Solute and isotope geochemistry of subsurface ice melt seeps in Taylor Valley, Antarctica

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ABSTRACT

The McMurdo Dry Valleys of Antarctica are a polar desert region with watersheds dominated by glacial melt. Recent ground exploration reveals unusual surface-flow-seep features not directly supplied by glacial melt. Much of this seep water is potentially derived from permafrost, snow patches, refrozen precipitation accumulated in the subsurface, buried glacier ice, or even groundwater from the deep subsurface. Flow features that lack obvious glacier melt sources were identified in archived aerial photographs of Taylor Valley. This valley was surveyed for extant and extinct seeps, and the locations of geomorphic features in five active seeps were documented. Water samples from seeps were analyzed for major ions and stable isotopes of hydrogen and oxygen. Solute chemistry and isotopic signatures of seeps are distinct from those of nearby streams and glaciers, with the seeps having elevated solute concentrations.

All but one seep had water isotopically heavier than water from nearby glaciers and streams, suggesting that seep waters have been substantially modified if they had been derived originally from the same meteoric sources that supply local glaciers and streams. The seeps are important because they compose a previously overlooked component of the desert hydrological cycle. Seep features in the dry valleys are potential terrestrial analogs for the geologically young gullies observed on Mars, which are thought to be evidence of groundwater seepage and surface runoff.

Keywords: Antarctica, groundwater, stable isotopes, dry valleys, ice, hydrology.

INTRODUCTION

The McMurdo Dry Valleys, located from 76°30′ to 78°30′S lat and 160° to 164°E long, compose the largest relatively ice-free region in Antarctica, with an approximate area of 4800 km^2. This condition exists because the Transantarctic Mountains dam the flow of the East Antarctic Ice Sheet. Moreover, glaciers do not form in the valley bottoms because the sublimation and melt of snow and ice exceed snow accumulation in all seasons (Fountain et al., 1999). Taylor Valley, in the middle of the McMurdo Dry Valleys region, is a landscape featuring a mosaic of glaciers, exposed soils and bedrock, ephemeral streams, and perennially ice-covered lakes (Fig. 1). The valley is oriented NE-SW and extends from the terminus of Taylor Glacier at the western end to the coast of the Ross Sea at the eastern end, a distance of ~35 km. Precipitation is negligible at <5 mm per year (water equivalent), and mean annual temperatures range from −16 °C to −20 °C (Doran et al., 2002).

Despite the harsh climatic conditions in Taylor Valley, the region is host to a polar desert ecosystem. Soils are characterized by extremely low invertebrate biodiversity, with life restricted by low moisture, cold temperatures, high salt concentrations, and low productivity (Courtright et al., 2001). Mosses and algal and cyanobacterial mats persist from summer to summer in ephemeral streams (McKnight et al., 1998). Lakes support a plankton community dominated by algae and bacteria, but with some protozoans and rotifers present (Priscu et al., 1999). Liquid water is the primary limiting condition for life in Antarctica (Kennedy, 1993). For this reason, processes that affect the formation and distribution of liquid water strongly influence biodiversity in Taylor Valley (Fountain et al., 1999). The hydrologic regime in Taylor Valley is based upon glacial melt. During the austral summer, streams are fed by liquid water from thawing glacier margins. Depending on summer temperatures, these streams flow for periods of 4–12 weeks. Streams discharge into closed basin lakes with 3–6-m-thick permanent ice covers, and the lakes lose water only through evaporation and sublimation (Fountain et al., 1999). Ice-cemented permafrost occurs in the upper 1 m of the Taylor Valley soil surface and extends downward to depths of several hundred meters (Bockheim, 2002; McGinnis and Jensen, 1971). At elevations generally below 300 m in the McMurdo Dry Valleys, the active layer is ~0.5–1 m, with the base of the active layer being the top of the permafrost (Campbell et al., 1998). Campbell et al. (1998) point out that the extent to which moisture is lost from, or accumulates within, the permafrost is unknown.

Since 1993 the McMurdo Dry Valleys have been the site of a Long Term Ecological Research (LTER) study. During an unseasonably warm austral summer in 2001–2002, an

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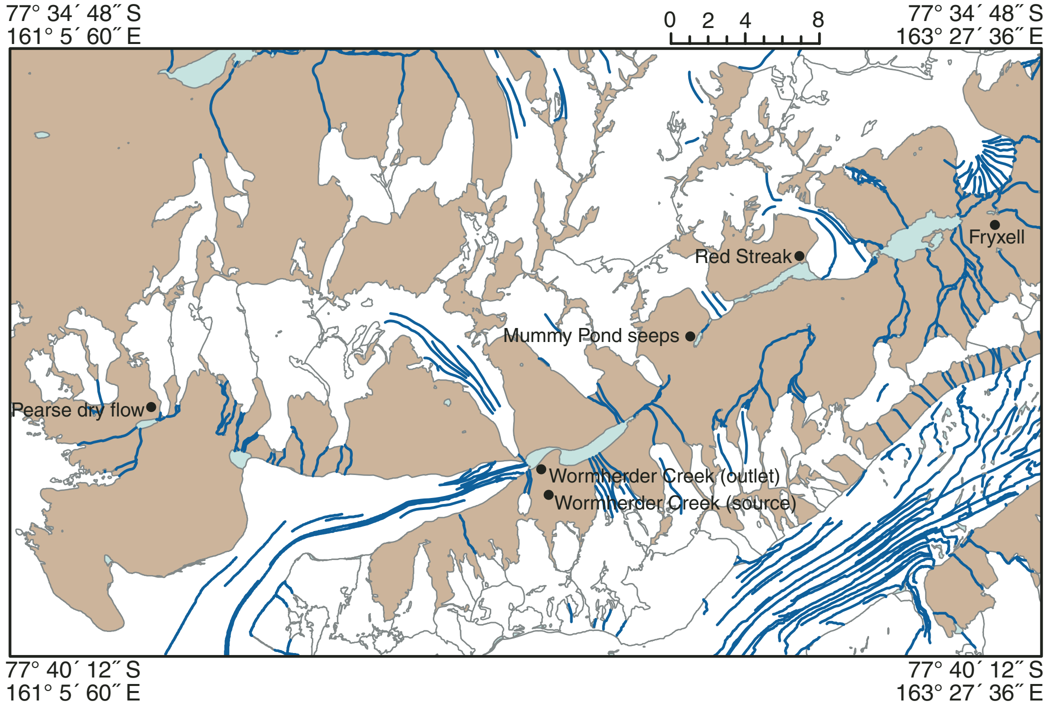

Figure 1. Map of relevant seep features in Taylor Valley, McMurdo Dry Valleys, Antarctica. Glaciers are depicted in white, exposed ground in brown, and ponds in blue.

ephemeral water seep, now named Wormherder Creek, was discovered in Taylor Valley, where flow had not been observed previously, although surface morphology suggested a relict stream channel (Csathó et al., 2005; Lyons et al., 2005). Without any obvious water source (e.g., snow patches, glacier), the seep water was attributed to the melting of subsurface ice. Although the present study revealed the meltwater source to be a large snow patch with subsurface flow paths (see below), this work drew attention to other unstudied wet spots commonly observed in the region.

Other hyperarid landscapes, including polar ones, show evidence of past and present subsurface water seepage. For example, in the Atacama Desert of northern Chile, large quebradas were produced as the climate dried out and groundwater sapping occurred (Hoke et al., 2004). On Axel Heiberg Island in the Canadian High Arctic (79°26′N), mineralized springs occur that are not associated with meteoric water recharge (Pollard et al., 1999). Thermal springs occur on Svalbard that are related to deep crustal faulting (Banks et al., 1998). However, these examples differ importantly from the McMurdo Dry Valleys seep occurrences either in their scale or their probable sources. The Chilean seeps are very large-scale features of the landscape, whereas the Axel Heiberg seeps are likely related to deep groundwater flow that may be derived from relict seawater input.

The goals of our work were to (1) inventory seep features in Taylor Valley, Antarctica, using aerial photographs and ground-based surveys; (2) analyze seep water samples for major ions and δD and $\delta^{18}O$ isotopes to ascertain seep water origins; and (3) compare the seeps to similar Martian landforms.

HYDROGEOLOGIC BACKGROUND

The valley floors are covered with Quaternary glacial, alluvial, and lacustrine deposits. In Taylor Valley the glacial deposits have been produced by the inflow of the West Antarctic Ice Sheets during glacial periods and the advance and retreat of Taylor Glacier (the eastern extent of the East Antarctic Ice Sheet) and local alpine glaciers during interglacials (Hall and Denton, 2000; Hendy, 2000). The primary water source is glacier melt from the alpine glaciers that descend from the surrounding mountains (Fig. 1), because the snow (~5 cm water equivalent) typically sublimates before making a hydrologic contribution (Gooseff et al., 2003). Melt occurs from November to February (Fountain et al., 1998) and drains to permanent stream channels, which flow intermittently for ~10 weeks each summer (McKnight et al., 1998). The glacial melt and streamflow are highly variable on daily, seasonal, and interannual time scales (McKnight et al., 1999).

No evidence exists for significant groundwater flow in Taylor Valley, as permafrost at depths, often <40–50 cm, is continuous throughout the valley except along the coastal margin and under the lakes (McGinnis and Jensen, 1971; Bockheim, 2002). About 40% of the McMurdo Dry Valleys soils are without ice in the top 1 m, and the rest have ice within the top 10–50 cm (Bockheim, 2002). Campbell and Claridge (1982) noted that moisture movement in the soils was primarily in the form of vapor, but there was limited migration of snowmelt. Owing to the hyperaridity of the climate, the sublimation rates can be extremely high (Ng et al., 2005). Thus, the polar desert climate restricts groundwater flow, particularly shallow groundwater flow, because there is limited snowfall and minimal to nonexistent recharge.

Cartwright and Harris (1981) recognized that some shallow subsurface flow occurs in Taylor Valley and Wright Valley (to the north of Taylor Valley), which takes place at the base of the active layer at rarely more than 1 m deep. They speculated that one or a combination of the following agents recharged these shallow flow systems: surface water (e.g., glaciers and perennial snowfields), snowfall, ground ice (i.e., permafrost), and buried ice. They estimated that only 1% of the McMurdo Dry Valleys contain shallow-subsurface-flow environments, but on the basis of their examination of aerial photographs these features in Wright Valley were persistent. Since their work, no research has been undertaken to investigate these features.

Little research on the chemistry and isotopic composition of the permafrost and buried ice at lower elevations has been undertaken (Stuiver et al., 1981). There has been much more interest in ground ice above 1000 m in the McMurdo Dry Valleys owing to its potential use as a paleoclimate proxy (Sugden et al., 1995). Recently, a detailed description of the chemical composition of permafrost at these higher elevations in the Table Mountain region of the McMurdo Dry Valleys was published (Dickinson and Rosen, 2003). These data suggest that the waters sourcing this permafrost are not simply frozen meltwater runoff, because the chemistry is significantly different, with higher total dissolved solids (TDS) and enriched δD and $\delta^{18}O$ values. The $\delta^{18}O$ values of surficial permafrost on the lower elevation valley floors, such as Taylor Valley, suggest that the ground ice could have been derived from the freezing of local glacier meltwater (Stuiver et al., 1981).

MATERIALS AND METHODS

Photo Archive Search

We examined the archived aerial photographs of Taylor and Wright Valleys at the Antarctic Resources Center at the U.S. Geological Survey facility in Reston, Virginia (usarc.usgs.gov). Landscape flow features, such as dark areas of soil but lacking obvious glacial melt sources, were identified in photographs and located on topographic maps. Possible seep features were identified for years both warmer and colder than average. Additional potential seep features and ephemeral streams were identified on topographic maps.

Ground Survey

During the 2005 Antarctic summer field season, we walked the length of Taylor Valley to survey the extant and extinct seeps, with a focus on the regions of interest identified in the archived photo search. The global positioning system (GPS) location and geomorphic features of each seep were documented and photographed. No pH, temperature, or TDS data were measured in the field. Water samples from seeps were collected using precleaned polyethylene bottles, and within 24 h these water samples were filtered through 0.4 µm pore-size Nuclepore™ polycarbonate membrane filters using a bell jar and precleaned polyetherimide filter funnels, allowing filtration directly into sample bottles. Analysis of major ions by ion chromatography analytical measurements is described by Welch et al. (1996). The total error in anions and cations using these techniques is <4%. Seep water samples were collected in polyethylene bottles and returned to the Institute of Arctic and Alpine Research at the University of Colorado at Boulder for isotopic analysis of δD and $\delta^{18}O$. Oxygen isotopic values were determined using the technique of Epstein and Mayeda (1953), and hydrogen isotopic values were determined using the technique of Vaughn et al. (1998). Isotopic values are presented as per mil (‰) values relative to Vienna standard mean ocean water (VSMOW):

$$\delta^{18}O = \frac{\left({}^{18}O/{}^{16}O\right)_{\text{sample}} - \left({}^{18}O/{}^{16}O\right)_{\text{standard}}}{\left({}^{18}O/{}^{16}O\right)_{\text{standard}}} \times 1000‰$$

The precision of the δD measurements is ±1‰, and of the $\delta^{18}O$ measurements, ±0.1‰.

RESULTS

Photo Archive Search

Areas we identified as potential seeps were found in photographs of Taylor Valley taken in 1958, 1960, 1963, 1970, 1972, 1975, 1982, 1983, and 1999. The limited resolution of the photographs permitted identification only of large-scale features, such as Wormherder Creek, whose channel was seen on most archival photographs. Without exception, the dimensions of the seep-like candidates identified in the photos were far greater than those of the actual seeps discovered and sampled in Taylor Valley. The small scale of near-surface ice-melt features required ground exploration.

Field Survey for Seep Features

During the austral summer of January 2005 a field survey of Taylor Valley revealed five unusual flow features. In four of the five examples—seeps named Red Streak, West Mummy, East Mummy, and East Fryxell—water flowed directly out of the ground, with no nearby glaciers to supply the water. This suggested a subsurface origin of the waters. In the fifth example, Wormherder Creek, water was supplied by melt off a large deposit of snow. With the exception of Wormherder Creek (Lyons et al., 2005), none of these near-surface ice-melt seeps had been observed flowing before, although the seep channels appear to have been excavated by repeated sporadic flow events. Unfortunately, we were unable to estimate flows at any of the sites.

Red Streak

This slow-flowing seep consists of two branches, one that originated at the base of a small hill of piled rocks, and the other that oozed from the ground in front of a large boulder (Fig. DR1[1]). The ground was saturated with moisture within ~10 m of the flow. Rust-red algae covered the length of the seep to its outlet into the moat of Lake Hoare. The seep was fringed by green moss, and the seep water clearly supports life in a nutrient-poor region of Taylor Valley.

West Mummy

At this location, water flowed from the northwest slope of the valley adjacent to Mummy Pond (also known as Lake Henderson; Chinn, 1993) (Fig. DR2; see footnote 1). Two water samples were taken from this seep, one from the putative seep source, and the other from the outlet of the seep. The origin of this feature was carefully considered in the field, and, based on the lack of nearby snow patches or glaciers, the seep source appears to be subsurface melt. The seep disappears periodically beneath sandy, boulder-strewn terrain before flowing into the pond. No visible signs of life were observed in this seep.

East Mummy

This seep gently flowed from the northeast slope of the valley adjacent to Mummy Pond (Fig. DR3; see footnote 1). Actively flowing seep water disappeared upslope into a channel bed with a damp-looking sandy pavement of soil, rocks, and scattered boulders. As the seep passes beneath a snow patch, its flow velocity apparently increased and the water then flowed into Mummy Pond at an alluvial fan of fine-grained material and scattered rocks.

East Fryxell

This seep consisted of two distinct channels ~7 m apart that eventually merged. One channel was dry but covered in moss, and the other was wet and flowing. The seep was discovered on a cold, cloudy day, and a thin layer of ice covered the flowing water. However, mosses adjacent to the seep bed provided evidence of stronger, long-term water flow. Flow was toward the direction of Commonwealth Glacier. Seep water was apparently subsurface in origin, because no snow patches or glaciers nearby provided meltwater.

Wormherder Creek

Wormherder Creek (Fig. DR4; see footnote 1) was initially misinterpreted as a groundwater seep in aerial photographs of Taylor Valley (Lyons et al., 2005). From a distant perspective, the Wormherder channel morphology is misleading. Upslope, flow regularly dips beneath sections of talus, making the water appear to seep out of the ground. Instead, further investigation revealed the water source to be melt from a snow patch south of Lake Bonney. Although Wormherder

[1]GSA Data Repository item 2007115, photographs of Red Streak seep, West Mummy seep, East Mummy seep, Wormherder Creek, and Pearse dry flow and a table of major element molar ratios for seep samples and streams, is available on the Web at http://www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

TABLE 1. GEOGRAPHICAL COORDINATES AND ELEVATIONS FOR FEATURES SURVEYED AND SAMPLED IN TAYLOR VALLEY

Name	Feature	Coordinates	Elevation (m)
Red Streak	Seep	77°37′30.0″S, 162°53′19.2″E	134
West Mummy, source	Seep	77°39′44.1″S, 162°39′05.5″E	133
West Mummy, outlet	Seep	77°39′44.2″S, 162°39′04.9″E	120
East Mummy	Seep	77°39′36.4″S, 162°39′40.6″E	108
Fryxell	Seep	77°36′20.2″S, 163°19′54.8″E	50
Wormherder Creek, source	Snow-fed stream	77°44′23.1″S, 162°20′54.4″E	428
Wormherder Creek, outlet	Snow-fed stream	77°43′29.7″S, 162°18′46.0″E	120

was not a groundwater seep, the feature held considerable interest as an example of a climatically dependent water source in a polar desert, distinct from glacier-fed streams. Despite the ephemeral nature of this creek, light brown to green algal mats were found beneath a clear, thin ice veneer at elevations as high as ~400 m. The creek terminated in a small tongue of deposited sediment near the edge of the lake. There, the water percolated into porous soil, and there was no visible surface flow directly into the lake.

Pearse Valley Dry Flow Channel

Pearse Valley lies on the north side of Taylor Glacier at ~77°40′ S lat. Within this valley, Lake House, a frozen lake at 350 m elevation (Chinn, 1993), formed from glacier melt derived from Taylor Glacier as well as from a series of alpine glaciers draining from the Aasgard Range (Fig. 1). Although water was not running at the time of our observations, a channel ~2 m wide could easily be discerned, owing in part to the white salts that stain the channel bed (Fig. DR5; see footnote 1). At higher elevations the channel was aligned south to north but was aligned east to west near the bottom of the valley. The source of flow in this channel was thought to be an ice-cored moraine next to the beginning of the channel and north of the edge of Nylen Glacier (Fig. 1). The water flowed downslope, widening into a fanlike structure, presumably discharging into the lake. The locations of these seeps and channels are listed in Table 1.

Seep Geochemistry

In general, the seeps all had higher TDS and specific ion concentrations than nearby glacial-fed streams (Table 2). The exceptions to this are NO_3^- for Red Streak (in comparison with Andersen Creek), SO_4^{2-} for East Fryxell (in comparison with Von Guerard Stream), and Cl^-, K^+, and Mg^{2+} for Wormherder Creek (in comparison with Bartlette Creek). This is also supported by LTER records in which the average values for all streams in the Fryxell, Hoare, and East Bonney basins, over the period 1991–2000, are 305 µM, 102 µM, and 397 µM for Cl^-, and 264 µM, 203 µM, and 293 µM for Ca^{2+}, respectively. The mean TDS for the seeps is ~400 mg/L^{-1}, whereas the mean for the streams is ~70 mg/L^{-1}. The seep Cl^- values are tenfold greater than the stream mean, and the Ca^{2+} values are four- to sixfold greater than the streams (Table 2). These data indicate that the seep waters have undergone a different type or mode of landscape interaction than the stream waters. The residence time of water in the streams is relatively short, with little to no contact with previously unsaturated streambeds. Although the extent of hyporheic zone interactions in these Taylor Valley streams is different or more extensive than in most temperate streams (Runkel et al., 1998; Gooseff et al., 2002), because there is no overland flow or recharge, there is minimal contact with the unsaturated zone or active layer of the valley flow. Previous studies have demonstrated that when Taylor Valley soil interacts with liquid water, high concentrations of salts can be readily solubilized (Lyons and Welch, 1997) and that infrequently wet channels can produce water with higher TDS and different ion concentrations and ion ratios than streams that flow annually (Lyons et al., 2005). The δD and $\delta^{18}O$ data from the seeps and nearby streams are shown in Table 3. The seeps are both depleted and enriched in comparison with nearby glacier ice and glacier melt, depending upon their location in the valley.

DISCUSSION

During the ground survey of January 2005 we could only define the water source of Wormherder Creek and Pearse seep. The sources of the other seeps we observed were unknown, but we speculate that the sources are either snow or ice that has melted and then refrozen at depth, possibly through multiple seasons, and hence multiple freeze-thaw events or permafrost-buried ice melt. In the first scenario of freeze-thaw events, snow accumulates in a depression and eventually melts, becoming isotopically heavier through the preferential sublimation of light isotopes during direct atmospheric exposure. The melt percolates into

TABLE 2. MAJOR ION CONCENTRATIONS FOR SEEP SAMPLES AND CREEKS

Sample name	F µM L^{-1}	Cl^- µM L^{-1}	NO_3^- µM L^{-1}	SO_4^{2-} µM L^{-1}	Na^+ µM L^{-1}	K^+ µM L^{-1}	Mg^{2+} µM L^{-1}	Ca^{2+} µM L^{-1}	HCO_3^- µM L^{-1}	TDS mg L^{-1}
Red Streak seep	14	1280	7.1	460	1345	167	417	769	1663	270.2
Anderson Creek	4	170	9	111	192	33	46	214	339	53.4
West Mummy seep, source	18	5576	184	928	3826	266	1004	1606	1678	588.4
West Mummy seep, outlet	14	5088	199	913	3087	230	955	1741	1582	550.5
East Mummy seep	40	9056	339	1650	5357	488	1683	2561	1598	885.2
House stream	2	82	4	31	108	21	28	209	453	46.2
East Fryxell seep	24	1887	22	89	2374	192	374	656	2515	320.6
Von Guerard stream	6	257	0	69	445	74	92	467	1234	125.2
Wormherder Creek, source	24	398	59	174	504	61	107	396	742	112.7
Wormherder Creek, outlet	14	1254	127	555	796	113	284	1162	1296	261.3
Wormherder Creek, outlet (2002)	31	723	90	284	673	130	237	805	1475	207.7
Vincent Creek (1993–2003)	0	77	4	16	83	21	39	122	313	32.2
Bartlette Creek (1993–2003)	0	713	3	58	296	71	262	301	661	99.4
Blank	0	0	0	0	3	2	3	2	0	—

Note: All samples are from 2005 unless otherwise indicated. Streams are listed below the closest seep. All stream solute data are derived from austral summer average except where stated otherwise. TDS—total dissolved solids.

TABLE 3. STABLE ISOTOPE DATA FOR SEEPS AND NEARBY STREAMS, GLACIERS, AND PERMAFROST IN TAYLOR VALLEY

Sample	Mean δD (‰)	Mean $\delta^{18}O$ (‰)
Commonwealth Glacier	–225.9	–28.2 ± 2.4 (n = 30)
DVDP II permafrost (Stuiver et al., 1981)		–33
Fryxell seep	–243.5	–30.4
Von Guerard Stream	–222.1	–26.7
Canada Glacier	–251.4	–31.9 ± 3.3 (n = 45)
Anderson Creek	–236.1	–28.9
Red Streak seep	–247.7	–29.1
West Mummy seep, source	–228.7	–26.3
West Mummy seep, outlet	–230.4	–26.7
East Mummy seep	–190.9	–21.6
House Stream	–241.9	–30.4
Suess Glacier	–248.5	–31.4 ± 1.8 (n = 3)
Wormherder snowmelt, source	–189.1	–22.54
Wormherder snowmelt, outlet	–191.2	–21.7
Hughes Glacier	–244.2	–30.8 ± 1.5 (n = 4)
Vincent Creek	–236.7	–29.2
Bartlette Creek	–231.1	–28.6

Note: Features are listed in increasing distance from the coast. Glacier data are from Gooseff et al. (2006); stream data are from Long Term Ecological Research (LTER) Web site.

the soil and refreezes to become even more enriched in heavier isotopes through freeze fractionation. McKay et al. (1998) speculated that processes such as this occur in the dry valleys and act sporadically to supply water to the shallow subsurface. During warm austral summer months, this accumulated supply of subsurface ice melts and seeps to the surface, and could generate some of the liquid water we observed. It is not clear, however, whether this source alone could supply the amount of water observed, as loss by sublimation would be quite high (Clow et al., 1988; Lewis et al., 1998; Gooseff et al., 2003). How much melt could be recharged by this process is unknown. The Mummy Pond seeps and Red Streak originate on south-facing slopes, suggesting that enhanced radiation from direct austral summer sunlight may be important to their operation.

A plot of δD and Cl^- concentrations in the seep waters shows that, in general, the Cl^- concentrations increase as the δD becomes enriched (Fig. 2). We interpret this relationship as a strong evaporitic signal. The most enriched sample is the one from the East Mummy Pond seep. The source and outlet water in the West Mummy seep are nearly identical isotopically, but the sample farther from the source indicates that it has been evapoconcentrated, as its Cl^- concentration is higher and its δD is slightly more enriched than the source water (Table 3). The Wormherder snowmelt flows for nearly 1 km as it moves alternately over the surface and under poorly sorted morainal material. The West Mummy seep flows only tens of meters, and this length difference is reflected in the isotopic differences between source and outlet of these two seeps. The Wormherder Creek water is isotopically much more enriched than the other seep waters but has relatively low Cl^- concentrations (Fig. 2). In general, primary precipitation becomes more depleted as it moves away from the ocean in Taylor Valley, with the Hughes and Calkin glaciers, the two closest sources of this seep, having $\delta^{18}O$ values of –30 to –31‰ (Gooseff et al., 2006). Therefore, these enriched values for Wormherder Creek must signify that the snow-patch source of these waters has already been significantly affected by evaporation and sublimation. The most isotopically depleted values are associated with Red Streak and East Fryxell seeps. The Red Streak value is slightly more depleted than the modern precipitation accumulating in the glaciers (Gooseff et al., 2006). The $\delta^{18}O$ value for Commonwealth Glacier snow is –28.2 ± 2.4‰. The similar values for East Fryxell and the modern glacier ice might suggest that the source of this water is ice-cored morainal material. On a plot of δD versus $\delta^{18}O$, values for seeps plot distinctly to the right of the local meteoric water line for glaciers in Taylor Valley, as derived by Gooseff et al. (2006) (Fig. 3). Ground ice samples from below 1 m depth at higher elevations in the McMurdo Dry Valleys also plot to the right of the local meteoric water line (Dickinson and Rosen, 2003). Thus, both the seep waters and the deeper ground ice indicate extensive modifications if they originated from glacier melt. The seep samples have deuterium excess values between −0.3 and −18.0, with a mean of −13.5. This value is more negative than the glacier meltwater streams in Taylor Valley (Gooseff et al., 2006) but not so negative as much of the higher elevation ground ice (Dickinson and Rosen, 2003).

The higher TDS in the seep waters in comparison with the streams suggest that the source of the melt (i.e., refrozen precipitation and/or

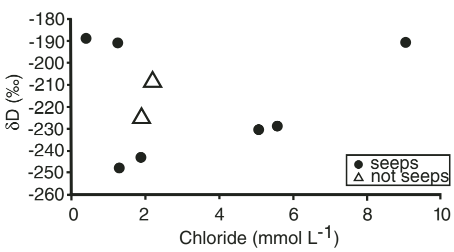

Figure 2. Plot of δD vs. chloride of Taylor Valley (TV) water samples. Seep samples are shown as circles. Triangles represent stream and lake samples.

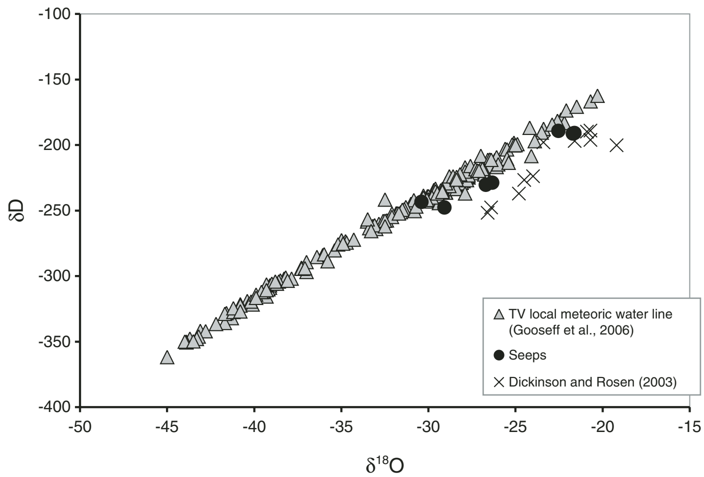

Figure 3. Plot of stable isotopes of water ($\delta^{18}O$ and δD) for Taylor Valley (TV) seeps, glaciers, and ground ice.

permafrost) had a higher solute concentration or that the solutes were added as the water flowed over the ground that had accumulated salts since the previous flow period. More than 30 different salts have been reported in McMurdo Dry Valleys soils (Keys and Williams, 1981; Campbell and Claridge, 1987). The 10 most widespread are thenardite, gypsum, halite, calcite, darapskite, soda niter, mirabilite, boedite, epsomite, and hexahydrite. Clearly, the dissolution of these salts by running water would potentially enrich the solution in Na^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-}, and HCO_3^-. The higher TDS and ion concentrations at the sources of the Mummy Pond seeps indicate that evapoconcentration is not the primary source of the salts at this location. Permafrost in the top few meters in Taylor Valley has low TDS (Stuiver et al., 1981), whereas permafrost at higher elevations (>1000 m) has TDS values as high as ~7 g/L^{-1} (Dickinson and Rosen, 2003). The McMurdo Dry Valleys landscape accumulates salt, especially in the higher elevation areas (Powers et al., 1998; Bao et al., 2000). The extremely high NO_3^- concentrations in most of the seeps suggest that the source of the solutes to these waters is from dissolution of soil salts, especially in higher elevations and/or locations farther inland where nitrate salts can accumulate to high levels (Keys and Williams, 1981). Wormherder Creek gains NO_3^- along its flow path (Table 2), but the gain is less relative to either Cl^- or SO_4^{2-}. This suggests that NO_3^- is lost through biological uptake along the seep flow path. This is clearly the case for Red Streak seep, as NO_3^- concentrations were very low, and actively photosynthesizing algal mats (based on observations of gas bubbles assumed to be O_2) were observed in the lowest reaches of this seep. The very high NO_3^- concentrations in the seeps make them an important, previously unrecognized pathway for the transport of fixed nitrogen

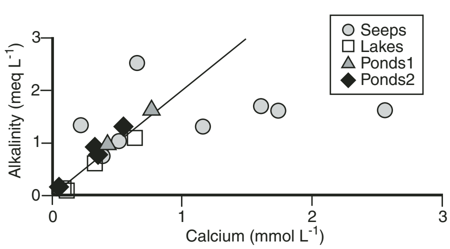

Figure 4. Plot of alkalinity versus calcium concentration in seeps (circles), lakes (squares), and ponds (triangles and diamonds). Pond 1 and pond 2 samples were collected from ponds in two different areas of the valley. The line represents a 2:1 alkalinity to Ca^{2+} ratio.

from higher to lower points in the landscape. Although the small number of seeps in Taylor Valley means that NO_3^- transport is probably quantitatively insignificant, in some places such as Mummy Pond it may be highly significant to the overall nitrogen budget of the pond.

The Mummy seeps have relatively low major ion:chloride ratios, especially for the cations, while the East Fryxell seep has a SO_4:Cl ratio close to that of seawater (Table DR1; see footnote 1). The shallow permafrost at higher elevations in the McMurdo Dry Valleys is enriched in SO_4^{2-} relative to Cl^- (Dickinson and Rosen, 2003), implying that melting permafrost alone is not the source of the salts. Frequent freeze-thaw cycles probably also exert an influence on the solute concentrations by excluding some ions, as evidenced by saline seep research in the Northern Great Plains of North America (Timpson and Richardson, 1986), where Na^+ is enriched relative to Ca^{2+} and Mg^{2+} in the winter. Solute fractionation from changes in relative humidity as one proceeds from snow accumulation regions to the valley floors has also been proposed for the differences in salt distribution in the McMurdo Dry Valleys (Wilson, 1979).

The low ratios in the Mummy seeps might indicate that they have more frequent flow, as observed in our initial investigations of the aerial photographs, and that the soils have been regularly flushed of their salts. Such flushing leads to a solute distribution resembling that of a marine aerosol, which is probably the primarily source of Na^+, Cl^-, and SO_4^{2-} to the eastern section of the McMurdo Dry Valleys (Keys and Williams, 1981). Calcium is greatly enriched relative to Cl^- in all the seep waters but not so much as in the glacier melt streams. The primary source of Ca^{2+} to the streams is the weathering of Ca-rich alumino-silicates in the hyporheic zones of the streams and the distribution of windblown $CaCO_3$ (Nezat et al., 2001; Gooseff et al., 2002; Fortner et al., 2005). The low Ca:Cl ratios in the seeps indicate that less chemical weathering occurs in these environments than in the streams.

Most lakes and ponds in Taylor Valley fall very close to the 1:2 line (Fig. 4), suggesting that $CaCO_3$ dissolution is the primary control of Ca^{2+} and alkalinity concentrations (i.e., $CaCO_3 + H_2CO_3 \Leftrightarrow Ca^{2+} + 2HCO_3^-$).With the possible exception of Red Streak and the West Mummy outlet, most seep water has a Ca^{2+} concentration greater than twice the HCO_3^- (Fig. 4). Four of the seeps have excess Ca^{2+} that must be derived either from Ca^{2+} salts other than $CaCO_3$ or from alumino-silicate weathering. One seep water (East Fryxell) has excess HCO_3^-. Previous work that others and we have done has demonstrated that surface waters in the Fryxell basin should evolve to become Na-HCO_3 waters, as alkalinities are greater than the Ca^{2+} concentrations (Green et al., 1988; Lyons et al., 1998). The source of the HCO_3^- must come from silicate mineral weathering, as noted by Lyons et al. (1998) for Fryxell basin streams.

Although some of these features were observable on aerial photographs dating from 1970 and earlier, some were not. Cartwright and Harris (1981) proposed four possible explanations for shallow-subsurface-flow features in the McMurdo Dry Valleys:

1. The progressive loss of surface soil by wind or other disturbance, thereby exposing permafrost to more ground-surface–like conditions;
2. Local snow accumulation anomalies not apparent in the austral summer;
3. Obscure connections between these flow systems and more traditional surface sources of melt (e.g., glaciers);
4. Changes in climate, causing recent subsurface permafrost and buried ice to melt.

We can attempt to evaluate these explanations on the basis of our more extensive knowledge about the McMurdo Dry Valleys region gained over the past 25 yr since Cartwright and Harris' seminal work. The erosion of soil can be related to eolian transport within the McMurdo Dry Valleys. The eolian flux within the dry valleys area, especially the flux of silt- and clay-sized particles, is 1–3 orders of magnitude less than in most other desert regions of the world (Lancaster, 2002). The flux also decreases with elevation, with values ≤0.5 g m^{-2} yr^{-1} of fine-grained material (Lancaster, 2002). These very low eolian fluxes suggest to us that progressive soil loss, especially in the intermediate elevations within the valley where most seeps occur, is not a likely explanation of the seeps' occurrences.

Although we cannot a priori rule out the possibility of local snow accumulation anomalies as a cause of seep development, it seems unlikely that direct snow accumulation is the source of the seeps. We have walked the length of these seeps and only at Wormherder Creek did we observe a reservoir of snow at the source. The measurement of snowfall in this region is extremely difficult, and even after 12 yr of LTER and >45 yr of research in the McMurdo Dry Valleys region, only snowfall estimates exist. Our best estimates come from LTER snow accumulation stakes on the glaciers. These estimates represent only net accumulation, which is extremely low, and the large buildup of snow that would be needed to sustain these seeps through a warm austral summer seems unlikely. Therefore, at this time it is impossible to evaluate the potential influence of temporal snowfall variations on the seeps, but we suspect that this, too, is not a viable source.

It would require a far more comprehensive investigation than ours to examine whether or not there are connections between the source of glacier melt and the seeps where we have not been able to detect water sources. There is spatial variability of solar irradiance in the valleys, with higher solar flux from east to west owing to marine-produced cloudiness and higher irradiance fluxes on the north-facing slopes (Dana et al., 1998). This spatial variability may exert an influence on where melt is produced and where refrozen primary precipitation could accumulate. The seeps we observed that originated above the valley floor mainly occur on south-facing slopes. This may suggest that south-facing slopes have a great ability to retain subsurface ice for longer periods owing to less solar intensity and a shorter season of illumination. On the north-facing slopes, water may be lost more readily owing to higher solar intensities and longer seasonal illumination. Shading by topographic features also plays an important role in the radiative balance in Taylor Valley, with narrower, steep parts of the valley shaded for greater amounts of time (Dana et al., 1998). This clearly will have a greater influence on meltwater generation, both from glaciers and from the frozen subsurface.

Although the overall climate of the McMurdo Dry Valleys has been warming over the past century (Chinn, 1993; Bomblies et al., 2001; Bertler et al., 2004), the temperature of Taylor Valley has been decreasing over the past 15 yr (Doran et al., 2002). This is particularly the case in the austral summer and autumn during which the temperatures declined an average of 1.2 °C and 2.0 °C per decade, respectively. We do not believe that climate warming is currently a valid explanation for the occurrence of these seeps.

Our best speculation at this stage of our investigations is that snow melts at the surface, percolates into a region of coarse-grained soils, and is subsequently refrozen where little sublimation occurs. During cooler summers a reservoir of refrozen snowmelt accumulates in the subsurface that can later melt and flow during warmer summers. To our best knowledge, Wormherder Creek has flowed only at the location where we initially observed it during two austral summers since 1996—January 2002 and January 2005. Although Wormherder Creek has a definite snow-patch source, the other seeps with as-yet-unidentified sources may behave in the same manner, accumulating water in the subsurface, only to flow during *extreme* events. How often these events occur is undocumented, even through the use of the older photographs. Modeling efforts by Ebnet et al. (2005) suggest that summer flows approaching those of 2001–2002 could also have occurred during 1973–1974, 1985–1986, 1986–1987, 1987–1988, and 1991–1992. Another potential source of seep water, at least at the East Fryxell and Red Streak sites, is older, buried ice or ice-cored morainal materials.

Groundwater Seepage on Mars

In 2000 the Mars Orbiter Camera on the Mars Global Surveyor orbiter detected gully landforms in the walls of craters and valleys at middle and high Martian latitudes (Malin and Edgett, 2000). The absence of superimposed landforms and crosscutting features, such as impact craters and eolian dunes on the gullies, indicates that they are geologically young features. In a terrestrial context, similar geomorphic features are attributed to fluid seepage and surface runoff processes.

The McMurdo Dry Valleys region of Antarctica is a polar desert environment that provides the best terrestrial approximation of the conditions found on Mars (Vishniac and Mainzer, 1973; Andersen et al., 1992). Although the Taylor Valley seep flows span tens of meters in length in comparison with kilometers in length for the Martian gullies, both landforms were possibly generated by the thawing of subsurface ice as a result of local warming. In the McMurdo Dry Valleys, warming occurs from unseasonably high temperatures during the austral summer. On Mars, warming could have resulted from increased solar insolation during periods of high obliquity. Both scenarios lead to liquid water flowing in a typically dry, frozen landscape. Recent modeling by Heldmann et al. (2005) indicated that fluvially induced gully formation on Mars could take place under current Martian conditions.

SUMMARY AND CONCLUSIONS

The seeps described in this paper are unusual because they are not supplied by direct glacier melt, the primary source of liquid water in the polar desert of the McMurdo Dry Valleys. Instead, seep water is potentially derived from permafrost, snow patches, refrozen precipitation that has accumulated in the subsurface, or buried glacier ice (e.g., ice-cored moraine).

Geochemical data favor a subsurface origin for the seeps. The solute chemistry and isotopic signatures of the seeps are distinct from those of nearby streams and glaciers. Subsurface melt is typically enriched in certain solutes owing to its long residence time in the soil. By contrast, glacial melt is relatively depleted in those same solutes. The seep water shows elevated solute concentrations in comparison with glacial streams in the vicinity.

These findings indicate that local precipitation does not serve as the direct source for the seeps. Isotopic data reveal that seep waters have been extensively modified and that delineating the source of the original water is difficult. Chemical and isotopic analyses of ground ice at or near the seeps sites would provide insight into the source of seep water.

We suggest an indirect precipitation origin for seep waters. Snowmelt and refreezing occur over a number of years, accumulating a subsurface ice volume. The cycles of freeze-thaw and evaporation-sublimation of the subsurface water and ice fractionate the hydrogen and oxygen isotopes of water. The upper limit to the volume of ice stored in this way is the soil surface at maximum and at minimum the depth to which the local energy balance in the soil maintains the freezing level during the summer. During episodic warming events this subsurface reservoir of ice becomes depleted. It is certainly possible that larger reservoirs of ice may result from past glacial deposits, and this is certainly true for seeps near the east end of Taylor Valley. If true, however, then this ice is also substantially modified by freeze-thaw cycles before exiting the soil as a seep.

Seeps contribute a small volume of water to the valley floor in comparison with the streams, but their ecological contribution is significant. The seeps deliver a relatively rich pulse of inorganic solutes and nutrients to the lakes, and the seep flows themselves serve as transient abodes for mosses and algae.

These seeps of the McMurdo Dry Valleys could prove useful analogs for processes that potentially operate on Mars. Martian gullies and the Taylor Valley seeps differ in scale by an order of magnitude, but both landforms appear to have been generated by the melting of water ice in the top few meters of the subsurface.

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