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Wet streaks in the McMurdo Dry Valleys, Antarctica: Implications for Recurring Slope Lineae on Mars

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ABSTRACT

Recurring Slope Lineae (RSL) are dark streaks that seasonally propagate and fade on Martian slopes. The morphology and dynamics of RSL suggest that they might be brine flows; however, more recent hypotheses propose that they are dry, granular flows. To determine if RSL are consistent with brine flows, we investigated Mars analog wet streaks in Wright Valley Antarctica using new chemical analyses of soils and waters, time-lapse photography, and satellite images. Results show that the source of water to wet streaks is primarily local snowmelt, which seasonally percolates downslope. Meltwater leaches hygroscopic $CaCl_2$-rich salts from soils and underlying Ferrar dolerite bedrock. These salts accumulate at soil surfaces via evapoconcentration and deliquesce/effloresce in response to daily relative humidity changes, causing the surface brightness to fluctuate. Over several years, the active $CaCl_2$ salt component leaches back into the subsurface and the streaks dry, leaving a residue of less hygroscopic salts at the surface. Applied to Mars, wet streaks are inconsistent with the surface expression and dynamics of RSL. Wet streaks propagate and fade over multiple years, drain onto low angled slopes, and have a characteristic pattern of dark downhill and lateral edges. In contrast, RSL are seasonal features, terminate on angle-of-repose slopes, and typically appear monochromatic. These inconsistencies provide evidence against brine flow hypotheses of RSL formation.

1. Introduction

Recurring Slope Lineae (RSL) are narrow, dark streaks that seasonally lengthen and fade on Martian slopes (McEwen et al., 2011). Leading hypotheses propose that RSL are brine flows (McEwen et al., 2014; Stillman et al., 2016) or avalanching dry dust and/or sand (Dundas, 2020; Dundas et al., 2017; McEwen et al., 2021). Brine flow hypotheses assume deep or shallow aquifer sources (Abotalib and Heggy, 2019; Stillman et al., 2016) and/or the formation of mobile brines via absorption of atmospheric water vapor by hygroscopic salts (McEwen et al., 2015; Ojha et al., 2015). In contrast, dry flow mechanisms suggest triggering by water (Massé et al., 2016), a limited role for water (Dundas et al., 2017; Gough et al., 2020), or anhydrous processes (Dundas, 2020; Schmidt et al., 2017). Consequently, RSL have broad implications for the existence of present-day liquid water on Mars' surface, as well as its potential composition, extent, and habitability.

To understand how RSL form, we investigated Mars analog RSL features (here referred to as "wet streaks") that occur in the South Fork of Wright Valley (Head et al., 2007), within the McMurdo Dry Valleys (MDV) of Antarctica, an extremely cold and dry Mars analog site (e.g., Dickinson and Rosen, 2003; Marchant and Head, 2007). Wet streaks are dark due to elevated soil moisture and are distinct from dark streaks on hill slopes in the MDV caused by dark-colored talus (e.g., Ferrar dolerite) intermingled with light-color talus (e.g., Beacon Sandstone). Wet streaks also differ from other seasonally wet soil features that are common in the MDV during the austral summer (e.g., "water tracks") (Levy et al., 2011) because they are perennial and persist in the same positions for multiple years (Head et al., 2007), whereas water tracks typically reform every year in response to melting snow and ground-ice. Water tracks also typically occur in depressions or meltwater channels as surface flows, whereas wet streaks do not flow on the surface and are not associated with distinctive hillslope morphology. Wet streaks are strikingly similar in morphology to RSL. They provide clues about what wet flows might look like on Mars, their mechanism of formation, and their dynamics.

Harris and Cartwright (1981) first noted extensive wet streak formation on slopes above Don Juan Pond (DJP) (see their Fig. 9).

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They hypothesized that wet streaks form via deliquescence of hygroscopic salts and/or upward wicking water from shallow saline groundwater. Later studies pointed out that wet streaks often occur below snow-filled alcoves in cliffs, and hypothesized that snow and ice-melt supply water to wet streaks (Head et al., 2007; Levy et al., 2011), although the low salt content in snowmelt cannot explain high wet streak salinity (Dickson et al., 2013). Several studies have also found that wet streaks darken during high relative humidity (RH) (Dickson et al., 2013; Gough et al., 2017; Harris and Cartwright, 1981), which suggests that deliquescence drives wet streak formation. In general, it is difficult to evaluate these separate hypotheses because there are no published analyses of wet streak chemistry (see Levy et al., 2011 for chemical analyses of water tracks), and there are few analyses of nearby soils and waters.

We report on extensive chemical analyses of wet streaks, nearby soils, shallow groundwater, and surface water collected in the South Fork of Wright Valley over the 2017-2018 field season. We also present results from a month-long time-lapse video of the wet streaks and analyses of satellite images from 2003 to 2017. Our goal is to determine how wet streaks form, their morphology and evolution, and to compare our observations to Martian RSL.

2. Methods

2.1. Site description

The South Fork of Wright Valley, Antarctica, occupies a closed basin bounded by the Dais to the north (a plateau separating the North and South Forks of Wright Valley) and the Asgard Range to the south (Fig. 1). To the east, the valley gradually rises in a series of small basins that host ephemeral ponds, culminating in a 234 m elevation valley threshold. To the west, a rock glacier occupies the valley floor. Considerable meltwater drains from the Asgard Range and the rock glacier, as indicated by the formation of seasonal meltwater streams on north-facing slopes and along the valley axis, and the occurrence of large alluvial fans emanating from the Asgard Range.

The lowest point in the South Fork (64 m elevation) is occupied by DJP, one of the most unique surface waters on Earth because of its high salinity and $CaCl_2$-rich composition (Harris and Cartwright, 1981; Toner et al., 2017). Near DJP, much of the valley floor is composed of glacial drift or pond sediments underlain by a sill of dark-toned Ferrar dolerite bedrock, which transitions to light-toned porphyritic granite at ~300 m elevation (McKelvey and Webb, 1962). This granite outcrops as a prominent cliff band south of DJP and forms a ~2 km-wide bench at ~630 m elevation.

Wet streaks occur above DJP on southern, sun-facing slopes below prominent cliffs of granitic rock. Most wet streaks are narrow, several-meter-wide lineations that occur in soils underlain by Ferrar dolerite; however, several large wet streaks (~100 m wide) form SE of DJP and extend into soils underlain by granitic rock. Wet streaks only occur on slopes south of DJP, and do not occur on slopes with similar angle/aspect elsewhere in the South Fork of Wright Valley, or in the adjacent North Fork. Wet streaks are distinct from wetted soils associated with near-surface groundwater and ponds east of DJP along the valley axis.

To investigate changes in wet streaks above DJP over time, we installed a time-lapse camera north of DJP (Fig. 1B, blue asterisk; Fig. 2), and collected images at five-minute intervals over 23 days from December 25th, 2017, to January 17th, 2018. We then analyzed the video to quantify changes in streak brightness (B; the mean of the red, green, and blue color coordinates) relative to adjacent, non-streak surfaces, as well as changes in the spatial extent of wet streaks. For each streak location, we calculated the average brightness of nine pixels located within the darkened portion of the streak (B_{streak}), the average brightness of nine adjacent pixels located outside of the darkened streak (B_{adjacent}), and then the brightness ratio as $B_{\text{ratio}} = B_{\text{streak}} / B_{\text{adjacent}}$. We also corrected for small shifts in the camera orientation and removed images with sun glare. The rationale for comparing wet streaks to non-streak surfaces is to remove uniform effects caused by changes in the sun intensity and angle, and atmospheric absorption. Finally, we compare the time-lapse images with RH data collected from a meteorological station in DJP basin (Fig. 1B, yellow cross) at 15-minute intervals from December 29th, 2017, to January 16th, 2018.

To investigate changes in wet streaks over longer periods than possible with the time-lapse video, we analyzed WorldView-1 and QuickBird panchromatic satellite images of DJP from 2003 to 2017. Representative images were chosen for each year where images were available between October and March (some years lacked images). We excluded images with substantial distortion, cloud cover, shading, or images taken at night.

2.2. Soil, rock, and water samples, and chemical analysis

Water samples were collected throughout the South Fork of Wright Valley from ponds, streams, shallow groundwater, and a single fresh snowfall sample from a storm collected during the field season (Fig. 1A, B). Pond waters were collected from a series of small meltwater ponds east of DJP. Stream samples were collected from drainage channels on the rock glacier west of DJP, and from channels draining the Asgard Range east of DJP. Shallow groundwater locations were identified by damp surface soils, which often occurred within small depressions or channels. In many cases, shallow groundwater was observed in depressions that probably hosted small ponds in the past, such as VXE-6 pond east of DJP and a small basin on top of the bench at 630 m elevation south of DJP (Cartwright and Harris, 1981), but were dry during the 2017-2018 field season. To sample shallow groundwater, a pit was excavated to the depth of the water table (typically 20 to 40 cm depth) and allowed to fill with water. After collection, all samples were filtered in the field at 0.22 μm and stored in a cold room prior to analysis at the University of Washington.

Soils were sampled as either detailed soil pits (green circles in Fig. 1) or without extensive characterization to 10 cm depth (red circles in Fig. 1). For detailed soil pits, each soil horizon was described and sampled down to either hard ice-cemented soil, bedrock, or one-meter depth. The ice-cemented soil or bedrock was sampled for the top few cm. We also sampled dolerite bedrock outcrops south of DJP (brown circles in Fig. 1) by chipping surface samples off with a rock hammer. All samples were sealed in Whirl-Pak® bags.

Soil and rock samples were analyzed for water-soluble salts using a 1:10 soil:water extraction. Soil samples were processed by drying overnight at 60°C, sieving at 2 mm (saving the <2 mm fraction), and then subsampling for the <2 mm size fraction using a sample splitter. We then added 50 ml of deionized water to the soil split, agitated the suspension for an hour, centrifuged the suspension, removed the supernatant, and finally filtered the supernatant at 0.22 μm.

All water and soil:water extraction samples were analyzed for cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) using a Perkin Elmer Optima 8300 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) and anions (Cl^-, SO_4^{2-}, NO_3^-) using a Dionex 120 Ion Chromatograph (IC). Results of soil and water analyses, as well as detailed pit descriptions, are presented in Supplementary Material. We also include soluble salt data from soils measured by McLeod (2012), who sampled soils along the valley axis east of DJP and at higher elevations in the Asgard Range. To compare the overall chemistry of soils, which vary in depth and the number of hori-

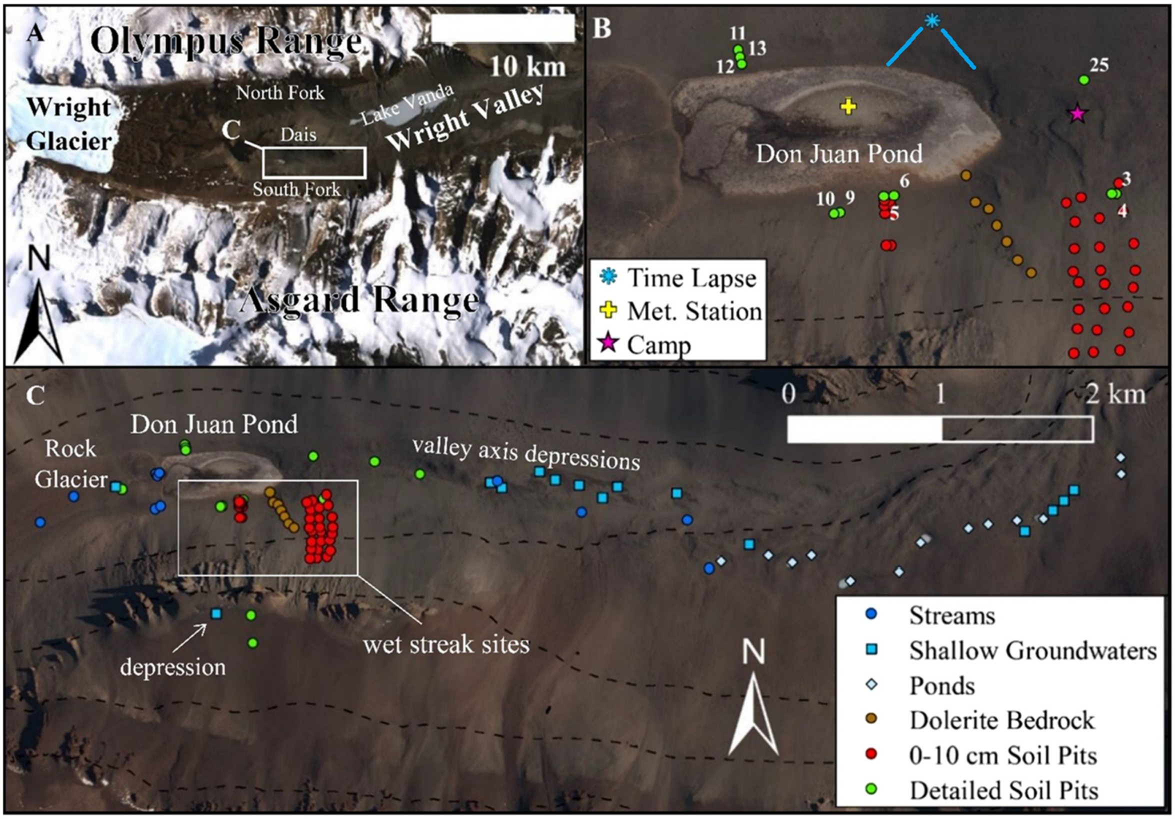

Fig. 1. The location of the study site and sampling locations on a Landsat Image Mosaic of Antarctica (LIMA). (A) The area of the South Fork within the larger Wright Valley system, with the location of panel C indicated. (B) A detailed view of the study site near DJP, showing the location of the time-lapse camera (field of view indicated by blue lines), the meteorological station, and out camp. In addition, detailed soil pits are labeled by pit number. (C) An overview of the South Fork of Wright Valley, showing soil sample locations (for both 0-10 cm soil pits and detailed soil pits), bedrock samples, and water samples (pond, streams, and shallow groundwater). Contour intervals are at 250 m elevation increments. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

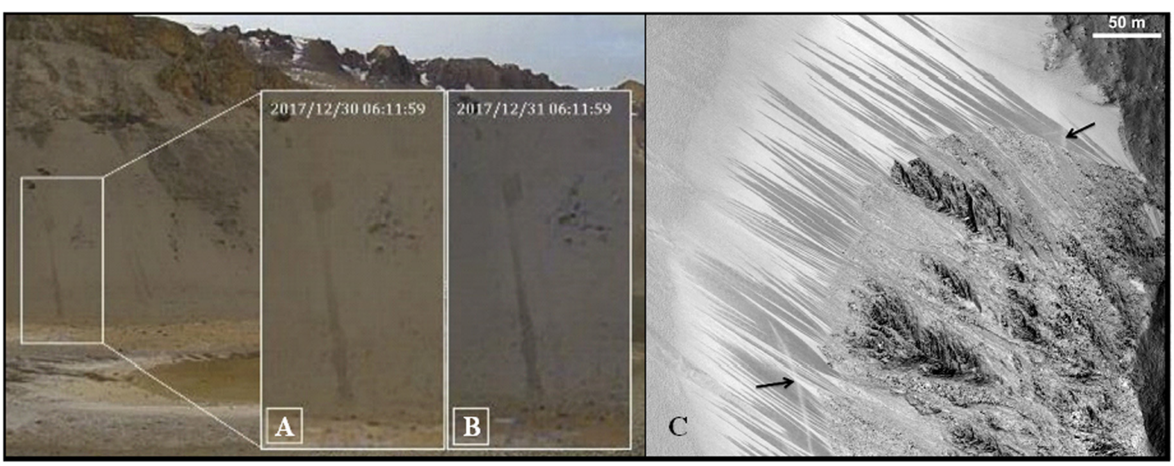

Fig. 2. Images from the time-lapse video, showing relatively dry (A) and relatively moist (B) periods. (C) An image of RSL from Garni Crater (arrows show the locations of dust-devil tracks) (from McEwen et al., 2021).

zons sampled, we calculate the total soluble salt content per m^2 of soil surface area (in units of mol m^{-2}), as in Toner et al. (2013).

3. Results

3.1. Time-lapse images

The time-lapse video shows that wet streaks brighten/darken over diurnal timescales, which correlates with RH and temperature changes (Fig. 3, see Sletten et al. (2022) for archived video). When temperatures are high and RH is low during the daytime, wet streaks dry out and become brighter. On the warmest and driest days, wet streaks effloresce to form a white salt crust (e.g., see December 27th at noon in the time-lapse video). Similar salt efflorescence events also occur on the playa floor of DJP and on exposed dolerite bedrock SE of DJP during periods of relative streak brightness. During the nighttime, when temperatures decrease and RH is high, wet streaks hydrate and darken relative to adjacent non-streak surfaces, which also corresponds to relatively wet conditions on the playa surface and on exposed dolerite rocks SE of DJP. In the field, we observed that many rocks and soil surfaces around DJP were visibly wet during high RH conditions. In con-

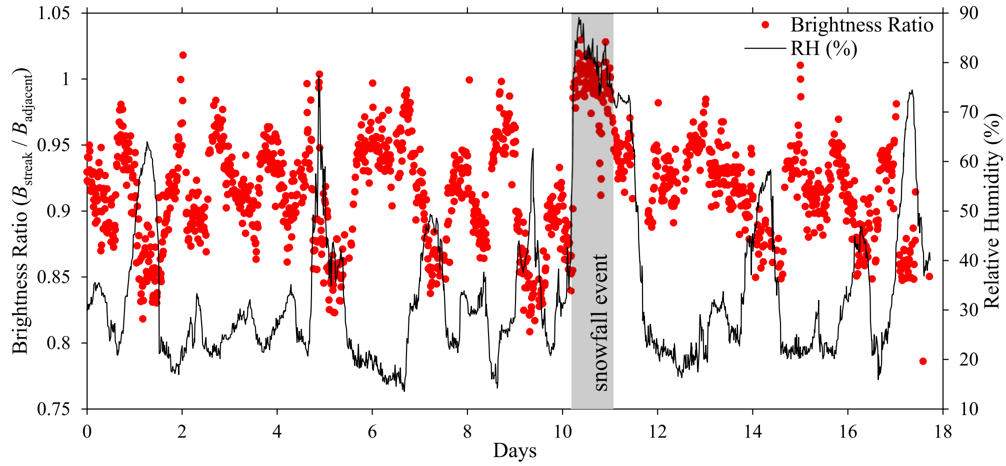

Fig. 3. The brightness ratio (red circles) of a wet streak, and RH (black line) measured from a meteorological station. The location for the measured brightness ratio is -77.56475° latitude and 161.19712° longitude (WGS1984). The gray area indicates the timing of a snowfall event. Changes in brightness ratios are like other wet streaks.

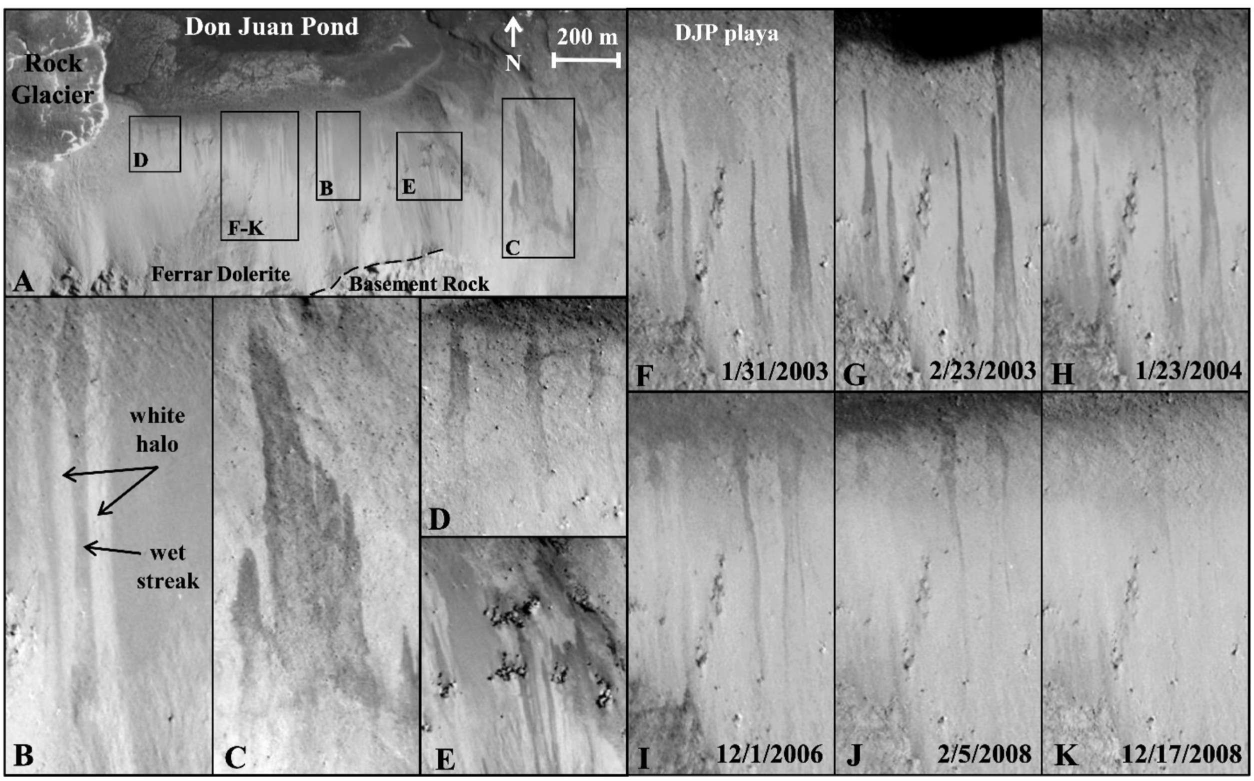

Fig. 4. Changes over time for different wet streaks above DJP. (A) An overview of DJP and the wet streaks. (B) A wet streak showing white halos surrounding a dark, wetted core. (C) A ~100 m wide wet streak E of DJP. Note that the wet streak abruptly darkens below the expected contact between granitic rock and Ferrar dolerite. (D) Small wet streaks show the characteristic dark leading and marginal edges, and preferential fading on the upslope and interior streak portions. (E) Numerous wet streaks associated with dolerite outcrops. (F-K) A sequence of wet streak images showing changes over time. This was the most active propagation event observed. Typically, little wet streak activity is apparent in satellite images.

trast to changes in streak brightness, their spatial extents (length and width) did not change over 23 days to within the resolution of the time-lapse video (~1 m). This is despite occasional times of >50 % RH, and even a snowfall event (indicated by the gray box in Fig. 3), which deposited ~1 cm of snow on the wet streaks.

3.2. Satellite images

Satellite images from 2003 to 2017 indicate that wet streaks above DJP are dynamic features that occasionally propagate downslope as relatively dark flows, followed by gradual fading and widening. The most pronounced period of wet streak growth occurred in 2002-2004 (~15 and ~45 m of downhill propagation in the 2002-2003 and 2003-2004 seasons respectively, Fig. 4F-H). The 2003-2003 streak propagation event occurred after an anomalously high meltwater year in 2001-2002 known as the “flood year” (Doran et al., 2008), which suggests that meltwater from this year caused the wet streaks to propagate downslope. Furthermore, wet streak growth and fading dynamics are consistent with downslope propagation of a discrete meltwater pulse. Following the 2001-2002 meltwater event, downward wet streak propagation occurred in steps over multiple years, probably because wet streaks only flow during the short Austral summer, freeze during the winter, and then resume flowing when they thaw.

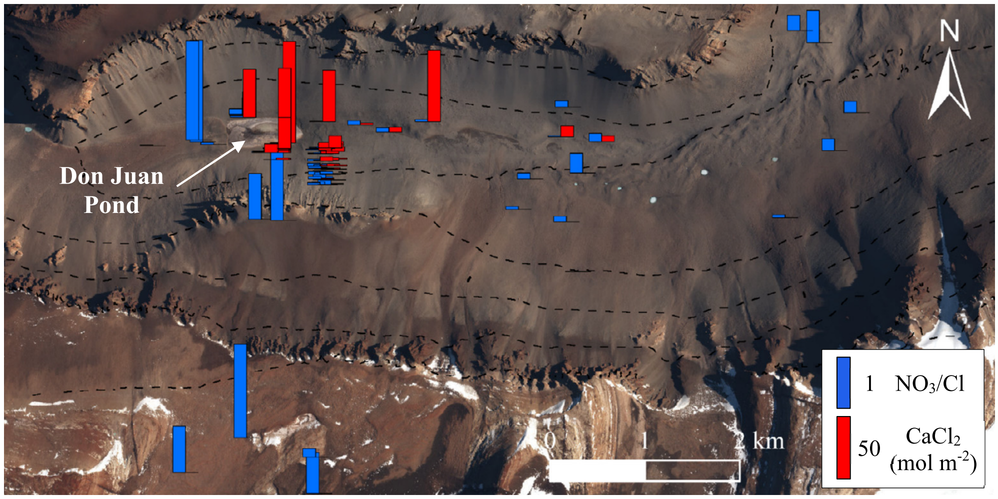

Fig. 5. The distribution of NO_3/Cl ratios (relative to $NO_3/Cl = 1$) and $CaCl_2$ (mol m^{-2}) (relative to 50 mol m^{-2}) in soils of the South Fork, Wright Valley. Data are from this study, as well as from McLeod (2012), which analyzed many of the soils east of DJP and at the highest elevations in the Asgard Range. Contour lines are given at 200 m elevation intervals, and reference bar heights are given in the caption.

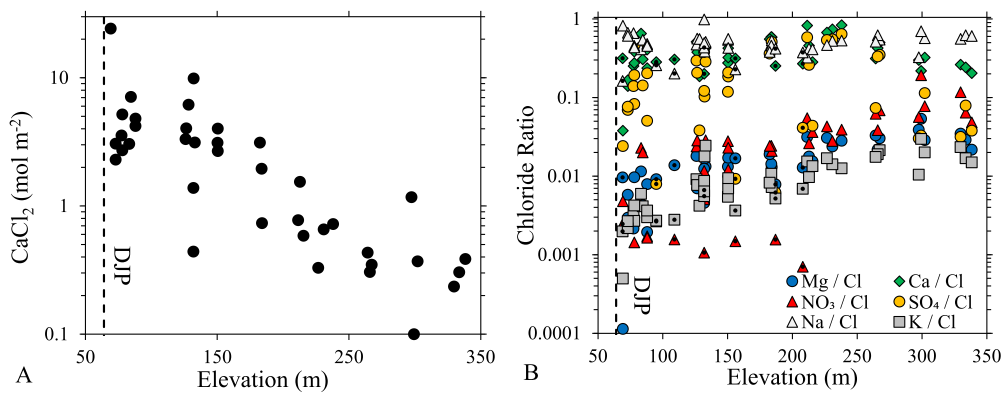

Fig. 6. Changes in the chemistry of wet streaks soils with elevation (for both "on" and "off-"streak soils, as discussed in the results). The dashed line indicates the elevation of DJP. (A) The $CaCl_2$ enrichment in on/off streak soils on a mol per m^2 basis, calculated as $CaCl_2 = Ca^{2+} - SO_4^{2-}$. (B) Ionic ratios relative to Cl^- for soils and dolerite bedrock (dolerite samples are indicated by black dots within symbols).

After the 2002-2004 propagation events, the wet streaks gradually fade and widen. Fading starts at the upslope end and within the core of the flow, leading to a characteristic appearance of dark downhill edges and light-toned interiors (Fig. 4C, D, F-K). As the wet streaks fade, they also gradually widen by several meters, which is probably driven by lateral capillary flow into surrounding dry soils. Over multiple years (2004 to ~2012), wet streaks become nearly indistinguishable from surrounding soils (Fig. 4K).

Wet streaks are also characterized by "halos" of relatively light-toned soil (Fig. 4B). These "halos" are probably caused by surface salt accumulations from past wet streaks, which implies much more extensive wet streak formation in the past. In fact, the earliest published image of wet streaks in January 1976 by Harris and Cartwright (1981) (their Fig. 9) shows that wet streaks were much more extensive than in post-2003 satellite images. Furthermore, the MDV climate has been cooling by about 0.7°C per decade since 1966 (Doran et al., 2002), which is consistent with more meltwater production and associated wet streak activity in the past.

3.3. Soil chemistry

The chemistry of wet streaks and surrounding soils provide clues to their source of water and salts, and the identity of the salts responsible for wet streak deliquescence. Overall, two distinct endmember soluble salt assemblages occur in South Fork soils: (1) DJP-like $CaCl_2$-rich salts and (2) NO_3-rich salts characteristic of upland soils (Fig. 5). $CaCl_2$-rich salt accumulations occur near DJP, and reflect DJP's low NO_3/Cl (0.0012) (Samarkin et al., 2010), K/Cl (0.00066), and Mg/Cl (0.011) ratios (Toner et al., 2017). For comparison, these ratios are 10 to 100 times higher in most South Fork soils. $CaCl_2$-rich soils also occur east of DJP along the South Fork axis, which may be due to strong west-to-east katabatic winds that transport material from the DJP playa (Friedmann et al., 1995). In contrast, NO_3-rich soils occur with higher elevation and distance from DJP, and have considerable SO_4^{2-}, Na^+, and Cl^-. Salt accumulations in these soils are distinct from DJP because of long-term accumulation of NO_3^- and SO_4^{2-} enriched marine aerosols sourced from the East Antarctic Ice Sheet, and K/Mg-rich salts from chemical weathering (Claridge and Campbell, 1968, 1977).

Wet streaks and adjacent soils are $CaCl_2$-rich (defined here as $CaCl_2 = Ca^{2+} - SO_4^{2-}$) (see Toner and Sletten, 2013 for a discussion of calcium chloride brine definitions), with high Ca^{2+}, Na^+, and Cl^- contents relative to low K^+, Mg^{2+}, NO_3^-, and SO_4^{2-} (Fig. 5). Furthermore, wet streaks become more DJP-like with decreasing elevation (Fig. 6). $CaCl_2$ concentrations increase by a factor of ten from the highest wet streak sampled down to DJP (Fig. 6A), and diagnostic NO_3/Cl, Mg/Cl, and K/Cl ratios decrease by a factor of ten (Fig. 6B). Adjacent dolerite bedrock samples are similar in composition to wet streaks (Fig. 6B, indicated by black dots) but are even

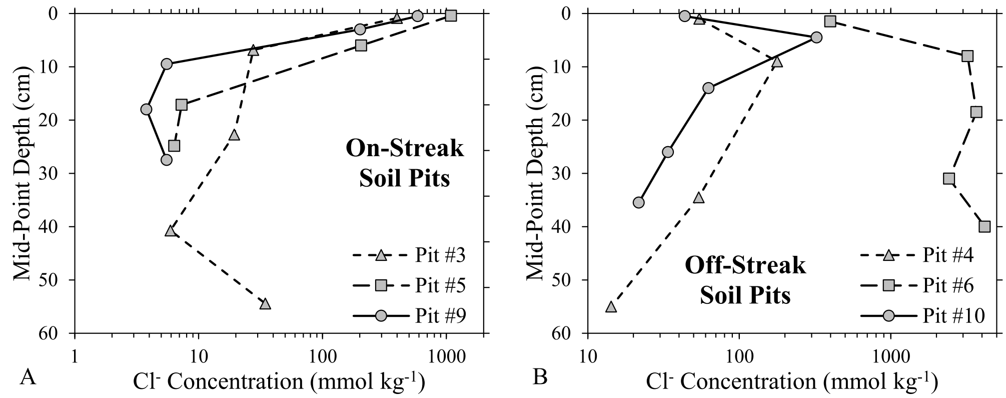

Fig. 7. Changes in Cl^- concentration with depth (middle of sampled horizons) in wet streak soils (A) and adjacent dry, off-streak soils (B). For the on-streak soil pits #3, #5, and #9, the adjacent off-streak soils are pits #4, #6, and #10 respectively.

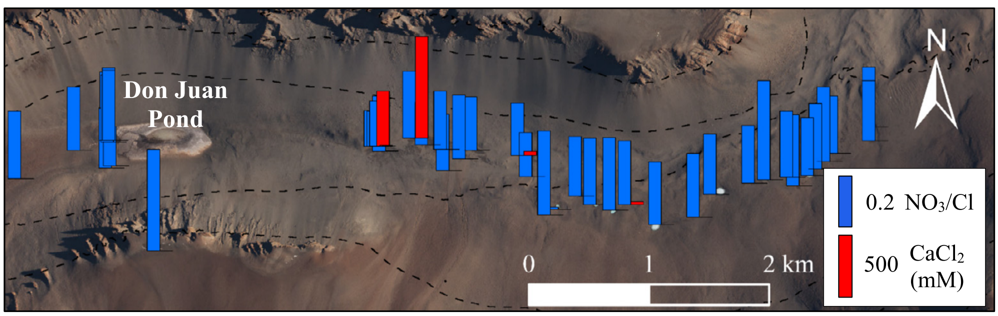

Fig. 8. The distribution of NO_3/Cl ratios (relative to NO_3/Cl = 0.2) and $CaCl_2$ (relative to 500 mM) in stream, shallow groundwater, and pond waters in the South Fork of Wright Valley. Contour intervals are given at 250 m elevation increments. For clarity, the $CaCl_2$-rich brine in DJP is not shown.

more DJP-like. In particular, NO_3/Cl ratios are much lower in the dolerite (averaging 0.0016), which is comparable to 0.0012 NO_3/Cl in DJP. The soluble salt chemistry of wet streaks, adjacent soils, and dolerite bedrock are distinct from NO_3-rich soils sampled only several hundred meters elevation higher on the bench of granitic rock south of DJP (Fig. 5).

The overall chemistry, morphology, and water content is essentially the same between wet streak soils that were visibly wet (on-streak) and visibly dry soils sampled several meters away (off-streak). The only substantial difference between on and off-streak soils is the slightly wet surface appearance of on-streak soils, which is barely perceptible up-close but is readily apparent when viewed from a distance (as in the time-lapse video and satellite images). In most other respects, such as topography, desert pavement surface, and cobble/boulder density, on- and off-streak surfaces appear identical (cf. Head et al., 2007).

Although on- and off-streak soils have similar chemistry and morphology, their chemical profiles differ with depth. On-streak soils have maximum salt contents at the surface, which sharply decrease with increasing depth (Fig. 7A); however, adjacent off-streak soils have relatively low salt contents at the surface and high salt contents at ~5-10 cm depth (Fig. 7B). Salt distributions in on-streak soils are consistent with upwards wicking and evaporating water (evapoconcentration) in wetted MDV soils (Gooseff et al., 2007; Toner et al., 2013), whereas salt profiles in off-streak soils are consistent with downward salt leaching by snowmelt (Toner et al., 2013). Off-streak soils occur within the relatively light-toned "haloes" that surround wet streaks. Given that these "halos" were probably wetted in the past (see section 3.2), off-streak soils likely had elevated surface salts when they were wet. Then, as the wet streaks faded, snowmelt leached salts downwards.

3.4. Water chemistry

The chemistry of surface and shallow groundwaters in the South Fork indicates potential sources of water and salts to wet streak soils. Chemical analyses show that streams, shallow groundwaters, and ponds in the South Fork (except for DJP) are uniformly characterized by high NO_3^- contents (average NO_3/Cl = 0.27, Fig. 8, Table 1), which reflects NO_3-rich soluble salt accumulations in most South Fork soils but is distinct from NO_3-poor wet streak soils. Soils may contribute their NO_3^- to streams, and shallow groundwater flows via direct dissolution of salts, leaching by snow and ice melt, or wind transport of salt-rich fines (Toner et al., 2013). These drainage waters then contribute their salts to ponds and groundwater-saturated depressions (Green et al., 1988). The only exceptions to high NO_3/Cl waters in the South Fork are DJP (NO_3/Cl = 0.0012) and fresh snow (NO_3/Cl = 0.04) (Table 1).

Most ponds and shallow groundwaters in the South Fork are freshwater, but in some cases drainage waters have accumulated in depressions and evaporated to form brines. A series of small depressions east of DJP contain shallow groundwater with up to ~0.5 M NO_3^- and 0.7 M $CaCl_2$ (e.g., sample #40 in Table 1). The $CaCl_2$ component in these depressions may derive from wind transport of fines from DJP along the valley axis or from groundwater discharge like DJP, whereas NO_3^- derives from the accumulation and subsequent evaporation of NO_3-rich stream and shallow groundwaters (which we observed draining into these basins). The bench south of DJP at 630 m elevation also hosts a depression that contains a shallow groundwater brine (sample #12 in Table 1), but its composition is $CaCl_2$-deficient and NO_3-rich. This is consistent with the lack of a $CaCl_2$ component in NO_3-rich higher elevation meltwater draining into this basin.

Table 1
The chemistry of representative pond, stream, and shallow groundwater samples in the South Fork of Wright Valley. Ion concentrations are in mM. See Supplementary Material for further details on these and other samples.

ID	Description	Na	K	Ca	Mg	Cl	NO_3	SO_4	NO_3/Cl
46	pond, E of DJP	44.7	1.3	2.3	15.2	56.7	18.8	2.1	0.33
8	stream, rock glacier	2.7	0.1	1.1	0.28	3	0.89	0.91	0.30
103	stream, E of DJP	7.1	0.15	1.2	1.7	5.5	2.1	2.3	0.38
61	fresh snow	0.14	0.01	0.06	0.01	0.24	0.01	0.02	0.04
79	shallow groundwater, E of DJP	10.6	0.23	2.9	2.5	11.9	3.5	3.6	0.29
12	Dry depression, bench above DJP	1229	17.1	17.9	318	989	460	178	0.47
41	Dry depression, E of DJP	582	23.3	704	597	2213	528	7.8	0.24
[a]	DJP groundwater	347	2.86	2062	48.3	4752	–	1.11	0.0012[b]

[a] From Cartwright and Harris (1981).
[b] From Samarkin et al. (2010).

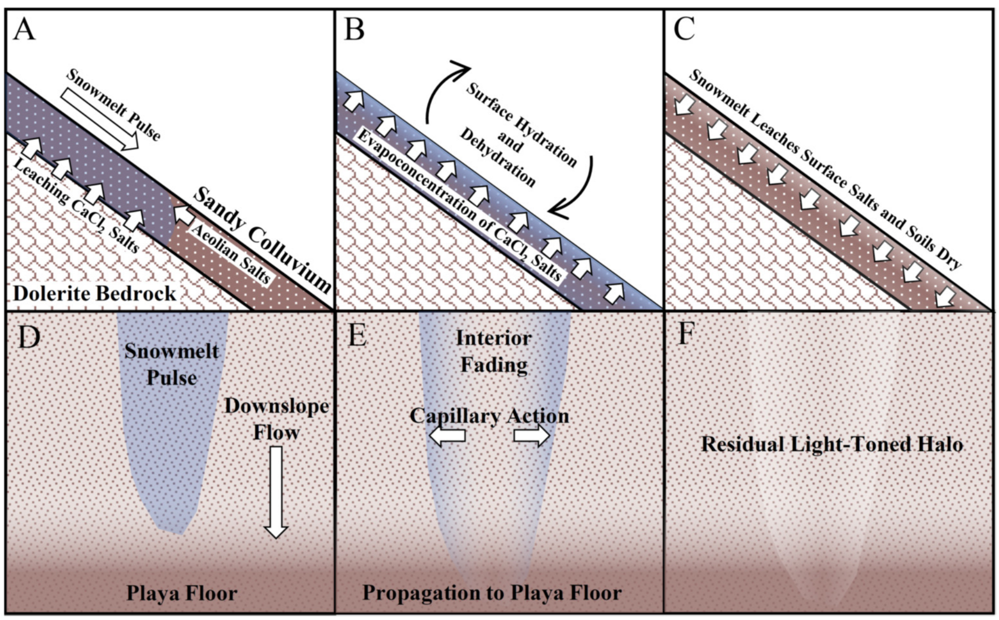

Fig. 9. The formation and dynamics of wet streaks. Panels A-C depict a soil transect on a wet streak slope showing (A) a snowmelt pulse flowing on top of dolerite bedrock, entraining $CaCl_2$ salts, (B) evapoconcentration bringing $CaCl_2$ salts to the surface and cyclical surface hydration, and (C) salt leaching and soil drying. Panels D-F provide an aerial depiction of (D) initial wet streak flow in a meltwater pulse, (E) fading, widening, and propagation, and (F) wet streak drying to a residual light-toned halo.

4. Discussion

Based on the satellite and time-lapse imagery and chemical analyses of soils and waters in this study, we can now piece together the formation and dynamics of wet streaks (Fig. 9). Satellite images from 2002-2017 suggest that wet streaks form in response to meltwater pulses and lengthen over multiple years in a step-wise fashion; percolating downslope during the austral summer and freezing during the winter (see section 3.2). These meltwater pulses, and therefore the wet streaks, only propagate occasionally in response to heightened meltwater production during warmer Austral summers. Given that dolerite bedrock lies near the surface on slopes south of DJP (as indicated by abundant bedrock outcrops), this meltwater would flow on top of bedrock (or on top of ice-cemented soil where present) and visibly darken overlying soil surfaces via capillary wetting (Head et al., 2007).

As meltwater evaporates, it concentrates hygroscopic $CaCl_2$ salts at soil surfaces via evapoconcentration (Toner et al., 2013). Hygroscopic $CaCl_2$ salts probably reduce water loss from the soil surface, and periodically darken soil surfaces by adsorbing atmospheric water vapor and hydrating at high RH conditions (Fig. 3). Evaporation also dries out the core of the flow first, whereas the lateral edges and downhill margins have higher water contents and remain wet longer owing to gravity-driven plug flow of meltwater. This causes the characteristic wet streak morphology of dark downhill and lateral margins and light-toned cores. Finally, as wet streaks completely dry out over several years, soil chemical profiles indicate that surface salts leach downwards, likely during periodic snowmelt events. Once $CaCl_2$ salts have leached from the surface, wet streaks become inactive and no longer darken in response to RH changes (Fig. 4K).

This sequence of events explains the formation and dynamics of RSL but does not address the source of water or salts to the MDV wet streaks. Water may come from several sources, including snowdrifts, ground-ice, and shallow/deep groundwater. Similarly, salts may derive from these water sources, as well as the accumulation of marine aerosols and wind-transport salt-rich fines from soils. In the following section, we discuss geochemical constraints on the source of water and salts to wet streaks.

4.1. The source of water and salts to wet streaks

The most likely water source to wet streaks is local snowmelt from snowdrifts in wind-protected alcoves that occur above wet streak slopes in granitic rock outcrops south of DJP (Head et al., 2007). This is strongly supported by NO_3/Cl ratios in wet streak soils averaging 0.035, which is like fresh snowfall (NO_3/Cl = 0.04), but differs markedly from NO_3-rich stream, pond, and shallow groundwaters in the South Fork (average NO_3/Cl = 0.27) (Fig. 8). Furthermore, NO_3/Cl ratios in wet streaks are distinct from nearby

NO_3-rich soils located on the bench south of DJP (NO_3/Cl >1), and from shallow saline groundwater sampled from a small depression on this bench (NO_3/Cl = 0.46). This indicates that drainage waters above this bench (630 m elevation) do not flow down wet streak slopes, which supports a highly local snowmelt source to wet streaks.

Snowmelt is consistent with NO_3/Cl ratios in wet streaks, but it cannot explain their $CaCl_2$-rich salt composition because snow lacks a $CaCl_2$ component. This suggests an additional source of $CaCl_2$-rich salt and/or brine to percolating snowmelt. $CaCl_2$-rich soluble salts are highly unusual on Earth's surface (Garrett, 2004) (although they are common in the deep subsurface), and only a few possible sources have been identified in the MDV. Wilson (1979) hypothesized that $CaCl_2$ salts form in the MDV because $CaCl_2$ is highly soluble and deliquescent relative to other salts. As a result, $CaCl_2$ brines preferentially migrate downslope from high elevation soils and accumulate in basins to form $CaCl_2$-rich pond and shallow groundwaters. However, later geochemical arguments have shown that $CaCl_2$ cannot form in this way because relatively high carbonate and sulfate ions concentrations in soils combine with Ca^{2+} to immobilize it in insoluble calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) (Green and Canfield, 1984; Lyons and Mayewski, 1993; Toner and Sletten, 2013). Furthermore, brines leaching from high elevation soils would also be enriched in NO_3-salts, which is inconsistent with low NO_3/Cl ratios in wet streaks.

Cation exchange reactions (i.e., reactions that exchange cations bound to negatively charged sites on soil surfaces) may also form $CaCl_2$ brines in soils (Toner and Sletten, 2013). Na^+ ions in downward migrating brines cause $CaCl_2$ enrichment by preferentially displacing exchangeable Ca^{2+} into solution at cold and dry conditions. However, this mechanism is inconsistent with $CaCl_2$-rich salts in wet streaks because Na^+ ions will only exchange with adsorbed Ca^{2+} if the percolating solution is highly concentrated by freezing or evaporation; otherwise, in more dilute solutions, the exchange process reverses (i.e., Ca^{2+} ions exchange with adsorbed Na^+). Given that wet streaks form via percolating snowmelt, which has low salt concentrations, cation exchange would not enrich the flow in $CaCl_2$ salts. Furthermore, the supply of exchangeable Ca^{2+} limits how much $CaCl_2$ can form via exchange reactions. For sandy soils in the MDV, exchangeable Ca^{2+} concentrations are $\sim$10 mmol kg^{-1} (Toner and Sletten, 2013), but soluble Ca^{2+} concentrations measured in wet streak soils commonly exceed this value (i.e., >50 mmol kg^{-1} Ca^{2+}).

A major source of $CaCl_2$ salts in the South Fork is from upwelling $CaCl_2$-rich groundwater, which actively discharges into DJP and evaporates to form concentrated brines (Harris and Cartwright, 1981; Toner et al., 2017). A borehole drilled into DJP basin during the Dry Valley Drilling Project found groundwater saturated sediments to 12.67 m depth, within highly fractured Ferrar Dolerite from 12.67 to 52.2 m depth, and in granitic rock below 52.2 m depth. Subsequent hydrogeological surveys concluded that the groundwater is upwelling from a confined aquifer in the Ferrar dolerite (Harris and Cartwright, 1981). Furthermore, the geochemistry of DJP indicates that it must be part of an active flow-through system, which continually exchanges its brine with a larger, regional deep groundwater system (Toner et al., 2017). The ultimate source of the DJP brine is controversial, but it is likely from a mixture of deep continental groundwater given its similarity to other continental brines (Lyons and Mayewski, 1993) and surface brines that contribute nitrate (Samarkin et al., 2010).

Soluble salts in wet streak soils are consistent with a two-component mixture of DJP and snowmelt. The chemical signature of DJP is diagnostic because it is highly enriched in $CaCl_2$ ($\sim$2 mol kg^{-1} $CaCl_2$) and depleted in NO_3^- (NO_3/Cl = 0.0012), which differs considerably from generally NO_3-rich and $CaCl_2$-deficient soils and waters in the South Fork. Importantly, DJP's

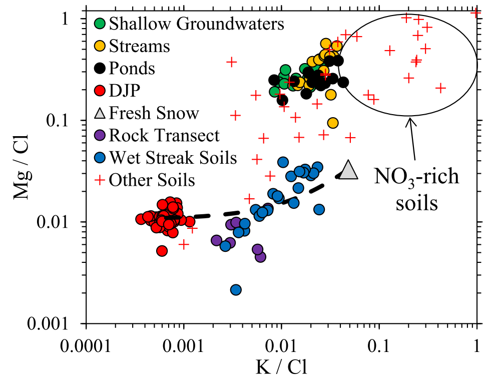

Fig. 10. K/Cl vs. Mg/Cl ratios for waters and wet streak soils in the South Fork of Wright Valley. Samples from shallow groundwaters, ponds, streams, fresh snow, and wet streak soils were collected and measured in this study. The DJP values come from Marion (1997). The dashed line represents mixing between DJP and fresh snow.

$CaCl_2$ component can account for the $CaCl_2$ enrichment measured in wet streak soils, without adding NO_3^-, which would increase the NO_3/Cl ratio. In fact, NO_3/Cl ratios in wet streaks are somewhat lower than in fresh snow, which is the expected trend for mixing between snowmelt and NO_3-poor DJP.

Another defining characteristic of DJP is its low K/Cl and Mg/Cl ratios relative to all other surface, lake, and shallow groundwaters in Wright Valley (Toner et al., 2017) (Fig. 10). Mixture models between DJP and fresh snowfall endmembers (Fig. 10, dashed line) explain low K/Cl and especially Mg/Cl ratios in wet streak soils relative to surface and shallow groundwaters. Similarly, wet streak and adjacent soils are distinct from generally high K/Cl and Mg/Cl ratios found in all other South Fork soils, which follow a mixing trend between NO_3-rich soils (the upper right corner of Fig. 10) and DJP. Mixing models also predict that <0.1 vol. % of DJP brine is needed to explain the chemistry of wet streak soils, but this accounts for >95 % of the soil salt content because of the extremely high salt concentration in DJP. Hence, the water in wet streaks comes from snowmelt, whereas only a small DJP salt component is needed to explain their salt content.

The presence of a DJP salt component in wet streaks requires a mechanism to emplace these salts in percolating snowmelt. The simplest explanation is that winds along the valley axis transport $CaCl_2$-rich aerosols from the surface of DJP to wet streaks (Winsor et al., 2020). However, winds will also transport dust from surrounding NO_3-K-Mg-rich soils (e.g., soils and waters directly east and west of DJP have high NO_3/Cl, K/Cl, and Mg/Cl ratios). Consequently, it is difficult for an aeolian source alone to explain the extremely low ratios found in wet steaks, particularly the DJP-like salts measured in Ferrar dolerite bedrock. A common aeolian salt source is also inconsistent with the chemical difference between dolerite bedrock and nearby wet streaks (see Fig. 6B and Fig. 10). These observations suggest an additional, purer DJP-like source of $CaCl_2$ salts to wet streaks.

The distinctive salt chemistry of the Ferrar dolerite suggests that it might be contributing $CaCl_2$-rich salts to wet streaks. Evidence for a regional confined groundwater aquifer in Ferrar dolerite beneath DJP (Harris and Cartwright, 1981; Toner et al., 2017) suggests that the same dolerite sill that outcrops above DJP may be a primary source of $CaCl_2$ salts to soils (i.e., salty bedrock). The stronger DJP-like chemistry of the dolerite implies that the dolerite would be the source of $CaCl_2$ salts to the wet streaks, not *vice versa*. Wet streaks adjacent to DJP typically occur in soils underlain by shallow Ferrar dolerite bedrock and often emanate from dolerite outcrops (Fig. 4E). Percolating snowmelt flowing downslope on top of dolerite bedrock would entrain $CaCl_2$-rich salts from both the bedrock and aeolian inputs. If wet streaks are long-lived features, then this suggests a mechanism to recharge $CaCl_2$ salts in the dolerite, possibly via slow groundwater seepage (amounting to <0.1 vol. % of the flow). Otherwise, snowmelt will completely leach salts from the dolerite over time. Regardless of the longevity of wet streaks, evidence for a $CaCl_2$-rich Ferrar dolerite source suggests an aerially extensive source of $CaCl_2$-rich salts to soils and waters in the South Fork wherever the dolerite bedrock associated with DJP outcrops.

To summarize the preceding discussion, geochemistry and field observations point to snowmelt as the source of water to wet streaks. However, snowmelt has low salt content and cannot explain the distinctive salt composition of wet streak soils. The chemistry of wet streak soils, nearby waters, and nearby soils points to the source of salts to wet streaks from (1) salt-rich aeolian material blown by strong east-west winds and (2) a DJP-like salts within underlying Ferrar Dolerite bedrock that are leached by percolating snowmelt.

5. Implications for Mars

Since the discovery of RSL on Mars in 2011 (McEwen et al., 2011), several wet flow hypotheses have been proposed, including groundwater discharge (Abotalib and Heggy, 2019; Stillman et al., 2016) and the formation of percolating brines via deliquescence of hygroscopic salts (Chevrier and Rivera-Valentin, 2012; McEwen et al., 2011; Ojha et al., 2015). Wet streaks in the South Fork of Wright Valley provide an analog to understand how wet flows might form on Mars, their evolution over time, and what they might look like from orbit. Here we evaluate several RSL formation mechanisms and compare the morphology and dynamics of wet streaks to RSL.

We first consider mechanisms of RSL and wet streak formation. The primary driver of wet streak formation in the MDV is percolating meltwater from snowdrifts, which is of limited relevance to present-day Mars (Head et al., 2007); however, both deliquescence and deep groundwater outflow processes play a role in MDV wet streaks, and are potentially relevant to Mars. With respect to deliquescence, $CaCl_2$ is the active hygroscopic salt in wet streaks, which darkens slopes by wetting soil surfaces. This is interesting because several Martian brine flow hypotheses for RSL and other features propose $CaCl_2$ salts (Chevrier and Rivera-Valentin, 2012; Knauth and Burt, 2002; Stillman et al., 2016), and $CaCl_2$ salts may deliquesce at Mars-relevant conditions (Gough et al., 2016). Perchlorate salts, which have similar hygroscopic properties to $CaCl_2$, may also occur in Martian soils and RSL in particular (Ojha et al., 2015); however, previous detections of perchlorate in RSL have been shown to be spurious (Leask et al., 2018).

A major issue for brine flow hypotheses is that while deliquescence darkens slope surfaces, the amount of soil water involved is insufficient to propagate wet streaks downslope. Despite repeated cycles of deliquescence/efflorescence (and even a snowfall event), there was no perceptible movement in any wet streak margins in time-lapse observations (Fig. 3) and satellite images often show no changes in wet streak margins over multiple years. MDV wet streaks require considerable soil water (from snowmelt) to propagate downslope. On Mars, this is problematic because observations of Martian RSL indicate an upper limit of 0.5 – 3 wt. % water content at Garni Crater (Edwards and Piqueux, 2016), which is insufficient to drive brine flows. Atmospheric water contents on Mars are also much lower and less favorable for deliquescence than in the MDV. Models of salt hydration on Mars indicate that deliquescence is infrequent in RSL regions and could only occur with highly hygroscopic $Ca(ClO_4)_2$ salts (Rivera-Valentín et al., 2018), which are unlikely to exist on Mars surface because of high alkalinity and soluble sulfate (Toner et al., 2014).

Another potentially Mars-relevant process observed in wet streaks is the possibility of $CaCl_2$-rich groundwater seepage from Ferrar dolerite bedrock, and groundwater upwelling into DJP. On Mars, deep groundwater may remain liquid due to the geothermal gradient (Clifford et al., 2010) and could form artesian outflows to Mars' surface along crustal fractures (Abotalib and Heggy, 2019). The $CaCl_2$-rich groundwater brine discharging into DJP is a potential analog for such an aquifer because it forms artesian outflows (Harris and Cartwright, 1981), and its $CaCl_2$ composition allows it to remain liquid at Mars-relevant temperatures (down to -50°C) (Marion, 1997). However, the groundwater outflow in the South Fork is concentrated at the valley low point in DJP, whereas only a trace groundwater component potentially occurs on wet streak slopes (<0.1 vol. % of the wet streak flow). Even if groundwater in the MDV is actively seeping out onto wet streak slopes, the small amounts are insufficient to form wet streaks in the absence of snowmelt; however, groundwater outflows may be possible on Mars in different geological settings.

The morphology and dynamics of wet streaks may also be compared to RSL. While some wet streak features are similar to RSL (e.g., their overall appearance as dark streaks on sun-facing slopes) (cf. Head et al., 2007; Levy, 2012), several features are inconsistent. Features not found in Martian RSL, but present in MDV wet streaks, are patterns of darker leading and marginal edges relative to the upslope and interior portions (likely caused by downhill plug flow and lateral capillary migration), whereas RSL are typically monochromatic along their length and width. In fact, RSL sometimes have the opposite appearance of darker upper portions, which is probably due to new RSL forming on top of older flows. Finally, RSL terminate mid-slope at the angle of repose ($\sim$30°) (Dundas et al., 2017), whereas many wet streaks propagate down to the low-angled playa floor.

The dynamics of MDV wet streaks are also generally inconsistent with Martian RSL. Wet streaks are persistent features that typically show no growth and stay in the same mid-slope locations from year-to-year. When wet streaks do propagate downslope, they do so seasonally over several years (in the case of wet streaks that formed after the MDV "flood year") or incrementally each year following presumably smaller meltwater events. Fading also occurs over multiple years, starting at the uphill and interior portions of wet streaks and progressing downhill and towards their margins. In contrast, RSL are seasonal features, and in some cases form several times per season (Stillman and Grimm, 2018).

6. Conclusions

Time-lapse photography, satellite images, soluble salt analyses of soils, and chemical analyses of stream, pond, and shallow groundwaters indicate the formation and dynamics of MDV wet streaks. Wet streaks propagate in response to episodic snowmelt, which percolates downslope on top of shallow Ferrar dolerite bedrock and ice-cemented soil. The resulting flow darkens soils via capillary wetting and wicks salts entrained in the flow to soil surfaces. Wet streak surfaces remain visibly dark long after the initial meltwater flow because of hygroscopic $CaCl_2$ salts, which deliquesce/effloresce in response to diurnal RH changes. Over multiple years wet streaks fade, starting from the upslope and interior areas of wet streaks, and proceeding downhill and towards the margins. Fading occurs because snowmelt leaches the hygroscopic $CaCl_2$ salt component from the surface, leaving a residue of less hygroscopic salts (visible as light-toned halos around active wet streaks).

The $CaCl_2$-rich chemistry of wet streaks is distinct from generally NO_3-rich soils and drainage waters (ponds, streams, and shallow groundwater) in the South Fork. Based on the unique chemical signature of endmember salt sources ($CaCl_2$-rich DJP, NO_3-rich upland soils, and fresh snow), we conclude that local snowmelt is the source of water to wet streaks, whereas their $CaCl_2$ salt content is sourced from DJP-like $CaCl_2$-rich salts permeating Ferrar dolerite bedrock and aeolian inputs.

Comparing MDV wet streaks to Martian RSL provides evidence against mechanisms of RSL formation via deliquescence of hygroscopic salts and/or groundwater discharge. In the MDV, neither deliquescence nor groundwater discharge are sufficient to propagate wet streaks downslope in the absence of snowmelt, which is even more problematic for Mars because it is much colder and drier than the MDV. Furthermore, the morphology and dynamics of the MDV wet streaks are inconsistent with RSL. In particular, the multi-year propagation and persistence of wet streaks, their distinctive morphology, and their pattern of fading, are different from Martian RSL. These inconsistencies suggest that RSL form via different processes than MDV wet streaks, which implies little or no role for water in RSL formation.

CRediT authorship contribution statement

J.D. Toner: Conceptualization, Formal analysis, Funding acquisition, Investigation, Writing – original draft. **R.S. Sletten:** Conceptualization, Funding acquisition, Investigation, Writing – review & editing. **L. Liu:** Data curation, Writing – review & editing. **D.C. Catling:** Writing – review & editing. **D.W. Ming:** Investigation, Writing – review & editing. **A. Mushkin:** Investigation, Writing – review & editing. **P.-C. Lin:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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References

Abotalib, A.Z., Heggy, E., 2019. A deep groundwater origin for recurring slope lineae on Mars. Nat. Geosci. 12, 235–241.
Cartwright, K., Harris, H.J.H., 1981. Hydrogeology of the dry valley region, Antarctica. In: McGinnis, L.D. (Ed.), Dry Valley Drilling Project. American Geophysical Union, Washington, D. C., pp. 193–214.
Chevrier, V.F., Rivera-Valentin, E.G., 2012. Formation of recurring slope lineae by liquid brines on present-day Mars. Geophys. Res. Lett. 39, 1–5.
Claridge, G.G.C., Campbell, I.B., 1968. Origin of nitrate deposits. Nature 217, 428–430.
Claridge, G.G.C., Campbell, I.B., 1977. The salts in Antarctic soils, their distribution and relationship to soil processes. Soil Sci. 123, 377–384.
Clifford, S.M., Lasue, J., Heggy, E., Boisson, J., McGovern, P., Max, M.D., 2010. Depth of the Martian cryosphere: revised estimates and implications for the existence and detection of subpermafrost groundwater. J. Geophys. Res., Planets 115, 1–17.
Dickinson, W.W., Rosen, M.R., 2003. Antarctic permafrost: an analogue for water and diagenetic minerals on Mars. Geology 31, 199–202.
Dickson, J.J., Head, J.W., Levy, J.S., Marchant, D.R., 2013. Don Juan Pond, Antarctica: near-surface $CaCl_2$-brine feeding Earth's most saline lake and implications for Mars. Sci. Rep. 3, 1–7.
Doran, P.T., McKay, C.P., Fountain, A.G., Nylen, T., McKnight, D.M., Jaros, C., Barrett, J.E., 2008. Hydrologic response to extreme warm and cold summers in the McMurdo Dry Valleys, East Antarctica. Antarct. Sci. 20, 499–509.
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., 2002. Antarctic climate cooling and terrestrial ecosystem response. Nature 415, 1–4.
Dundas, C.M., 2020. An aeolian grainflow model for Martian Recurring Slope Lineae. Icarus 343, 1–16.
Dundas, C.M., McEwen, A.S., Chojnacki, M., Milazzo, M.P., Byrne, S., McElwaine, J.N., Urso, A., 2017. Granular flows at recurring slope lineae on Mars indicate a limited role for liquid water. Nat. Geosci. 10, 903–907.
Edwards, C.S., Piqueux, S., 2016. The water content of recurring slope lineae on Mars. Geophys. Res. Lett. 43, 8912–8919.
Friedmann, E.I., Rafter, A., Smith, G.I., 1995. A thermal, isotopic, and chemical study of Lake Vanda and Don Juan Pond, Antarctica. In: Elliot, D.H., Blaisdell, G.L. (Eds.), Contributions to Antarctic Research IV. American Geophysical Union, Washington, D. C., pp. 47–74.
Garrett, D., 2004. Handbook of Lithium and Natural Calcium Chloride: Their Deposits, Processing, Uses, and Properties, 1st ed. Elsevier Academic Press, Amsterdam.
Gooseff, M.N., Barrett, J.E., Northcott, M.L., Bate, B.D., Hill, K.R., Zeglin, L.H., Bobb, M., Takacs-Vesbach, C.D., 2007. Controls on the spatial dimensions of wetted hydrologic margins of two Antarctic lakes. Vadose Zone J. 6, 841–848.
Gough, R.V., Chevrier, V.F., Tolbert, M.A., 2016. Formation of liquid water at low temperatures via the deliquescence of calcium chloride: implications for Antarctica and Mars. Planet. Space Sci. 131, 79–87.
Gough, R.V., Nuding, D.L., Archer Jr, P.D., Fernanders, M.S., Guzewich, S.D., Tolbert, M.A., Toigo, A.D., 2020. Changes in soil cohesion due to water vapor exchange: a proposed dry-flow trigger mechanism for recurring slope lineae on Mars. Geophys. Res. Lett. 47, 1–10.
Gough, R.V., Wong, J., Dickson, J.L., Levy, J.S., Head, J.W., Marchant, D.R., Tolbert, M.A., 2017. Brine formation via deliquescence by salts found near Don Juan Pond, Antarctica: laboratory experiments and field observational results. Earth Planet. Sci. Lett. 476, 189–198.
Green, W.J., Angle, M.P., Chave, K.E., 1988. The geochemistry of Antarctic streams and their role in the evolution of four lakes of the McMurdo Dry Valleys. Geochim. Cosmochim. Acta 52, 1265–1274.
Green, W.J., Canfield, D.E., 1984. Geochemistry of the Onyx River (Wright Valley, Antarctica) and its role in the chemical evolution of Lake Vanda. Geochim. Cosmochim. Acta 48, 2457–2467.
Harris, H.J.H., Cartwright, K., 1981. Hydrology of the Don Juan Basin, Wright Valley, Antarctica. In: McGinnis, L.D. (Ed.), Dry Valley Drilling Project. American Geophysical Union, Washington, D. C., pp. 161–184.
Head, J.W., Marchant, D.R., Dickson, J.L., Levy, J.S., Morgan, G.A., 2007. Slope streaks in the Antarctic Dry Valleys: characteristics, candidate formation mechanisms, and implications for slope streak formation in the Martian environment. In: Seventh International Conference on Mars. Lunar and Planetary Institute, Pasadena, CA.
Knauth, L.P., Burt, D.M., 2002. Eutectic brines on Mars: origin and possible relation to young seepage features. Icarus 158, 267–271.
Leask, E.K., Ehlmann, B.L., Dundar, M.M., Murchie, S.L., Seelos, F.P., 2018. Challenges in the search for perchlorate and other hydrated minerals with 2.1-μm absorptions on Mars. Geophys. Res. Lett. 45, 12180–12189.
Levy, J.S., 2012. Hydrological characteristics of recurrent slope lineae on Mars: evidence for liquid flow through regolith and comparisons with Antarctic terrestrial analogs. Icarus 219, 1–4.
Levy, J.S., Fountain, A.G., Gooseff, M.N., Welch, K.A., Lyons, W.B., 2011. Water tracks and permafrost in Taylor Valley, Antarctica: extensive and shallow groundwater connectivity in a cold desert ecosystem. Geol. Soc. Am. Bull. 123, 2295–2311.
Lyons, W.B., Mayewski, P.M., 1993. The geochemical evolution of terrestrial waters in the Antarctic: the role of rock-water interactions. In: Green, W.J., Friedman, E.I. (Eds.), Physical and Biogeochemical Processes in Antarctic Lakes. American Geophysical Union, Washington, D. C., pp. 135–143.
Marchant, D.R., Head, J.W., 2007. Antarctic dry valleys: microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars. Icarus 192, 187–222.
Marion, G.M., 1997. A theoretical evaluation of mineral stability in Don Juan Pond, Wright Valley, Victoria Land. Antarct. Sci. 9, 92–99.
Massé, M., Conway, S.J., Gargani, J., Patel, M.R., Pasquon, K., McEwen, A., Carpy, S., Chevrier, V., Balme, M.R., Ojha, L., Vincendon, M., 2016. Transport processes induced by metastable boiling water under Martian surface conditions. Nat. Geosci. 9, 425–428.
McEwen, A.S., Chojnacki, M., Dundas, C.M., Ojha, L., Massé, M., Schaeffer, E., Leung, C., 2015. Recurring Slope Lineae on Mars: Atmospheric Origin? European Planetary Science Congress, Nantes, France.
McEwen, A.S., Dundas, C.M., Mattson, S.S., Toigo, A.D., Ojha, L., Wray, J.J., Chojnacki, M., Byrne, S., Murchie, S.L., Thomas, N., 2014. Recurring slope lineae in equatorial regions of Mars. Nat. Geosci. 7, 53–58.
McEwen, A.S., Ojha, L., Dundas, C.M., Mattson, S.S., Byrne, S., Wray, J.J., Cull, S.C., Murchie, S.L., Thomas, N., Gulick, V.C., 2011. Seasonal flows on warm Martian slopes. Science 333, 740–743.
McEwen, A.S., Schaefer, E.I., Dundas, C.M., Sutton, S.S., Tamppari, L.K., Chojnacki, M., 2021. Mars: abundant Recurring Slope Lineae (RSL) following the Planet-Encircling Dust Event (PEDE) of 2018. J. Geophys. Res., Planets 126, 1–12.
McKelvey, B.C., Webb, P.N., 1962. Geological investigations in Southern Victoria Land, Antarctica: part 3 - Geology of Wright Valley. N.Z. J. Geol. Geophys. 5, 143–162.

McLeod, M., 2012. Soil and permafrost distribution, soil characterisation and soil vulnerability to human foot trampling, Wright Valley, Antarctica. University of Waikato, Hamilton, New Zealand.
Ojha, L., Wilhelm, M.B., Murchie, S.L., McEwen, A.S., Wray, J.J., Hanley, J., Massé, M., Chojnacki, M., 2015. Spectral evidence for hydrated salts in recurring slope lineae on Mars. Nat. Geosci. 8, 829–832.
Rivera-Valentín, E.G., Gough, R.V., Chevrier, V.F., Primm, K.M., Martínez, G.M., Tolbert, M., 2018. Constraining the potential liquid water environment at Gale crater, Mars. J. Geophys. Res., Planets 123, 1156–1167.
Samarkin, V.A., Madigan, M.T., Bowles, M.W., Casciotti, K.L., Priscu, J.C., McKay, C.P., Joye, S.B., 2010. Abiotic nitrous oxide emission from the hypersaline Don Juan Pond in Antarctica. Nat. Geosci. 3, 341–344.
Schmidt, F., Andrieu, F., Costard, F., Kocifaj, M., Meresescu, A.G., 2017. Formation of recurring slope lineae on Mars by rarefied gas-triggered granular flows. Nat. Geosci. 10, 270–273.
Sletten, R.S., Mushkin, A., Toner, J.D., 2022. Timelapse photography of Don Juan Pond and surrounding basin. U.S. Antarctic Program (USAP) Data Center.
Stillman, D.E., Grimm, R.E., 2018. Two pulses of seasonal activity in martian southern mid-latitude recurring slope lineae (RSL). Icarus 302, 126–133.
Stillman, D.E., Michael, T.I., Grimm, R.E., Hanley, J., 2016. Observations and modeling of northern mid-latitude recurring slope lineae (RSL) suggest recharge by a present-day martian briny aquifer. Icarus 265, 125–138.
Toner, J.D., Catling, D.C., Light, B., 2014. Soluble salts at the Phoenix Lander site, Mars: a reanalysis of the Wet Chemistry Laboratory data. Geochim. Cosmochim. Acta 136, 142–168.
Toner, J.D., Catling, D.C., Sletten, R.S., 2017. The geochemistry of Don Juan Pond: evidence for a deep groundwater flow system in Wright Valley, Antarctica. Earth Planet. Sci. Lett. 474, 190–197.
Toner, J.D., Sletten, R.S., 2013. The formation of Ca-Cl enriched groundwaters in the Dry Valleys of Antarctica by cation exchange reactions: field measurements and modeling of reactive transport. Geochim. Cosmochim. Acta 110, 84–105.
Toner, J.D., Sletten, R.S., Prentice, M.L., 2013. Soluble salt accumulations in Taylor Valley, Antarctica: implications for paleolakes and Ross Sea Ice Sheet dynamics. J. Geophys. Res. 118, 198–215.
Wilson, A.T., 1979. Geochemical problems of the Antarctic dry areas. Nature 280, 205–208.
Winsor, K., Swanger, K.M., Babcock, E.L., Dickson, J.L., Valletta, R.D., Schmidt, D.F., 2020. Origin, structure and geochemistry of a rock glacier near Don Juan Pond, Wright Valley, Antarctica. Antarct. Sci. 32, 273–287.