of *Quickbird* image 09FEB01213752. Images have been stretched to enhance contrast.

of linear flow paths that strongly correlate with the locations of dark and linear patches of soil identified as water tracks—particularly at contributing areas exceeding ~10^4 pixels (0.04 km^2) (Fig. 6). Water tracks identified in the DEM flow accumulation rasters deflect around topographic obstacles, such as ice-cemented moraines and ridges, suggesting that the downslope transport of water through the active layer is responsible for surface darkening visible from the ground and from orbit (Fig. 6). Topographic transects orthogonal to water tracks identified from satellite image data show that water tracks flow through broad, downslope-oriented surface troughs that are depressed up to ~1 m relative to the surrounding soil surface.

Water track DEM analyses were used to evaluate the estimate by Cartwright and Harris (1981) that no more than 1% of McMurdo Dry Valleys surfaces support shallow groundwater movement (i.e., water tracks). Flow accumulation raster pixels with >0.04 km^2 of upslope accumulating area (strong water track candidates) from a subset of the Taylor Valley DEM (focusing on the Lake Hoare basin) were converted into vector features in ArcMap. A 0.5 m buffer was created surrounding each water track vector to produce water track polygons with 1 m widths (a minimum width for typical water tracks visible at the surface). The combined surface area of these high-confidence water track polygons was 1% of the DEM area (287 km^2—the entire valley floor below 1300 m elevation, which is the DEM limit; as seen in Fig. 6, DEM-delimited water tracks extend at least this far upslope in Taylor Valley). Extending the accumulation criteria to smaller water track tributary pixels (DEM pixels with >0.02 km^2 of upslope accumulation area), the portion of the DEM potentially underlain by water track–related shallow groundwater rises to 4%. Water tracks that can be clearly resolved in 60 cm panchromatic *Quickbird* images are considerably wider than 1 m, suggesting that these spatial estimates are minimum values for the extent of shallow groundwater activity in Taylor Valley.

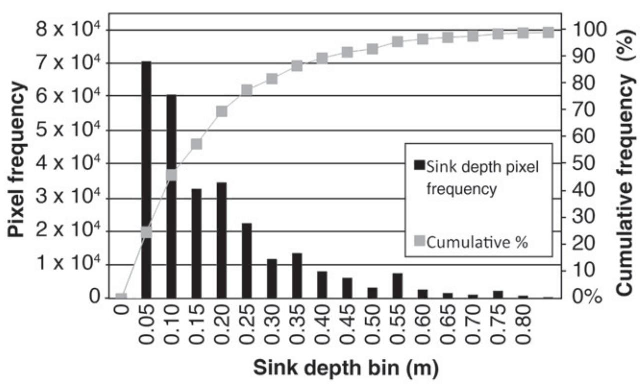

Figure 7. Histogram showing depth of digital elevation model sinks filled in by the Fill tool. Most sinks are less than 0.2 m deep, suggesting that internal drainages in the landscape may be real, and can fill through water track ponding, resulting in connectivity on the Taylor Valley hillslopes.

WATER TRACK GEOCHEMISTRY METHODS AND RESULTS

Major ion analyses have been used extensively to characterize the linkages between Antarctic surface water reservoirs, including glaciers, streams, and lakes (Gooseff et al., 2006, 2002; Harris et al., 2007; Lyons et al., 2005, 1998a, 1998b; Welch et al., 1996; Wilson, 1981). Water samples were collected from the active layer in Taylor Valley using sterile polyethylene syringes. Samples were filtered in the field using 0.45 µm HT Tuffryn membrane syringe filters into precleaned polyethylene bottles. Bottles were fully filled and were kept refrigerated at all times. When soil moisture levels were well below saturation, making direct water-sampling impossible, soil samples were collected in 1 L Whirl-Pak bags and were kept refrigerated until the samples could be centrifuged to separate water from soil grains. Permafrost (ice-cemented soil, excess ice, etc.) was collected using cleaned picks and scoops, and was thawed in Whirl-Pak bags before being syringe-filtered. Snow was collected using clean scoops into Whirl-Pak bags and was melted prior to filtering. Major ion concentrations were determined by ion chromatography as described in Welch et al. (1996), resulting in a total analytical error of <4%.

Major ion data for Taylor Valley water track systems are presented in Figure 8. Analyzed ions include Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}, NO_3^-, and F^-. We analyzed (1) samples of active-layer groundwater from within the water tracks, (2) ice-cemented permafrost (both pore ice and excess ice) from beneath the water tracks, (3) snow trapped in water track troughs,

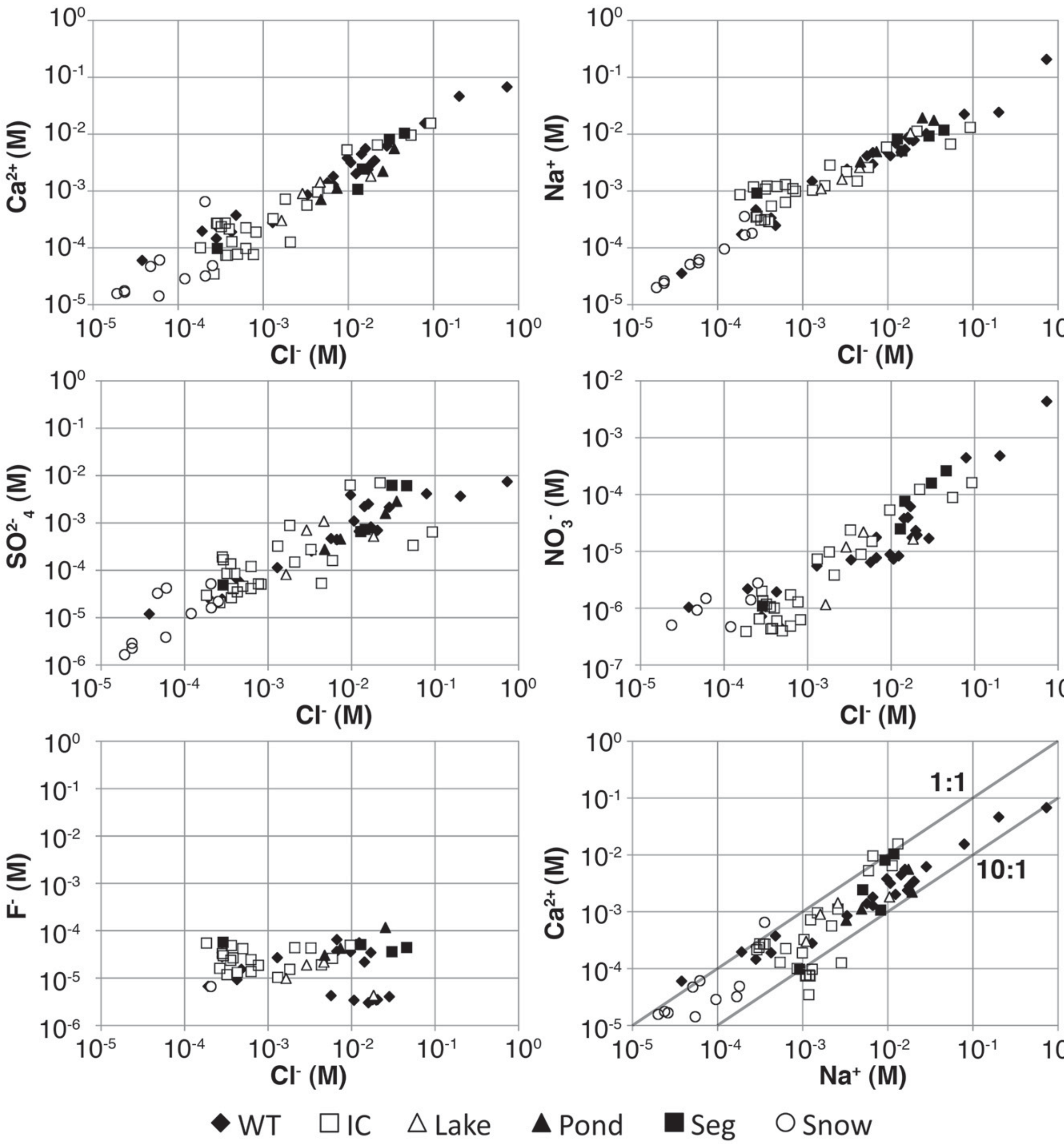

Figure 8. Major ion versus Cl^- concentration for Taylor Valley water track–related soil (WT), ice-cement (IC), excess ice (Seg), source snow (Snow), ponded flow (Pond), and contacts between Lake Hoare and water tracks (Lake).

TABLE 3. WATER TRACK δ18O, δD, AND D-EXCESS

Water track component	$\delta^{18}O$ (‰)	δD (‰)	D-excess* (‰)
Snow	–32.08 ± 4.27	–255.79 ± 32.24	10.84 ± 3.96
Active-layer groundwater	–22.68 ± 3.57	–201.37 ± 16.87	–9.93 ± 12.48
Ice-cemented permafrost	–16.72 ± 3.72	–172.75 ± 17.02	–28.97 ± 28.97
Water track–fed pond	–14.10 ± 7.29	–163.66 ± 40.09	–40.85 ± 18.51

Note: Stable isotope ratios for water track geomorphic components. Errors are standard deviations of the sample.
*D-excess is calculated after Craig (1961).

(4) water track–fed ponds, and (5) water from the shore of Lake Hoare where water tracks emptied into the lake. Major ion concentrations in the water tracks generally fall within the range of typical Taylor Valley surface waters (glaciers, streams, lakes) reported by Lyons et al. (1998a). Cl^- (considered a conservative ion), Ca^{2+}, Mg^{2+}, Na^+, and K^+ concentrations in water tracks fall within the Taylor Valley continuum reported by Lyons et al. (1998a), but in rare cases, concentrations are more concentrated than the Blood Falls hypersaline discharge (Fig. 8). NO_3^- in water track–related snow and ice-cement is comparable to Taylor Valley glacier ice concentrations (Lyons et al., 1998a), but other water track components (active-layer water, segregation ice, etc.) exceed these values by several orders of magnitude. Ca^{2+}/Na^+ molar ratios in the water tracks fall largely between 0.1 and 1 (Fig. 8), a pattern interpreted by Wilson (1981) as indicative of largely atmospheric (precipitation) sources for the water, rather than deep groundwater sources, based on their similarity to glacier Ca^{2+}/Na^+ ratios.

Water track fluids have low Na^+/Cl^- molar ratios on average (0.66, compared to 0.86 in seawater), suggesting the possibility of cryogenic concentration of salts during seasonal freezing (Starinsky and Katz, 2003). However, the high Ca^{2+}/Na^+ ratio (0.72 on average) more strongly suggests humidity-driven salt separation at the permafrost surface as a primary driver of solute enrichment (Wilson, 1979). Likewise, the K^+/Na^+ ratios of water track fluids average 0.17, which is very similar to Taylor Valley stream ratios (~0.16), which have not been shown to experience cryogenic concentration. Further analysis of water track fluids for Br content will resolve the precise origin of the salt enrichment relative to other Dry Valleys waters.

Stable isotope ($\delta^{18}O$ and δD) ratios were measured for fluids in water tracks using a Picarro WS-CRDS Analyzer for Isotopic Water, Model L1102-i. Samples analyzed for stable isotope ratios are splits from the major ion samples that were separated prior to ion chromatography (IC) analysis. Identical sample collection and curation procedures were followed for both sample sets. The $\delta^{18}O$, δD, and D-excess values for Lake Hoare basin water tracks are reported in Table 3 and are reported relative to standard mean ocean water (SMOW) with an analytical precision of ±0.25‰ for $\delta^{18}O$ and ±1.0‰ for δD. Stable isotope ratios for snow melting into the water tracks are close to the local meteoritic water line for Taylor Valley (Gooseff et al., 2006). Snowmelt feeding water tracks is the isotopically lightest water in the system, followed by water track active-layer groundwater, ice-cement underneath water tracks, and finally, by water track–fed pond water. Some isotopic values of the active-layer groundwater values associated with water tracks fall close to the meteoric water line, while others do not. We interpret these results to indicate that water that has been in the water track system through several freeze-thaw cycles (e.g., ice-cement), and that has experienced prolonged evaporation (e.g., water track pond water), is strongly depleted in D relative to ^{18}O. This suggests that water track solutions are a mixture of more evolved ground ice melt (ice-cement, seasonally frozen pond water) and fresh snowfall melt and infiltration.

Water Track Geochemistry Spatial Patterns

A transect down one water track is exemplary of water track geochemical spatial relationships in Taylor Valley (Fig. 9). Snow sources for water track moisture are relatively solute-poor; however, water track moisture in the active layer develops total dissolved solids (TDS) loads in excess of 1 g/L within 10 m of snowbanks (mean snowbank TDS is 9 mg/L, $N = 6$), analogous to the increase in stream solute concentrations from hyporheic weathering noted by Gooseff et al. (2002). Water track moisture undergoes evaporative concentration in ponds where flow through the water track intersects the surface (commonly upslope of ice-cemented ridges on the valley walls); however, variability in the slope of ion-to-Cl^- plots (Fig. 8) suggests that differential salt dissolution in water track soils is also a major factor in determining water track solution composition. Water track solutions are diluted by meltwater contributions from snowbanks present in the water track trough (e.g., Fig. 9, steps 4 and 7). Water track solute concentrations can remain relatively constant as water moves downslope over distances of several hundred meters (Fig. 9, steps 10–12). Water tracks deliver water from the active layer to the Taylor Valley lakes, as evidenced by the solute-rich, water track–like chemistry of samples collected from the shore waters of Lake Hoare at the mouth of water tracks (e.g., Fig. 9, step 12). This shore-water chemistry is approximately ten times more concentrated (by solute mass) than typical Lake Hoare interior water (Lyons et al., 2000).

Vertical transects of ice-cemented permafrost beneath water tracks provide insight into the interactions between active-layer solutions and the ice table. Typical, non-track-related, ice-cemented permafrost at low elevations in Taylor Valley (below ~300 m) has low TDS (<200 mg/L), which is largely uniform in the upper 10 cm of the ice-cement. In contrast, the ice-cement underlying water tracks is highly concentrated with solutes—over 4600 mg/L of solutes (notably Ca^{2+} and Cl^-) were found at the ice surface. The concentration tapers off rapidly with depth. TDS in 5–10 cm beneath the ice-cement table is only slightly more salt-rich than ice-cement located in non-track locations (~260 mg/L), suggesting freeze-concentration at the ice-table surface. For comparison, these ice-cement solute concentrations are slightly more than half the peak TDS concentrations (6900 mg/L) reported by Dickinson and Rosen (2003) for high-elevation (>1000 m) Taylor Valley wall permafrost. However, solute concentrations in the ice at the ice-table–water track interface are considerably higher than solute concentrations found in most water track solutions. Freezing point depression resulting from typical water track solution concentration averages ~0.5 °C; however, it can reach up to 6.8 °C in the concentrated solutions found in water track 3. These values represent minimum values, as samples were collected at peak water track dilution (maximum snowmelt input) during December and January 2009.

Comparison of Water Track and Seep Geochemistry

The geochemical linkages between water tracks and Taylor Valley groundwater seeps are of particular interest (Harris et al., 2007; Lyons et al., 2005). Figure 10 plots water track groundwater major ion data along with geochemical data for seeps and adjacent (glacier-fed) streams reported by Harris et al. (2007). For all elements analyzed, water flowing through the active layer in water tracks spans the range of concentrations measured in seeps and streams (~10^{-7}–0.3 *M*). However, water track concentrations also exceed solute concentrations in seeps by 1–2 orders of magnitude in all cases except F^+ and NO_3^-. NO_3^-

is the only ion for which seep concentrations are typically similar to water track concentrations. The presence of seep-like features in water tracks, coupled with the similarities in their chemistry, suggests that seeps are an emergent process associated with water track activity, and they are locations where saline solutions moving downslope through water tracks discharge at the surface due to abrupt changes in slope.

THERMAL AND HYDROLOGICAL MODELING AND DISCUSSION

Water track in situ and laboratory geochemical data, in situ thermal and physical data, and DEM hydrological data can be combined to assess the nature of water tracks in Taylor Valley and their role in geological, hydrological, and ecological processes.

Do water tracks represent isolated hydrological features, or are they part of the larger hydrological system in Taylor Valley? Water tracks identified in the field (Fig. 1) have regular length/accumulation-area trends when measured in the 2 m/pixel DEM. The ten water tracks identified in the Lake Hoare basin have a mean contributing length of 1.8 km (range: 1.3–2.7 km) and a mean contributing area of 0.37 km^2 (range: 0.06–1.2 km^2) based on the flow length and accumulation rasters. For comparison, nine of the streams in the Lake Fryxell basin were also analyzed using the DEM, and they have a mean contributing length of 4.1 km (range: 2.4–7.0 km) and a mean contributing area of 3.0 km^2 (range: 0.77–8.3 km^2). Taken together, these data reveal that water tracks and named streams/creeks in Taylor Valley fall along the same channel length/accumulation area curve $L = aA^m$ (where L is channel length, A is accumulating area, and a and m are empirical parameters) (Mandelbrot, 1982; McNamara et al., 1999). For Taylor Valley water tracks and streams, $L = 30A^{0.33}$ ($r^2 = 0.89$) (Fig. 11).

Water Track Role in Taylor Valley Water Budgets

If water tracks are a part of the near-surface hydrological system in Taylor Valley, what is the water flux through them, and how does it compare to the discharge from streams? Taking

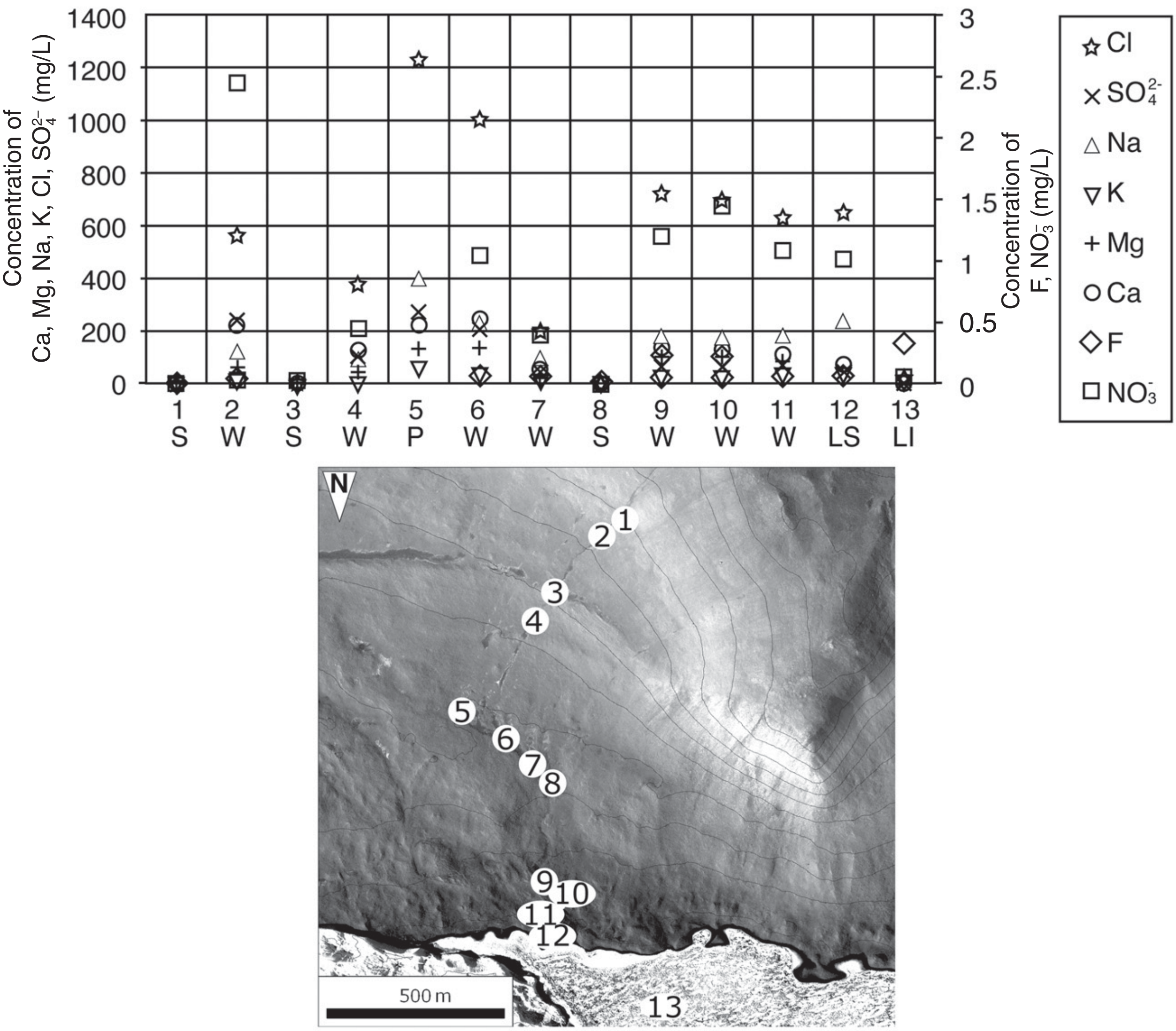

Figure 9. Geochemical transect down water track 1. Lower image shows sample site locations 1–13. S—source snow, W—water track solutions, P—surface ponding, LS—shore of Lake Hoare at the water track mouth, and LI—lake interior (a sample from 4 m depth collected in 2006; portion of *Quickbird* image 09FEB01213752). Image has been stretched to enhance contrast.

the largest water track observed during 2009–2010 (Figs. 3A–3B), here termed water track 1 (Fig. 1), the feature drops 170 m in elevation over 1900 m of flow length, yielding an average gradient of 5°. Taking the average hydraulic conductivity measured in Taylor Valley soils, we compute an average flux of 1.8×10^{-3} cm/s using Darcy's flow law. Interestingly, this rate is two orders of magnitude greater than ionic migration rates measured in non-water-track soils by Claridge et al. (1997), i.e., 1.7 m/yr for wet soils and 0.3 m/yr for dry soils. Field observations of water track 1 show that it is ~3 m wide on average, with a typical saturated (flowing) depth of 10 cm. Taking flux times cross-sectional area leads to a discharge through the water track of 5.4 cm^3/s, or ~470 L/d. The next largest water track observed in the Lake Hoare basin during 2009–2010 (Figs. 3C–3D), water track 2, has a similar slope (4°) and cross-sectional area, suggesting a similar discharge. For comparison, mean summer discharge of Delta Stream, the closest gauged stream to the water track is 33 L/s, or 2.9×10^6 L/d (based on mean daily values 2000–2009), draining into nearby Lake Fryxell.

Accordingly, water tracks do not appear to be a major contributor of water to McMurdo Dry Valleys lakes, as compared to streams. However, satellite image and field analysis suggest that water tracks are a major source of water to McMurdo Dry Valleys soil ecosystems. Unlike McMurdo Dry Valleys streams,

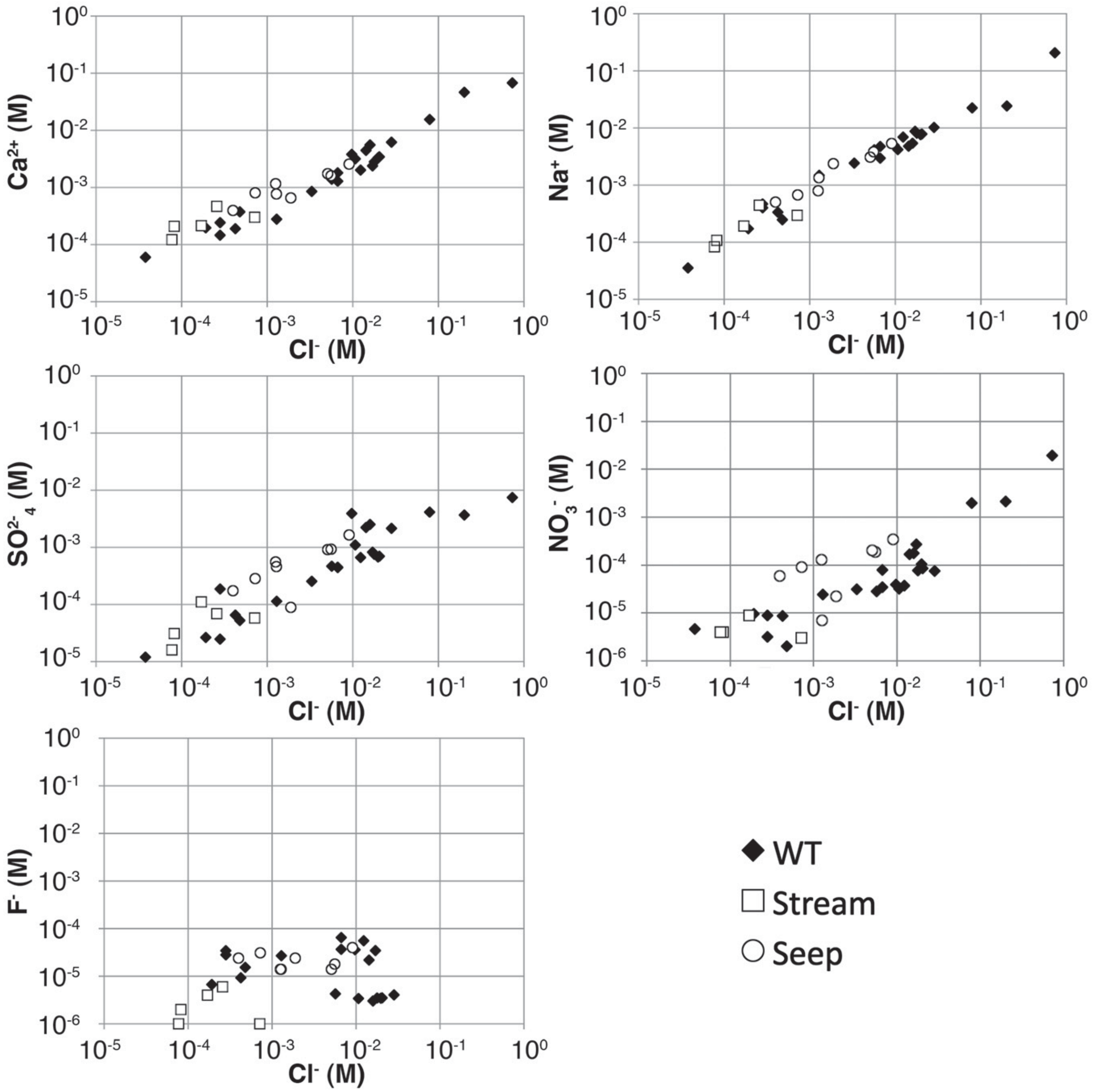

Figure 10. Major ion versus Cl^- concentration for Taylor Valley water tracks (WT) (this paper) and seeps/streams reported by Harris et al. (2007).

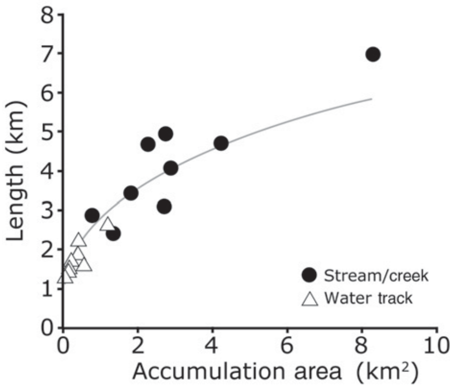

Figure 11. Plot of feature length (L) versus accumulation area (A) for water tracks and named streams/creeks in Taylor Valley. Lengths and accumulation areas were determined from analysis of a flow direction raster generated from a 2 m digital elevation model. Water tracks and creeks fall along the same length/accumulation area curve (gray line), $L = 30A^{0.33}$ ($r^2 = 0.89$).

the duration of water track contribution to lakes is mainly controlled by the source water dynamics (how much snow and/or ground ice is available for melt) and surface energy balance (that drives melting). Once water track saline solution transport is initiated, however, it is expected that their hydroperiod is limited by colder temperatures than the stream hydroperiod (see geochemistry section).

These flux calculations indicate that saline solutions moving along the ice table through water tracks may take ~75–150 yr (mean: 104 yr, $N = 10$) to move from the highest reaches of the water track to the lake shore, assuming constant flow. This suggests that there may be ample time for water track solutions to leech soluble species from surrounding soils—a chemical weathering pathway strongly suggested by the exceptionally high NO_3^- concentrations observed at water track termini (Harris et al., 2007) (see geochemistry section).

Water Track Role in Taylor Valley Salt Budgets

Although water tracks may not be a significant factor in the Taylor Valley water budget, their high salinity raises the possibility that they are significant sources of solutes to McMurdo Dry Valleys lakes. Cl^- is commonly used as a conservative element in Taylor Valley hydrological studies because it is unlikely to precipitate out of streams and lakes due to halite or antarcticite saturation (Lyons et al., 2005, 1998a). The Cl^- molarity of water entering Lake Hoare from water track 1 is 1.84×10^{-2} (Fig. 9), yielding a Cl^- flux to Lake Hoare from water track 1 of 8.6 mol/d by multiplying the molarity (mol/L) by the discharge (L/d). Track 2 is considerably less briny than water track 1 (1.64×10^{-3} mol/L Cl^- at the Lake Hoare shore), resulting in approximately an order of magnitude less Cl^- flux than from track 1. In contrast, the briniest water track in the Lake Hoare basin, water track 3, has a Cl^- concentration that reaches 7.31×10^{-1} mol/L, suggesting the possibility of large fluxes (~340 mol/d). However, field observations suggest that water track 3 is not currently discharging into Lake Hoare due to damming by an ice-cored ridge—solute transport into Lake Hoare would require cryptic flow through fractures (e.g., Dickinson and Rosen, 2003). For comparison, the Cl^- concentration of Andersen Creek (one of the two major streams in the Lake Hoare drainage) is highly variable, but it averages ~110 µ*M* (Lyons et al., 2003). Andersen Creek has an average discharge of ~30 L/s (based on 2000–2010 gauge data), yielding an average Cl^- flux of 285 mol/d.

Next, we calculate the effect of Cl^- flux from water tracks on Taylor Valley lake salt budgets. Lake Hoare has an average Cl^- concentration of ~5 m*M* and a volume of 17.5×10^6 m^3 (Lyons et al., 2000), yielding a Cl^- reservoir of 87.5×10^6 moles of Cl^-. Assuming constant (year-round) flow, the water tracks could account for the Lake Hoare Cl^- reservoir given 28 k.y. of flow from water track 1 alone (considerably longer than the age of the lake) (Doran et al., 1999, 1994), or ~700 yr of flow from water track 3 alone. Depending on water track salinity variations with time and location, water tracks may be an important contributing pathway in the Taylor Valley lake solute budget.

Water Track Discharge into Lakes

Analysis of water-column geochemical profiles reveals the presence of high-salinity waters at depth in Lakes Fryxell and Bonney, and, to a lesser extent, Lake Hoare (Doran et al., 1999, 1994; Lyons et al., 2000). These profiles have been interpreted to indicate desiccation of the lakes (complete, in the case of Lake Hoare) and refilling by stream water with little to no evapoconcentration within the past ~1 k.y., based on Cl^- diffusion rates and Li^+/Na^+ ratios (Lyons and Welch, 1997; Lyons et al. 1998b). Water track physical and chemical data suggest that water track solutions during 2009–2010 had a density of 1000.2 kg/m^3 (for water track 1) and up to 1001.7 kg/m^3 (for water track 3). Densities were determined using the equations of state in Fofonoff (1985) for surface water at 2.8 °C (measured in situ) and electrical conductivities of 0.033 S/m and 0.231 S/m (measured in situ), respectively. In contrast, Andersen Creek water entering Lake Hoare has a mean temperature of 0.2 °C and a mean electrical conductivity of 0.005 S/m (based on 2000–2010 gauge data), yielding a mean density of 999.9 kg/m^3. Density variability from temperature uncertainty is ±~0.01 kg/m^3. These calculations illustrate the strong dependence of solution density on TDS, relative to temperature, for small temperature differences and high solute loads. Based on conductivity-temperature-density measurements through the Lake Hoare water column collected by the MCM-LTER on 3 January 2010, Andersen Creek water would find an equal-density level at 3.3 m depth, saline waters from water track 1 would be neutrally buoyant at 6.3 m depth, and water track 3 solutions would sink to the bottom of the lake. This slight density imbalance may permit water track solutions to dip below surface water input by stream flow, to produce Cl^--rich, interfingered pockets of water under current conditions. Water track–lake intersection points are also the locations of subsurface anoxic channel features incised into the lake bed (Peter Doran, 2010, personal commun.). A shallow injection and interfingering mechanism like this was inferred by Wilson (1981) as a means for injecting bomb-generated tritium into deep, stratified, and ancient lake waters in Wright and Taylor Valleys. The presence of density-layered solutions raises intriguing questions about lake stability versus composition-dependent overturn (e.g., Lyons et al., 1996). Based on the similarity between water track Ca^{2+}/Na^+ ratios measured in the Lake Hoare basin (0.72) and Lake Hoare bottom water (0.27), it appears that water track solutions may contribute significantly throughout the Lake Hoare water column; however, water track fluids are not likely to be a major influence on the ionic ratio of Lake Fryxell ($Ca^{2+}/Na^+ = 0.03$) and Bonney ($Ca^{2+}/Na^+ = 0.01$) bottom water (the latter are thought to be composed of relict, evapoconcentrated paleobrines that are denser than water track solutions and that may have experienced Ca^{2+} loss from calcite precipitation; such brines are absent in Lake Hoare; Lyons and Mayewski, 1993).

Water Tracks and the Permafrost Thermal Regime

Next, we consider the thermal effect of water track fluid transport on permafrost in Taylor Valley. Apparent thermal diffusivity (ATD) is the ratio between soil thermal conductivity (its ability to transport heat) and soil heat capacity (the product of soil density and specific heat capacity, or the tendency of the soil to store heat). In the cold and ice-cemented soils of Antarctica, conductive heat transfer provides an important first-order measure of heat movement (Hagedorn et al., 2007; McKay et al., 1998).

As in previous studies of Taylor Valley seeps (Lyons et al., 2005), we employed an elementary thermal diffusion model that analytically determines temperature with depth and time based on a sinusoidal function that prescribes surface temperature (Campbell, 1977; Yershov, 1998).

$$T(z, t) = T_o + A(0)e^{-z/D}\sin(\omega t - z/D), \quad (1)$$

where T is temperature, T_o is mean annual surface temperature, z is depth, t is time, $A(0)$ is mean annual temperature at the surface, ω is the angular frequency of temperature oscillation (annual), and D is the damping (or e-folding) depth. $D = (2\kappa/\omega)^{1/2}$, where κ is the apparent thermal diffusivity (ATD). A major shortcoming of this model is that it does not account for heat exchange, nor does it account for the changing ATD with depth observed for Taylor Valley soils. Accordingly, it tends to dramatically overpredict the depth of thaw.

The sinusoidal-analytic model does not accurately predict the depth of thaw in Taylor Valley water tracks. However, it is possible to use it to illustrate the importance of water track moisture in changing surface soil thermal conditions. We used a manual fit to climate data (mean temperature −18 °C, amplitude 25 °C), and ATD values for sandy soil from Baver et al. (1972) of 0% VWC and 15% VWC (i.e., dry, off-track soil and wet, water track soil = 0.2 and 0.8 mm^2/s, respectively). In this scenario, thaw occurs at 60 cm depth in wet soils but is arrested above 60 cm in dry soils. These thawing depths exceed the on-track/off-track ice-table depths observed during 2009–2010. The discrepancies between modeled thaw depth and observed thaw depth result from a combination of complex thermal inputs (the r^2 of the sinusoidal models relative to the actual temperature data is ~0.84, owing to winter katabatic warming). Other error sources include the inability of the sinusoidal-analytic model to partition energy into melt generation or to change ATD with depth. Albedo differences on and off water tracks may also locally enhance summer warming on water tracks, while winter sublimation of soil moisture may locally enhance cooling on water tracks. Deep active layers in some water tracks suggest that over-the-ice-table fluid transport may be advecting heat down slopes (Yershov, 1998).

What is the role of latent heat in controlling thaw depth in water track soils? Although a complete thermodynamic treatment of water track soils is beyond the scope of this study, a simple energy budget can illustrate the role of latent heat of fusion in limiting water track thaw depth. Consider a typical 1 m^2 patch of water track soil that thaws to 45 cm depth from an average winter temperature of −30 °C (e.g., Table 1) and has an average porosity of 30% (and that is entirely ice-saturated). The volume initially contains 0.14 m^3 of ice and 0.32 m^3 of sediment. Assuming a volumetric heat capacity of 1.5 × 10^6 J/m^3•°C for the sediment (as measured in the field) and 1.9 × 10^6 J/m^3•°C for ice, to raise the intermingled ice and sediment to 0 °C would require 2.2 × 10^7 J of net heat addition (8.0 × 10^6 J for the ice; 1.4 × 10^7 J for the sediment). Once at 0 °C (neglecting the role of water track salts in depressing the freezing point), assuming a latent heat of fusion of water of 334 kJ/kg, an additional 4.3 × 10^7 J of net heat would be required to melt the water track ice to a liquid. This suggests that heat added to the water track is partitioned ~34% into warming and ~66% into thawing water track ice. In contrast, an adjacent (off-track) dry soil patch thawing to 20 cm depth from −30 °C requires only 9 × 10^6 J of net heat addition, suggesting the possibility of vastly different energy budgets for (wet) water track soils and (dry) off-track soils.

Despite analytical shortcomings, however, the sinusoidal-analytic model and a simple energy budget calculation clearly illustrate that increased ATD, resulting from high soil moisture, coupled with heat advected from warm water traveling along the water track, and from a decrease in water track albedo with wetting, has the potential to drive thaw depths (measured as depth to refusal) tens of centimeters deeper in water tracks than in off-track ("dry") soils. This enhanced depth of thaw in water tracks likely mobilizes water that is seasonally trapped as pore and excess ice within water track channels, contributing to water track flow, while leaving ground ice "locked" in permafrost outside of water tracks.

Given the importance of surface temperatures in driving the liberation of ground ice in water tracks, it is possible that these features are emerging from a multidecadal period of quiescence resulting from ~0.7 °C of cooling per decade in the McMurdo Dry Valleys over the 1986–2000 period (Doran et al., 2002b), and that active-layer transport of salts and nutrients to McMurdo Dry Valleys lakes may become more vigorous. Future warming of only 1–2 °C in the McMurdo Dry Valleys could significantly increase the volume of water moving through Taylor Valley water tracks by the end of this century (Arblaster and Meehl, 2006; Chapman and Walsh, 2007; Shindell and Schmidt, 2004). In addition, the enhanced depth of thaw in water tracks, coupled with the saturation of water track soils, may result in enhanced soil creep that transports sediments downslope faster than dry soils. Such a soil creep mechanism could, in part, provide a feedback that lowers the topography around water tracks, enhancing the gentle topographic channels through which they flow. Creep erosion in water tracks might account for the "overabundance" of channels in the Taylor Valley landscape reported by McKnight et al. (1999) relative to the rarity of overland flow.

Evaporative Concentration and Sublimation in Water Tracks

What is the role of evaporative concentration of water track solutions, and how does sublimation of seasonally frozen water track ice affect salt and water budgets within the water tracks? These questions are motivated by the seasonally and interseasonal persistence of dark, wet water track soils as well as the observations of light-toned salt deposits at some water track margins. Evaporation/sublimation rates in the McMurdo Dry Valleys have been calculated to be ~30 cm/yr for ice-covered lakes (Clow et al., 1988), or 6.17 mm/d for open-pan evaporation (Gooseff et al., 2003b; comparable to an ~50 d warm season with peak evaporation rates). Applying the 6.17 mm/d evaporation rate, this suggests that for the water tracks to remain visibly wet (dark) at the surface, for water track 1 (~3 m width, ~1000 m long), a volume of ~20 m^3/d of water is being delivered from the saturated active layer beneath the water track to the surface to meet evaporative demand, integrated over the full length of the feature. This evaporation rate should be considered a maximum, because it does not consider small changes in evaporation rate due to solute-driven depression of water track fluid vapor pressures (not more than ~1%). Where water tracks exhaust the water table (defined by the saturated active layer) at the margins of the water track, intense soil salination occurs, resulting in the deposition of visible salt efflorescences. In addition, winter sublimation rates are found to be small in water tracks. Follow-on observations of water track ice-table depths in October 2010 revealed that water track soils were commonly ice-cemented within 1 cm of the ground surface, in contrast to depths to the ice table of ~10 cm for off-track soils. This suggests minimal ice removal from within water tracks during Antarctic winter.

What is the role of evaporation on water track solution chemistry? An ideal site to measure evaporative concentration of water track solutions is in the stretch of water track 1 immediately above Lake Hoare (Fig. 9, steps 9–11). Here, over ~25 m of downslope flow (~2 wk transit time, based on flow rates calculated earlier), water track solution chemistry remains nearly unchanged. In fact, the water track solutions become more dilute with distance downslope, likely reflecting small additions of low-solute water from the incorporation of snowmelt and/or buried excess ice in the water track during summer heating. This suggests that on daily/weekly time scales, evaporation is not a major determinant of water track chemistry. In contrast, where water track solutions pond (either at the surface, or in the subsurface), for example, in the water track 1 pond (Fig. 9, step 5), or at the terminus of water track 3, solute concentrations can reach values up to 50 times greater than the solute concentrations of water track fluids found immediately upslope. This suggests that where flushing with freshwater (snow, or ground ice melt) is minimal, evaporative concentration can have a large effect on water track solution chemistry.

How strong is the evaporative concentration signal in water track stable isotope values? Taking the evapoconcentration–stable isotope relationships of Gremillion and Wanielista (2000), +1‰ $\delta^{18}O$ per 1% reduction in water volume by evaporation, and +0.62‰ δD per 1% reduction in water volume, it is possible to estimate evaporation losses during transitions between different components of the water track system (Table 3). Considering only $\delta^{18}O$, the snow to water track active-layer fluid transition results in a loss of ~9% water volume, the water track fluid to ice-cement transition results in an ~6% water loss, and the evaporative concentration of water track fluids in ponds reflects an ~9% volume loss. Comparable calculations using δD values result in percentage water losses 5–10 times greater. These calculations neglect kinetic fractionation effects on water track stable isotope values resulting from freezing, sublimation, and vapor diffusion. The pan evaporation experiments of Gooseff et al. (2003b) suggest that when peak evaporation occurs, stable isotope values for water track fluids may change rapidly, on hourly to daily time scales.

ECOLOGICAL IMPLICATIONS

Permafrost landforms provide structure to the nematode-dominated ecosystem in Taylor Valley by controlling the distribution of liquid water, salts, and heat in the soil (Barrett et al., 2004; Nkem et al., 2006; Poage et al., 2008; Virginia and Wall, 1999). Laboratory studies report that even Antarctic-adapted, endemic nematodes (the top predator in the Dry Valleys) cannot tolerate salinities in excess of 4.1 dS/m, but that some *Scottnema lindsayae* nematodes are able to tolerate ~2 dS/m solutions, and some *Eudorylaimus antarcticus* nematodes are able to survive in 1 dS/m solutions (Nkem et al., 2006). These laboratory studies have been verified by field observations in Taylor Valley showing species-dependent and asymptotic reduction in live nematodes as soils exceed salinities of 1 or 2 dS/m (Poage et al., 2008). These data suggest that saline portions of some water tracks may not be suitable habitats for some nematodes, and they may act as barriers to nematode colonization (Fig. 12). In addition, new water tracks may wick saline water (2–4 dS/m) into established nematode communities, with potentially lethal consequences.

Soil moisture has a more complicated effect on soil ecology. High soil moisture (up to 16% by mass or 29% by volume, assuming average Taylor Valley bulk densities) is strongly correlated with *E. antarcticus* presence; however, *S. lindsayae* is most commonly found in drier soils (<6% by mass, or 11% by volume) (Virginia and Wall, 1999). These data suggest that water track location may strongly influence nematode species distribution at the hillslope scale, as (low salinity) water track soils may be suitable for *E. antarcticus*, while off-track soils are more suitable for *S. lindsayae* (see geochemistry section).

Water tracks have had a systematic effect on some of the long-term manipulation experiments conducted in Taylor Valley (designed to test the response of soil ecosystems to changing environmental conditions; Freckman and Virginia, 1997; Virginia and Wall, 1999). The Lake Hoare long-term manipulation experiments conducted by the MCM-LTER are not affected by water tracks. They are located on topographic highs between water tracks (Fig. 13). Any meltwater accumulating at the ice table in these experimental sites is likely to drain downslope, providing contributions to larger, more established water tracks. In contrast, the Lake Bonney long-term manipulation experiment is located in the water track associated with the Wormherder Creek seep (Harris et al., 2007; Lyons et al., 2005). Monitoring at this site is currently assessing the response of soil ecosystems to the emergence of a water track.

CONCLUSIONS

Water tracks are a spatially extensive water transport pathway in the McMurdo Dry Valleys that can move meltwater derived from snow and ground-ice sources through active-layer soils, and ultimately to Dry Valleys lakes. In this manner, water tracks represent a significant source of hydrological, chemical, and ecological connectivity between Dry Valleys soils and lakes. Water tracks are the primary conduits of flow in this cryptic, shallow, groundwater system.

First, water tracks are a source of salts to McMurdo Dry Valleys lake and soil ecosystems. Water tracks transport atmospherically deposited and rock-weathering–derived solutes to lake water columns in a quantity comparable to, and potentially exceeding, stream inputs. Water track solute transport rates exceed non-water-track soil transport rates by two orders of magnitude, suggesting that water tracks are a "solute superhighway" through Taylor Valley soils.

Second, some water track fluids interfinger with stream water, producing the potential for complex lake chemistry with depth. The densest water track fluids are predicted to sink to the bottom of Lake Hoare, suggesting a new possible explanation for the source of Lake Hoare bottom waters. Water track fluids appear to

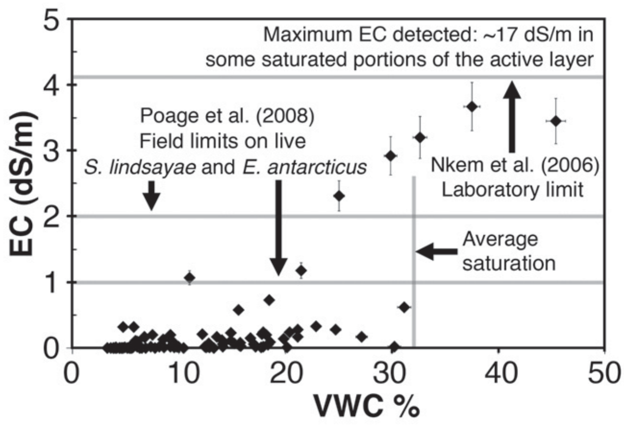

Figure 12. Water track solution electrical conductivity (EC) versus soil volumetric water content (VWC). Some water track soils may be inhospitable environments for nematodes, including *Scottnema lindsayae and Eudorylaimus antarcticus,* due to high salinity and/or high soil moisture.

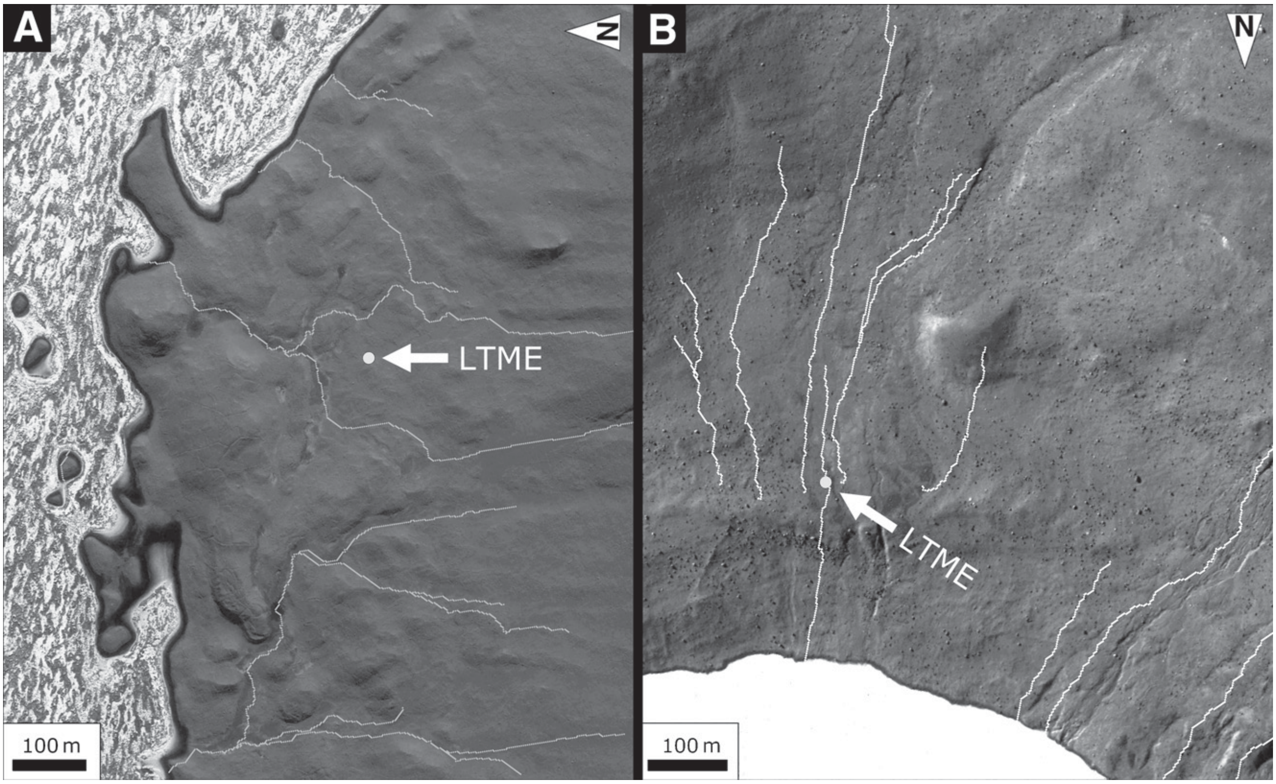

Figure 13. (A) Location of the Lake Hoare McMurdo Dry Valleys Long-Term Ecological Research project (MCM-LTER) long-term manipulation experiment (LTME) relative to water tracks (dark soil) and digital elevation model overlay showing pixels with >0.04 km^2 upslope accumulation area. The LTME is isolated from water track influence. (B) Location of the Lake Bonney LTME relative to a water track associated with Wormherder Creek. The Bonney LTME is seasonally inundated by the water track. Portion of *Quickbird* images 09FEB01213752 and 09DEC25204653.

interfinger at all depths in the Lake Hoare water column, including the base, but they are not likely candidates for the sources of the brines at the bases of Lakes Bonney and Fryxell.

Third, seeps identified in Taylor Valley, and across the Dry Valleys, represent locations where the saturated thickness of a water track is greater than the depth to the ice-cement table, producing a localized discharge of active-layer water. Accordingly, seeps are an emergent phenomenon associated with water track activity.

Fourth, when taken together, Dry Valleys streams, seeps, and water tracks represent a morphological continuum between a high-flow regime (producing overland flow in streams) and a low-flow regime (where only shallow active-layer flow occurs through water tracks). These results highlight the intense degree of connectivity among the cryosphere, hydrosphere, atmosphere, and biosphere in the McMurdo Dry Valleys.

Finally, water tracks are a permafrost landform that structures ecosystems in the Antarctic cold desert. Water tracks are an important source of moisture to soil ecosystems and produce patchy expanses of soil that are both suitable (because of locally elevated soil moisture content), and, in cases, nonsuitable (because of high salinities) for nematode-dominated ecosystems.

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REFERENCES CITED

Alger, A.S., McKnight, D.M., Spaulding, S.A., Tate, C.M., Shupe, G.H., Welch, K.A., Edwards, R., Andrews, E.D., and House, H.R., 1997, Ecological processes in a cold desert ecosystem: The abundance and species distribution of algal mats in glacial meltwater streams in Taylor Valley, Antarctica: Institute of Arctic and Alpine Research Occasional Papers, v. 51, p. 1–118.

Arblaster, J.M., and Meehl, G.A., 2006, Contributions of external forcings to southern annual mode trends: Journal of Climate, v. 19, p. 2896–2905, doi:10.1175/JCLI3774.1.

Barrett, J.E., Virginia, R.A., Wall, D.H., Parsons, A.N., Powers, L.E., and Burkins, M.B., 2004, Variation in biogeochemistry and soil biodiversity across spatial scales in a polar desert ecosystem: Ecology, v. 85, no. 11, p. 3105–3118, doi:10.1890/03-0213.

Barrett, J.E., Gooseff, M.N., and Takasc-Vesbach, C., 2009, Spatial variation in soil active-layer geochemistry across hydrologic margins in polar desert ecosystems: Hydrology and Earth System Sciences, v. 13, no. 12, p. 2349–2358, doi:10.5194/hess-13-2349-2009.

Baver, L.D., Gardiner, W.H., and Gardiner, W.R., 1972, Soil Physics: New York, New York, Wiley, 498 p.

Bockheim, J.G., Campbell, I.B., and McLeod, M., 2007, Permafrost distribution and active-layer depths in the McMurdo Dry Valleys, Antarctica: Permafrost and Periglacial Processes, v. 18, p. 217–227, doi:10.1002/ppp.588.

Bockheim, J.G., Prentice, M.L., and McLeod, M., 2008, Distribution of glacial deposits, soils, and permafrost in Taylor Valley, Antarctica: Arctic, Antarctic, and Alpine Research, v. 40, no. 2, p. 279–286, doi:10.1657/1523-0430(06-057)[BOCKHEIM]2.0.CO;2.

Campbell, G.S., 1977, An Introduction to Environmental Biophysics: New York, Springer-Verlag, 286 p.

Campbell, I.B., 2003, Soil characteristics at a long-term ecological research site in Taylor Valley, Antarctica: Australian Journal of Soil Research, v. 41, p. 351–364, doi:10.1071/SR02112.

Campbell, I.B., Claridge, G.G.C., Balks, M.R., and Campbell, D.I., 1997, Moisture content in soils of the McMurdo Sound and Dry Valley region of Antarctica, *in* Lyons, W.B., Howard-Williams, C., and Hawes, I., eds., Ecosystem Processes in Antarctic Ice-Free Landscapes: Rotterdam, Netherlands, A.A. Balkema, p. 61–76.

Cartwright, K., and Harris, H.J.H., 1981, Hydrogeology of the dry valley region, Antarctica, *in* McGinnis, L.D., ed., Dry Valley Drilling Project: Washington, D.C., American Geophysical Union, p. 193–214.

Chapman, W. L., and Walsh, J. E., 2007, A synthesis of Antarctic temperatures: Journal of Climate, v. 20, p. 4096–4117.

Chinn, T.J., 1993, Physical hydrology of the Dry Valleys lakes, *in* Green, W.J., and Friedman, E.I., eds., Physical and Biogeochemical Processes in Antarctic Lakes: Waco, Texas, American Society of Limnology and Oceanography, p. 1–51.

Claridge, G.G.C., Campbell, I.B., and Balks, M.R., 1997, Ionic migration in soils of the Dry Valley region, *in* Lyons, W.B., Howard-Williams, C., and Hawes, I., eds., Ecosystem Processes in Antarctic Ice-Free Landscapes: Rotterdam, Netherlands, A.A. Balkema, p. 137–143.

Clow, G.D., McKay, C.P., Simmons, G.M., Jr., and Wharton, R.A., Jr., 1988, Climatological observations and predicted sublimation rates at Lake Hoare, Antarctica: Journal of Climatology, v. 1, p. 715–728, doi:10.1175/1520-0442(1988)001<0715:COAPSR>2.0.CO;2.

Conovitz, P.A., McKnight, D.M., MacDonald, L.H., Fountain, A.G., and House, H.R., 1998, Hydrologic processes influencing streamflow variation in Fryxell Basin, Antarctica, *in* Priscu, J.C., ed., Ecosystem Dynamics in a Polar Desert: The McMurdo Dry Valleys, Antarctica: Washington, D.C., American Geophysical Union, p. 93–108.

Courtright, E.M., Wall, D.H., and Virginia, R.A., 2001, Determining habitat suitability for soil invertebrates in an extreme environment: The McMurdo Dry Valleys, Antarctica: Antarctic Science, v. 13, p. 9–17, doi:10.1017/S0954102001000037.

Craig, D., 1961, Isotopic variations in meteoritic waters: Science, v. 133, p. 1702–1703, doi:10.1126/science.133.3465.1702.

Decker, E.R., and Bucher, G.J., 1980, Geothermal studies in Antarctica: Antarctic Journal of the United States, v. 12, no. 1–2, p. 102–104.

Dickinson, W.W., and Rosen, M.R., 2003, Antarctic permafrost: An analogue for water and diagenetic minerals on Mars: Geology, v. 31, no. 3, p. 199–202, doi:10.1130/0091-7613(2003)031<0199:APAAFW>2.0.CO;2.

Doran, P.T., Wharton, R., and Lyons, W.B., 1994, Paleolimnology of the McMurdo Dry Valleys: Journal of Paleolimnology, v. 10, no. 2, p. 85–114, doi:10.1007/BF00682507.

Doran, P.T., Berger, G.W., Lyons, W.B., Wharton, R.A., Davisson, M.L., Southon, J., and Dibb, J.E., 1999, Dating Quaternary lacustrine sediments in the McMurdo Dry Valleys, Antarctica: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 147, p. 223–239, doi:10.1016/S0031-0182(98)00159-X.

Doran, P.T., McKay, C.P., Clow, G.D., Dana, G.L., Fountain, A.G., Nylen, T., and Lyons, W.B., 2002a, Valley floor climate observations from the McMurdo Dry Valleys, Antarctica, 1986–2000: Journal of Geophysical Research, v. 107, no. D24, doi:10.1029/2001JD002045.

Doran, P.T., Priscu, J.C., Lyons, W.B., Walsh, J.E., Fountain, A.G., McKnight, D.M., Moorhead, D.L., Virginia, R.A., Wall, D.H., Clow, G.D., Fritsen, C.H., McKay, C.P., and Parsons, A.N., 2002b, Antarctic climate cooling and terrestrial ecosystem response: Nature, v. 415, p. 517–520, doi:10.1038/nature710.

Doran, P.T., McKay, C.P., Fountain, A.G., Nylen, T., McKnight, D.M., Jaros, C., and Barrett, J.E., 2008, Hydrologic response to extreme warm and cold summers in the McMurdo Dry Valleys, East Antarctica: Antarctic Science, v. 20, doi:10.1017/S0954102008001272.

Fofonoff, N.P., 1985, Physical properties of seawater: A new salinity scale and equation of state of seawater: Journal of Geophysical Research, v. 90, no. C2, p. 3332–3342, doi:10.1029/JC090iC02p03332.

Fountain, A.G., Lyons, W.B., Burkins, M.B., Dana, G.L., Doran, P.T., Lewis, K.J., McKnight, D.M., Moorhead, D.L., Parsons, A.N., Priscu, J.C., Wall, D.H., Wharton, R.A., and Virginia, R.A., 1999, Physical controls on the Taylor Valley ecosystem, Antarctica: Bioscience, v. 49, no. 12, p. 961–971, doi:10.2307/1313730.

Fountain, A.G., Nylen, T.H., Monaghan, A., Basagic, H.J., and Bromwich, D., 2009, Snow in the McMurdo Dry Valleys, Antarctica: International Journal of Climatology, v. 30, p. 633–642.

Freckman, D.W., and Virginia, R.A., 1997, Low-diversity Antarctic soil nematode communities: Distribution and response to disturbance: Ecology, v. 78, no. 2, p. 363–369, doi:10.1890/0012-9658(1997)078[0363:LDASNC]2.0.CO;2.

French, H.M., 2007, The Periglacial Environment: West Sussex, UK, John Wiley and Sons, Ltd., 458 p.

Ghysels, G., and Heyse, I., 2006, Composite-wedge pseudomorphs in Flanders, Belgium: Permafrost and Periglacial Processes, v. 17, p. 145–161, doi:10.1002/ppp.552.

Gooseff, M.N., McKnight, D.M., Lyons, W.B., and Blum, A.E., 2002, Weathering reactions and hyporheic exchange controls on stream water chemistry in a glacial meltwater stream in the McMurdo Dry Valleys: Water Resources Research, v. 38, no. 12, doi:10.1029/2001WR000834.

Gooseff, M.N., Barrett, J.E., Doran, P.T., Fountain, A.G., Lyons, W.B., Parsons, A.N., Porazinska, D.L., Virginia, R.A., and Wall, D.H., 2003a, Snow-patch influence on soil biogeochemical processes and invertebrate distribution in the McMurdo Dry Valleys, Antarctica: Arctic, Antarctic, and Alpine Research, v. 35, no. 1, p. 91–99, doi:10.1657/1523-0430(2003)035[0091:SPIOSB]2.0.CO;2.

Gooseff, M.N., McKnight, D.M., Runkel, R.L., and Vaughn, B.H., 2003b, Determining long time-scale hyporheic zone flow paths in Antarctic streams: Hydrological Processes, v. 17, p. 1691–1710, doi:10.1002/hyp.1210.

Gooseff, M.N., Lyons, W.B., McKnight, D.M., Vaughn, B.H., Fountain, A.F., and Dowling, C., 2006, A stable isotopic investigation of a polar desert hydrologic system, McMurdo Dry Valleys, Antarctica: Arctic, Antarctic, and Alpine Research, v. 38, no. 1, p. 60–71, doi:10.1657/1523-0430(2006)038[0060:ASIIOA]2.0.CO;2.

Gooseff, M.N., Northcott, M.L., Barrett, J.E., Bate, D.B., Hill, K.R., Zeglin, L.H., Bobb, M., and Takacs-Vesbach, C., 2007, Controls on soil water dynamics in near-shore lake environments in an Antarctic polar desert: Vadose Zone Journal, v. 6, p. 841–848, doi:10.2136/vzj2006.0161.

Green, W.J., Angle, M.P., and Chave, K.E., 1988, The geochemistry of Antarctic streams and their role in the evolution of four lakes of the McMurdo Dry Valleys: Geochimica et Cosmochimica Acta, v. 52, p. 1265–1274, doi:10.1016/0016-7037(88)90280-3.

Gremillion, P., and Wanielista, M., 2000, Effects of evaporative enrichment on the stable isotope hydrology of a central Florida (USA) river: Hydrological Processes, v. 14, no. 8, p. 1465–1484

Hagedorn, B., Sletten, R.S., and Hallet, B., 2007, Sublimation and ice condensation in hyperarid soils: Modeling results using field data from Victoria Valley, Antarctica: Journal of Geophysical Research, v. 112, doi:10.1029/2006JF000580.

Harris, K.J., Carey, A.E., Lyons, W.B., Welch, K.A., and Fountain, A.G., 2007, Solute and isotope geochemistry of subsurface ice melt seeps in Taylor Valley, Antarctica: Geological Society of America Bulletin, v. 119, no. 5–6, p. 548–555, doi:10.1130/B25913.1.

Hastings, S.J., Luchessa, S.A., Oechel, W.C., and Tenhunen, J.D., 1989, Standing biomass and production in water drainages of the foothills of the Philip Smith Mountains, Alaska: Holarctic Ecology, v. 12, p. 304–311.

Head, J.W., III., Marchant, D.R., Dickson, J.L., Levy, J.S., and Morgan, G.A., 2007, Slope streaks in the Antarctic Dry Valleys: Candidate formation mechanisms, and implications for slope streak formation in the Martian environment, *in* Cooper, A.K., Barrett, P., Stagg, H., Storey, B., Stump, E., Wise, W., and the 10th International Symposium on Antarctic Earth Sciences (ISAES) Editorial Team, 10th International Symposium on Antarctic Earth Sciences, Santa Barbara, California, Extended Abstract 177: Washington, D.C., The National Academies Press.

Hunt, H.W., Fountain, A.G., Doran, P.T., and Basagic, H., 2010, A dynamic physical model for soil temperature and water in Taylor Valley, Antarctica: Antarctic Science, v. 22, p. 419–434, doi:10.1017/S0954102010000234.

Ikard, S.J., Gooseff, M.N., Barrett, J.E., and Takasc-Vesbach, C., 2009, Thermal characterisation of active layer across a soil moisture gradient in the McMurdo Dry Valleys, Antarctica: Permafrost and Periglacial Processes, v. 20, p. 27–39, doi:10.1002/ppp.634.

Kennedy, A.D., 1993, Water as a limiting factor in the Antarctic terrestrial environment: A biological synthesis: Arctic, Antarctic, and Alpine Research, v. 25, no. 4, p. 308–315, doi:10.2307/1551914.

Kleinberg, R.L., and Griffin, D.D., 2005, NMR measurements of permafrost: Unfrozen water assay, pore-scale distribution of ice, and hydraulic permeability of sediments: Cold Regions Science and Technology, v. 42, no. 1, p. 63–77, doi:10.1016/j.coldregions.2004.12.002.

Leffingwell, E. de K., 1915, Ground-ice wedges: The dominant form of ground-ice on the north coast of Alaska: The Journal of Geology, v. 23, p. 635–654, doi:10.1086/622281.

Levy, J.S., Head, J.W., and Marchant, D.R., 2008, The role of thermal contraction crack polygons in cold-desert fluvial systems: Antarctic Science, v. 20, doi:10.1017/S0954102008001375.

Liu, W., Baret, F., Gu, X., Tong, X., Zheng, L., and Zhang, B., 2002, Relating soil surface moisture to reflectance: Remote Sensing of Environment, v. 81, p. 238–246, doi:10.1016/S0034-4257(01)00347-9.

Lyons, W.B., and Mayewski, P.A., 1993, The geochemical evolution of terrestrial waters in the Antarctic: The role of rock-water interactions, *in* Green, W.J., and Friedman, E.I., eds., Physical and Biogeochemical Processes in Antarctic Lakes, Volume 59: Washington, D.C., American Geophysical Union, p. 135–143.

Lyons, W.B., and Welch, K.A., 1997, Lithium in waters of a polar desert: Geochimica et Cosmochimica Acta, v. 61, p. 4309–4319, doi:10.1016/S0016-7037(97)00203-2.

Lyons, W.B., Welch, K.A., Tyler, S.W., and Sharma, P., 1996, McMurdo Dry Valleys LTER: Density-driven mixing in Lake Hoare: Antarctic Journal of the United States, v. 31, no. 2, p. 205.

Lyons, W.B., Welch, K.A., Neumann, K., Toxey, J.K., McArthur, R., Williams, C., McKnight, D.M., and Moorhead, D., 1998a, Geochemical linkages among glaciers, streams and lakes within Taylor Valley, Antarctica, *in* Priscu, J.C., ed., Ecosystem Processes in a Polar Desert: The McMurdo Dry Valleys, Antarctica, Volume 72: Washington, D.C., American Geophysical Union, p. 77–92.

Lyons, W.B., Welch, K.A., Nezat, C.A., McKnight, D.M., Crick, K., Toxey, J.K., and Mastine, J.A., 1998b, Chemical weathering rates and reactions in the Lake Fryxell basin, Taylor Valley: Comparison to temperate river basins, *in* Lyons, W.B., Howard-Williams, C., and Hawes, I., eds., Ecosystem Processes in Antarctic Ice-Free Landscapes: Rotterdam, Netherlands, A.A. Balkema, p. 147–154.

Lyons, W.B., Fountain, A.G., Doran, P.T., Priscu, J.C., Neumann, K., and Welch, K.A., 2000, Importance of landscape position and legacy: The evolution of the lakes in Taylor Valley, Antarctica: Freshwater Biology, v. 43, p. 355–367, doi:10.1046/j.1365-2427.2000.00513.x.

Lyons, W.B., Welch, K.A., Fountain, A.G., Dana, G.L., Vaughn, B.H., and McKnight, D.M., 2003, Surface glaciochemistry of Taylor Valley, southern Victoria Land, Antarctica, and its relationship to stream chemistry: Hydrological Processes, v. 17, p. 115–130, doi:10.1002/hyp.1205.

Lyons, W.B., Welch, K.A., Carey, A.E., Wall, D.H., Virginia, R.A., Fountain, A.G., Doran, P.T., Csatho, B.M., and

Tremper, C.M., 2005, Groundwater seeps in Taylor Valley, Antarctica: An example of a subsurface melt event: Annals of Glaciology, v. 40, no. 1, p. 200–207, doi:10.3189/172756405781813609.

Mandelbrot, B.B., 1982, The Fractal Geometry of Nature: New York, New York, Freeman, 468 p.

Marchant, D.R., and Head, J.W., 2007, Antarctic Dry Valleys: Microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars: Icarus, v. 192, no. 1, p. 187–222, doi:10.1016/j.icarus.2007.06.018.

Matsubaya, O., Sakai, H., Toril, T., Burton, H., and Kerry, K., 1979, Antarctic saline lakes—Stable isotopic ratios, chemical compositions, and evolution: Geochimica et Cosmochimica Acta, v. 43, p. 7–25, doi:10.1016/0016-7037(79)90042-5.

McEwen, A., Ojha, L., Dundas, C., Mattson, S., Byrne, S., Wray, J., Cull, S., and Murchie, S., 2011, Transient slope lineae: Evidence for summertime briny flows on Mars?: Houston, Texas, Lunar and Planetary Institute, Lunar and Planetary Science Conference XLII, abstract 2314.

McGinnis, L.D., and Jensen, T.E., 1971, Permafrost-hydrogeologic regimen in two ice-free valleys, Antarctica, from electrical depth sounding: Quaternary Research, v. 1, p. 389–409, doi:10.1016/0033-5894(71)90073-1.

McKay, C.P., Mellon, M.T., and Friedman, E.I., 1998, Soil temperatures and stability of ice-cemented ground in the McMurdo Dry Valleys, Antarctica: Antarctic Science, v. 10, p. 31–38, doi:10.1017/S0954102098000054.

McKnight, D.M., Niyogi, D.K., Alger, A.S., Bomblies, A., Conovitz, P.A., and Tate, C.M., 1999, Dry Valley streams in Antarctica: Ecosystems waiting for water: Bioscience, v. 49, no. 12, p. 985–995, doi:10.2307/1313732.

McNamara, J.P., Kane, D.L., and Hinzman, L.D., 1999, An analysis of an Arctic channel network using a digital elevation model: Geomorphology, v. 29, p. 339–353, doi:10.1016/S0169-555X(99)00017-3.

Morgan, G.A., 2009, Cold-Climate (Periglacial) Landforms on the Earth and Mars; Geomorphic Evidence for Ice-Related Flow and Conditions for the Generation of Meltwater [Ph.D.]: Providence, Rhode Island, Brown University, 348 p.

Murton, J.B., 1996, Morphology and paleoenvironmental significance of Quaternary sand veins, sand wedges, and composite wedges, Tuktoyaktuk coastlands, western Arctic Canada: Journal of Sedimentary Research, v. 66, no. 1, p. 17–25.

Mushkin, A., Gillespie, A.R., Montgomery, D.R., Schreiber, B.C., and Arvidson, R.E., 2010, Spectral constraints on the composition of low-albedo slope streaks in the Olympus Mons Aureole: Geophysical Research Letters, v. 37, doi:10.1029/2010GL044535.

Nezat, C.A., Lyons, W.B., and Welch, K.A., 2001, Chemical weathering in streams of a polar desert (Taylor Valley, Antarctica): Geological Society of America Bulletin, v. 113, p. 1401–1408, doi:10.1130/0016-7606(2001)113<1401:CWISOA>2.0.CO;2.

Nkem, J.N., Virginia, R.A., Barrett, J.E., Wall, D.H., and Li, G., 2006, Salt tolerance and survival thresholds for two species of Antarctic nematodes: Polar Biology, v. 29, p. 643–651, doi:10.1007/s00300-005-0101-6.

Pewe, T.L., 1959, Sand-wedge polygons (tessellations) in the McMurdo Sound region, Antarctica—A progress report: American Journal of Science, v. 257, p. 545–552, doi:10.2475/ajs.257.8.545.

Poage, M.A., Barrett, J.E., Virginia, R.A., and Wall, D.H., 2008, The influence of soil geochemistry on nematode distribution, McMurdo Dry Valleys, Antarctica: Arctic, Antarctic, and Alpine Research, v. 40, no. 1, p. 119–128, doi:10.1657/1523-0430(06-051)[POAGE]2.0.CO;2.

Prentice, M.L., Arcone, S.A., Curren, M.G., Delaney, A.J., Horsman, J., Letsinger, S.L., Medley, E.A., and Gaynor, J.R., 2008, Stratigraphy and geomorphology of late Pleistocene moraine at the mouth of Taylor Valley, Antarctica: Implications for the melting history of the West Antarctic Ice Sheet during the Last Deglaciation: San Francisco, California, American Geophysical Union, Fall Meeting, abstract C31C–0504.

Pringle, D.J., Dickinson, W.W., Trodahl, H.J., and Pyne, A.R., 2003, Depth and seasonal variation in thermal properties of Antarctic Dry Valleys permafrost from temperature time series analysis: Journal of Geophysical Research, v. 108, no. B10, doi:10.1029/2002JB002364.

Priscu, J.C., 1998, Ecosystem Dynamics in a Polar Desert: The McMurdo Dry Valleys, Antarctica: Washington, D.C., American Geophysical Union, Antarctic Research Series, 369 p.

Putkonen, J., Rosales, M., Turpen, N., Morgan, D., Balco, G., and Donaldson, M., 2007, Regolith transport in the Dry Valleys of Antarctica, *in* Cooper, A.K., and Raymond, C.R., eds., Antarctica: A Keystone in a Changing World: Washington, D.C., U.S. Geological Survey, doi:10.3133/of2007-1047.srp3103.

Schenk, T., Csatho, B.M., Ahn, Y., Yoon, T., Shin, W.S., and Huh, K.I., 2004, DEM generation from the Antarctic LiDAR data: Site report, http://usarc.usgs.gov/lidar/lidar_pdfs/Site_reports_v5.pdf (September 2010).

Shindell, D.T., and Schmidt, G.A., 2004, Southern Hemisphere climate response to ozone changes and greenhouse gas increases: Geophysical Research Letters, v. 31, doi:10.1029/2004GL020724.

Starinsky, A., and Katz, A., 2003, The formation of natural cryogenic brines: Geochimica et Cosmochimica Acta, v. 67, no. 8, p. 1475–1484, doi:10.1016/S0016-7037(02)01295-4.

Stieglitz, M., Shaman, J., McNamara, J., Engel, V., Shanley, J., and Kling, G.W., 2003, An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport: Global Biogeochemical Cycles, v. 17, no. 4, doi:10.1029/2003GB002041.

Virginia, R.A., and Wall, D.H., 1999, How soils structure communities in the Antarctic Dry Valleys: Bioscience, v. 49, no. 12, p. 973–983, doi:10.2307/1313731.

Welch, K.A., Lyons, W.B., Graham, E., Neumann, K., Thomas, J.M., and Mikesell, D., 1996, Determination of major elements chemistry in terrestrial waters from Antarctica by ion chromatography: Journal of Chromatography, ser. A, v. 739, p. 257–263, doi:10.1016/0021-9673(96)00044-1.

Wilson, A.T., 1979, Geochemical problems of the Antarctic dry areas: Nature, v. 280, p. 205–208, doi:10.1038/280205a0.

Wilson, A.T., 1981, Geochemistry and lake physics of the Antarctic dry areas, *in* McGinnis, L.D., ed., Dry Valley Drilling Project: Washington, D.C., American Geophysical Union, p. 185–192.

Yershov, E.D., 1998, General Geocryology: Studies in Polar Research: Cambridge, UK, Cambridge University Press, 580 p.

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