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Don Juan Pond, Antarctica: Near-surface $CaCl_2$-brine feeding Earth's most saline lake and implications for Mars

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The discovery on Mars of recurring slope lineae (RSL), thought to represent seasonal brines, has sparked interest in analogous environments on Earth. We report on new studies of Don Juan Pond (DJP), which exists at the upper limit of ephemeral water in the McMurdo Dry Valleys (MDV) of Antarctica, and is adjacent to several steep-sloped water tracks, the closest analog for RSL. The source of DJP has been interpreted to be deep groundwater. We present time-lapse data and meteorological measurements that confirm deliquescence within the DJP watershed and show that this, together with small amounts of meltwater, are capable of generating brines that control summertime water levels. Groundwater input was not observed. In addition to providing an analog for RSL formation, $CaCl_2$ brines and chloride deposits in basins may provide clues to the origin of ancient chloride deposits on Mars dating from the transition period from "warm/wet" to "cold/dry" climates.

Don Juan Pond (DJP), found at the lowest point in the South Fork of Upper Wright Valley, Antarctica (Figure 1a), is the most saline natural body of water in the world[1]. As a consequence, it rarely freezes, even when the surface temperature descends to -50°C during Austral winter and it is a unique site for the study of habitability in extreme environments on Earth[2–4], and potentially for life on Mars[2,3]. Unlike larger, ice-covered lakes in the McMurdo Dry Valleys (MDV), DJP is isolated from fresh, glacial runoff as it is bounded to the north and south by steep inclines that expose outcrops of granitic basement material and Jurassic-aged dolerite sills[5], to the west by a channel-incised and ice-cemented sediment lobe (also mapped as an inactive rock glacier)[6,7], and to the east by a shallow slope characterized by ~20 cm of colluvium above an impermeable, ice-cemented permafrost layer[8]. Multiple water tracks[8] are observed within the colluvium to the east of DJP[7], as is a stream-channel system at the easternmost extent of the Don Juan basin (Figure 1b).

In addition to the hyper-salinity of DJP (~40% by mass)[1,2,10–14], the composition of the brine is unlike any other body of water in the world, as ~90% of the salt is $CaCl_2$[1,2,10–14]. Thus, any model that can successfully explain how salts are transported to DJP must also explain how the $CaCl_2$ is isolated. Previous studies have proposed both deep groundwater[13] and near-surface active layer transport for the DJP brine[14], with the majority of studies favoring upwelling from a weathered-dolerite aquifer[2,3,13,15]. We sought to document input into the pond by monitoring DJP during Austral spring/summer with high-resolution, long-duration, high-frequency time-lapse photography. These observations, synchronized with a suite of meteorological measurements and viewed in conjunction with previous studies of the geochemistry of Don Juan basin, permit a reassessment of the most likely contributors to the unprecedented salinity of Don Juan Pond.

Results

Sources of Water in Don Juan basin. Several potential sources for water are available within Don Juan basin[12,14] (Figure 1): (1) direct precipitation (snow); (2) stream input from the western lobe; (3) upwelling of a deep groundwater aquifer; and (4) active layer transport atop the permafrost table within the colluvium east of DJP.

First, while the pond is subject to direct snow precipitation, this produces only between 5 and 10 g/cm^2 annually[12], most of which is lost via sublimation[12,16]. Further, while direct snowfall inputs salt into the pond, there is no reason for snow-deposited salts to produce a fractionation in favor of $CaCl_2$[17]. Thus, direct snowfall is not considered a significant source of water and/or $CaCl_2$ within DJP.

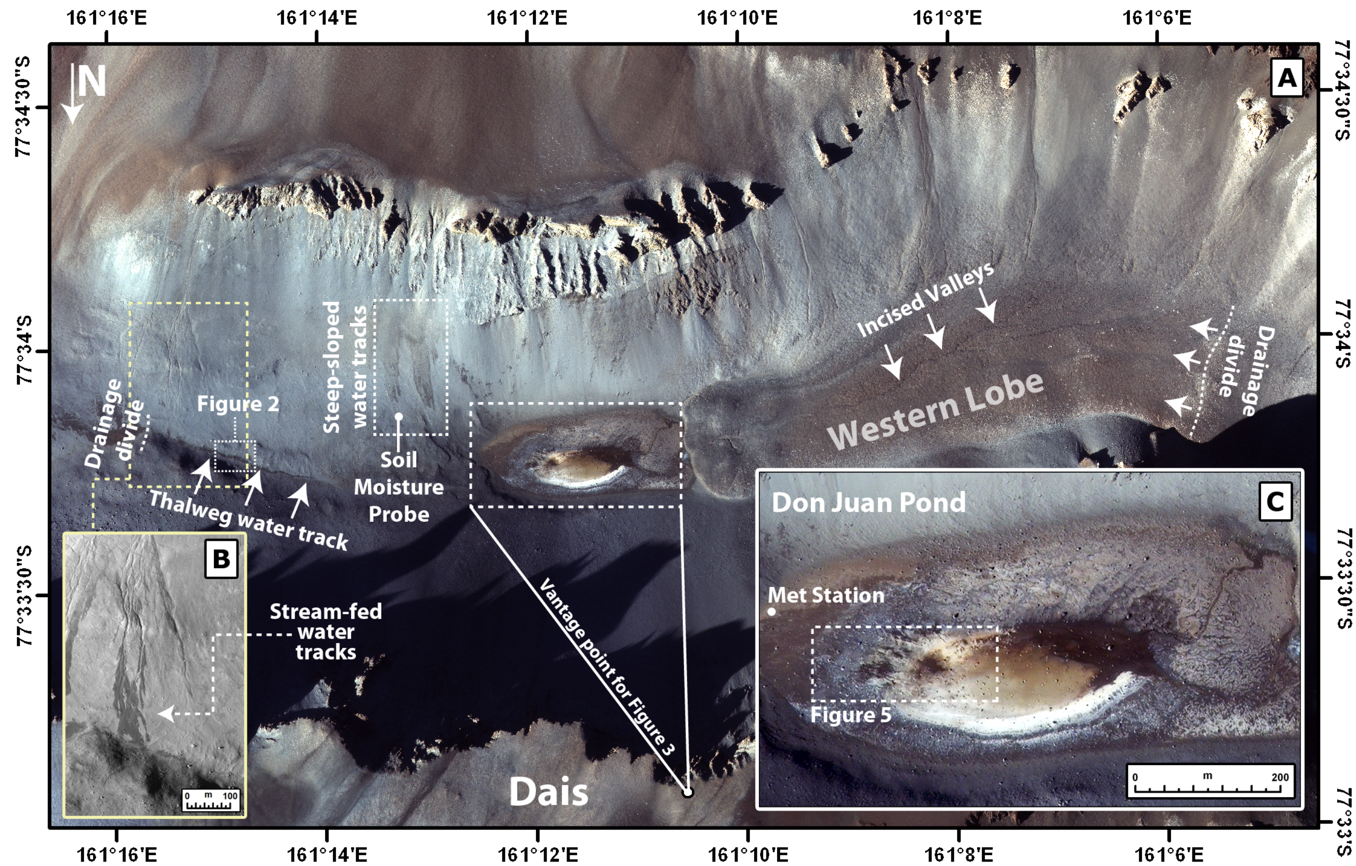

Figure 1 | (A) Don Juan basin in the South Fork of Upper Wright Valley, McMurdo Dry Valleys, Antarctica. Don Juan Pond is found at the lowest point of the basin. The pond is bounded by steep (~30°) slopes to the north and south, a debris-covered lobe to the west, and colluvium-mantled terrain to the east, where the most prominent water tracks are observed. IKONOS orbital color image, acquired on February 1, 2009. (B) The eastern-most channels within Don Juan basin. When active, these channels produce water tracks at their termini that connect to the water track on the thalweg east of Don Juan Pond (Figure 2). IKONOS orbital pan-chromatic image, acquired on January 31, 2003. (C) Inset of Don Juan Pond on February 1, 2009.

Second, the viscous lobe to the west of DJP[6,7] is incised by a small network of 1–2 m-wide channels (Figure 1a) that drain into DJP during peak summer conditions through distributaries adjacent to the western edge of the pond (Figure 1c). Several investigations[10,12,13] involving major ion analysis of water in this stream have shown that it is low salinity (TDS $<$ 500 ppm)[12] and is depleted in Ca^{2+} and Cl^- relative to Na^+ and SO_4^{2-}, respectively[13], suggesting a snowmelt origin for the water and salt ratios that preclude it from being a candidate for the source of $CaCl_2$ in DJP. This corroborates our own field observations that this water is sourced by channel-trapped snow on the surface of the western lobe.

Third, previous studies have attributed the extreme salinity to upwelling of a relatively deep (tens of meters) bedrock aquifer[2,13,15]. Electrical depth soundings[19,20] and seismic profiles[20] provided consistent findings that the terrain beneath DJP is unfrozen to depths of tens of meters. Abrupt shifts in both seismic velocity and resistivity were observed at ~30 m depth on the eastern margin of the pond, and this interface sloped to ~60 m depth below the western margin of DJP. The geophysical properties of each medium were interpreted as unfrozen basement rock superposed by wet lacustrine deposits immediately underlying the pond[20]. Samples of water collected during the Dry Valley Drilling Project (DVDP) showed that subsurface water beneath the pond was enriched in $CaCl_2$, though there was a contrast in weight percent of the total solution between samples at the surface and samples at depth: 17% and 18% $CaCl_2$ concentration for samples from 15 m and 58 m depth, respectively, versus 34% for surface waters[13]. Given that evaporation at the surface could concentrate the salts, this led to the prevailing model for transport of salts to DJP, in which upwelling from a weathered dolerite aquifer at ~60 m depth through an unfrozen stratum of lake sediments feeds the pond.

Finally, multiple studies have shown that water flows across the top of the permafrost table east of DJP[8,13,18]. At the surface, this process is manifested as water tracks[8,9,21,22], zones of high soil moisture that act as downslope paths for saline liquids on top of the permafrost table (~10 cm depth) that wick up to the surface in low-slope, fine-grained soils, creating linear patterns of seasonal surface darkening[8,9] (Figure 1a,b). Geochemical measurements[14] of this liquid to the east of DJP showed that, like DJP, it is enriched in Ca^{2+} relative to Na^+ and has low Na^+/Cl^- ratios, consistent with recent measurements of water tracks in the Lake Hoare basin in Taylor Valley[6]. This Ca^{2+} and Cl^- enrichment led *Wilson*[14] to propose that salts left by sublimated snow at the surface are separated when humidity fronts pass through Don Juan basin. Salts that deliquesce at lower relative humidity (like $CaCl_2$) are more mobile. During humidity optima, they preferentially deliquesce and percolate through the colluvium until they encounter the impermeable permafrost table. Once there, humidity-separated brines can be transported to DJP via flushing by seasonal snowmelt[8] from (1) a stream channel at the easternmost extent of Don Juan basin (Figure 1b) or (2) alcove-trapped snowpacks that accumulate above steep-sloped water tracks (Figure 1a)[8].

Time-lapse observations and measurements of relative humidity that we obtained of the thalweg east of Don Juan Pond (Figure 1a) in December, 2010, show that water tracks rapidly respond to moist air by hydrating and darkening (Figure 2), demonstrating that deliquescence and brine hydration is an active process within the DJP

Figure 2 | Frames from a time-lapse sequence of water track darkening on the thalweg of South Fork (location in Figure 1a). Full sequence can be accessed via supplementary information. Darkening occurs while the entire scene is under the shadow of the Asgard Range to the south, ensuring that darkening is not a photometric effect from variable solar incidence angle. The darkening directly correlates with a steep increase in relative humidity, such that salts in the water track are absorbing water from the atmosphere (deliquescence), and that hydration of these brines moistens the surface. Relative humidity measurement is from a meteorological station on the edge of DJP, ~975 m upvalley/downslope from the observation (Figure 1c). This same steep increase in relative humidity was observed 15 minutes earlier at another met station 1.1 km downvalley/upslope from this site. This is consistent with a mass of moist air moving inland from the coast towards the ice cap.

watershed. Since the water track on the thalweg east of DJP was already relatively damp compared to the surrounding terrain at the outset due to drainage from snowmelt channels found upslope (Figure 1b), this process appears to concentrate atmospheric-derived moisture in high salinity soils, rather than uniformly dampening all soils[23].

Here, we evaluate the relative importance of these hydrological processes by examining interactions among water tracks, snow-fed steams, and putative groundwater discharge. Since it is not recharged by glacial meltwater, DJP is very shallow (generally ~ 10 cm[1,10] though it can deepen to ~23 cm[20]). Thus, detailed monitoring during a relatively low precipitation year provides the opportunity to detect inputs into the pond. During the 2009–2010 summer field season, we imaged the pond at 5-minute intervals from late November 2009 through January 2010 from the southern end of the Dais, a mesa perched ~750 m above DJP (see Figure 1a for vantage point). From the 16,280 acquired images during this timespan, we mapped all evidence for input into the pond in order to evaluate the magnitude of contributions to lake surface area (a proxy for volume) from (1) deep groundwater upwelling from the central and southern portion of the pond, (2) water track discharge from the east, where water tracks are observed, and (3) fresh snow-fed stream discharge from the west. This imaging campaign was performed in concert with soil moisture measurements on one of the steep-slope water tracks above the pond to the east (Figure 1a), as well as a suite of meteorological observations acquired from the easternmost portion of the salt pan surrounding the pond (Figure 1c).

Our time-lapse observations of DJP show that discharge into the pond is controlled by diurnal surface temperature cycles, which are a function of insolation (Figure 3). While the sun does not astronomically set during this time period in the MDV, the steep southern wall of Upper Wright Valley creates a diurnal shadowing of the floor of the Don Juan basin (Figure 1a), such that surface conditions permit melting of near-surface/surface ice during the day but not at night, when the sun is behind the Asgard Range to the south (approximately 22:00 to 06:15 the next morning at summer solstice).

Using pond surface area as a proxy for volume, time-lapse image data reveal that the most significant input of liquid into DJP comes

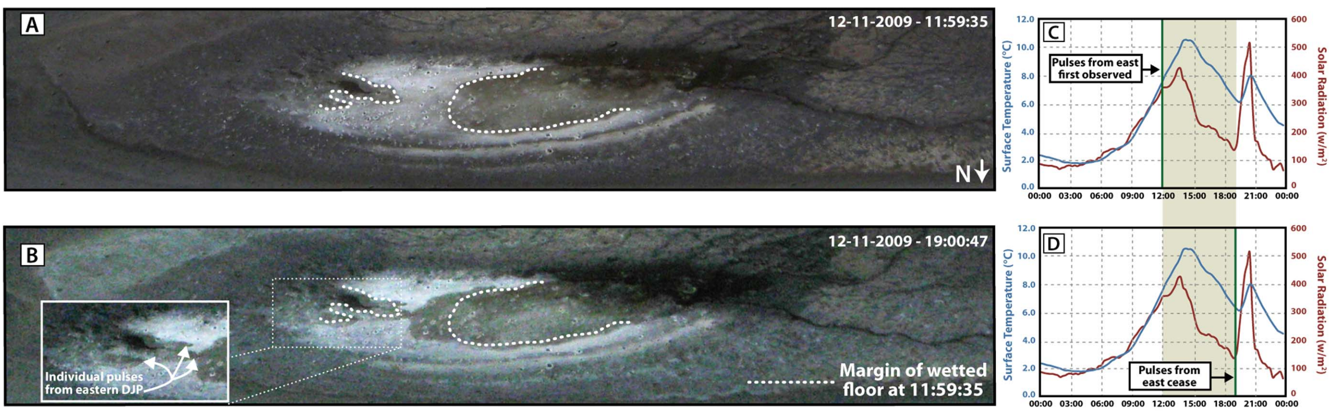

Figure 3 | Time-lapse image pair of discharge into Don Juan Pond on December 11, 2009, with discharge observed from both the west and the east. Full time-lapse sequence showing activity throughout late-spring/early-summer can be accessed via supplementary information. Images were acquired at 5-minute intervals from the southern margin of the Dais (see Figure 1a for vantage point). Daily pulses of fresh water input from stream activity atop the adjacent debris-covered lobe are observed to come from the west, while small swarms of discharge are observed to come from the eastern margin of the pond. These seeps are interpreted to be discharge of $CaCl_2$-rich brines that are transported through the dry active layer east of the pond on the top of the permafrost table. Pulses correlate with diurnal increases in surface temperature (measurements acquired from a meteorological station on the easternmost edge of the DJP salt pan – see Figure 1c for location).

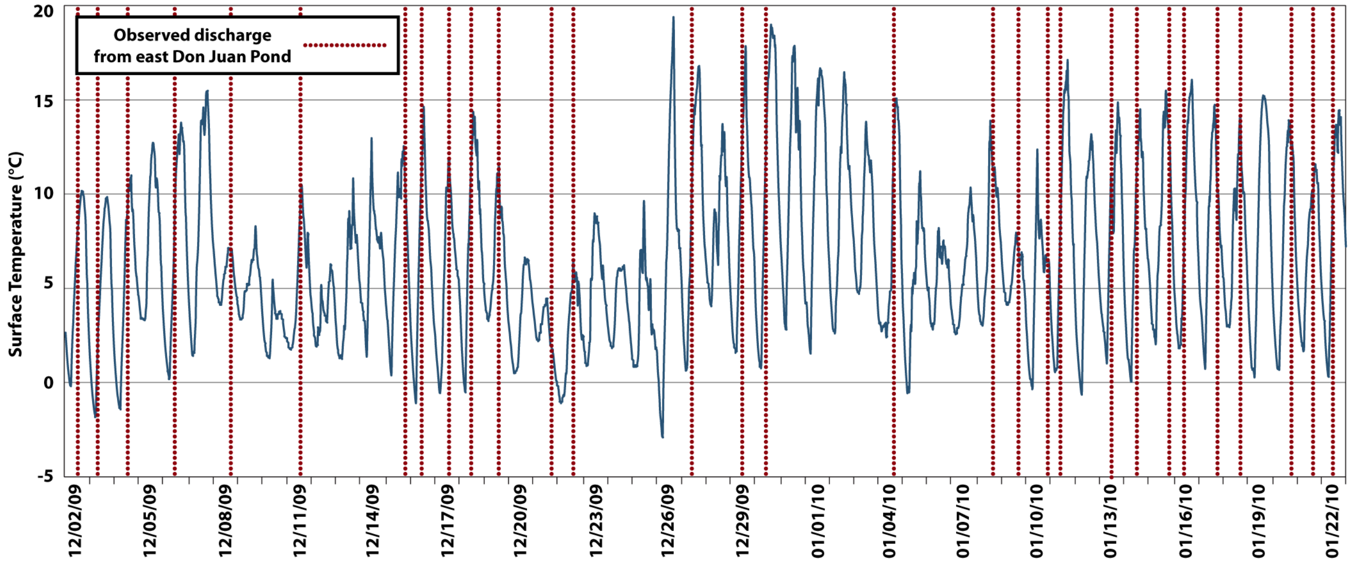

Figure 4 | The surface temperature record from the salt pan surrounding Don Juan Pond with discharge events from the eastern margin of DJP (red dashed lines). Discharge from the eastern margin of the pond is directly correlated with steep increases in surface temperature, which is controlled by diurnal cycles in peak insolation.

from the freshwater stream that incises the lobe adjacent to the western margin of the pond (Figure 3). Snow and ice trapped within the channel melt and produce surface area-expanding pulses that extend nearly across the entire pond on particularly warm days (Figure 3). These pulses occur at the same time of day as sudden spikes in the hydrograph measurements of Harris and Cartwright[13] from early December 1975 that they interpreted as seiches. The water pulses soak into the underlying lacustrine sediments on the floor of the pond, filling pore spaces in the pond shore zone. Samples from previous studies have shown that this water is fresh[10,12,13] and has an ionic ratio that precludes it from being the primary driver of DJP chemistry.

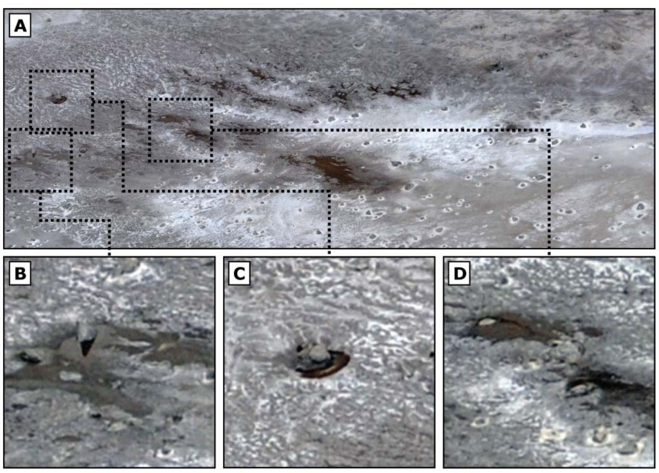

Figure 5 | (A) Discharge locations on the eastern margin of Don Juan Pond (see Figure 1c for location). (B) Multiple nearby boulders are observed to have liquid discharged at the surface, consistent with boulders depressing the near-surface permafrost table. (C) A large boulder hosts liquid in the downslope portion of its annular moat. (D) A boulder is nearly buried by discharged liquid that is flowing downslope, in the direction of DJP. Image was acquired on December 8, 2009, when time-lapse observations show discharge from this portion of the pond (Figure 4).

The other observed input to DJP is discharge from the eastern margin of the pond (Figure 3), observable on 30 of the 52 days of the study (Figure 4). Instead of one major pulse, as is observed from the freshwater stream to the west of the pond, this discharge is characterized by small swarms of individual pulses that start from large boulders embedded in the lake sediments (Figure 5) and migrate towards the center of the pond. Like the larger freshwater pulses from the west, these pulses are strongly correlated with steep increases in surface temperature (~8–10°C over ~5–7 hours), as activity is always observed during peak insolation conditions (Figure 4). There is little to no lag between peak temperature and discharge, suggesting that warming is not propagating into a deep aquifer. In 16,280 images, these small pulses are only observed on the eastern margin of the pond, which is above and outside of the potential groundwater discharge zone identified by Harris & Cartwright[13].

Detailed observations of the boulders on the eastern margin of the salt pan of DJP (Figure 5) show that they frequently host pond liquid in their annular moats, while others host bright halos of evaporites, relationships not commonly observed around other portions of the pond. In some cases, the pond liquids overtop their moats in the direction of the center of the pond and flow downslope (Figure 5d). Boulders generate breaks in slope in other Dry Valley water tracks, where they act as springs that discharge at the ground surface[9,24,25], as observed elsewhere in South Fork[26].

In order to determine if liquids were flowing through the water tracks east of DJP (Figure 1a) at the time that discharge was observed on the eastern margin of DJP (Figure 3), we instrumented one of the steep-sloped water tracks[8] with Decagon ECH$_2$O soil moisture probes on and off of the track starting on December 10, 2009 (location in Figure 1a). Soil moisture on the water track is consistently greater than soil moisture 1 m off the track's eastern margin (Figure 6). A noticeable increase in soil moisture on the track occurred close to 1 January, which followed a week-long period of extremely warm conditions when surface temperatures were never below 0°C and peak surface temperatures approached 20°C. This ~1-week lag between increased surface temperature and water track moisture increases is repeated several times through our three-year temperature/soil-moisture record of this site (austral spring 2009 through austral summer 2012), which favors a scenario by which fresh meltwater from (1) seasonal snow trapped in alcoves at

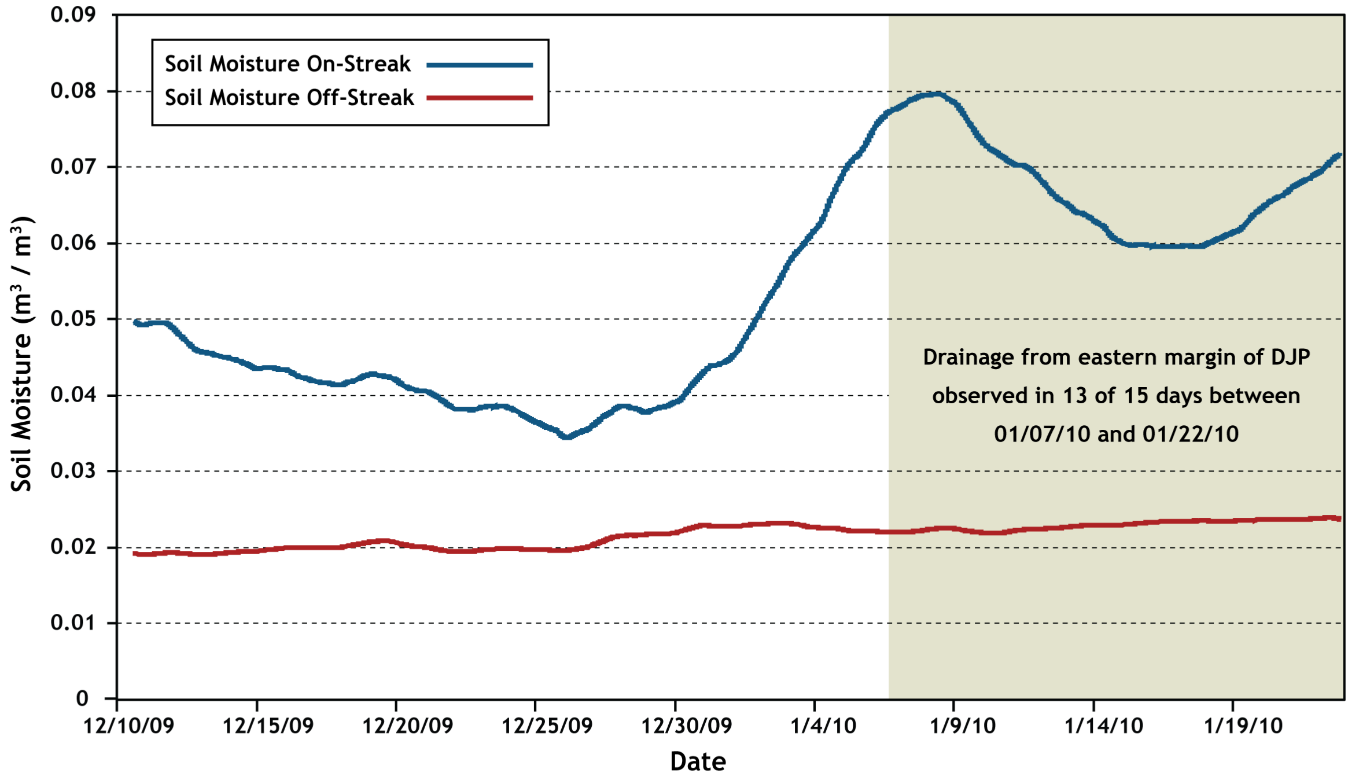

Figure 6 | Soil moisture recorded on and off of one of the major steep-sloped water tracks on the southern (equator-facing) wall above Don Juan Pond (see Figure 1a for location). Sensors were placed 1-meter on the track and 1-meter off the track. Values were recorded every 15 minutes, and plotted as 24-hour averages. Activity is clearly concentrated entirely within the track. Increased soil-moisture activity during the middle of January corresponds to the most concentrated activity of discharge into DJP from its eastern margin.

the heads of the steep-sloped water tracks[8] and (2) perennial snowbanks at the base of the neighboring Asgard Range[27] percolates downslope and flushes the deliquescence-derived $CaCl^2$ brine downslope towards DJP, using the channel system at the eastern-most extent of Don Juan basin as a conduit (Figure 1b). Soil moisture on the track also remained elevated from January 7 through the end of the month (Figure 6). On the eastern margin of DJP, pulses from the east were observed on 13 of the 15 days from January 7 until January 22, when data collection ceased for the season (Figure 4).

Discussion

Our observations indicate that discharge of $CaCl_2$-rich brines that flow across the top of the permafrost table are the likely source for the extreme salinity measured in DJP. Evidence for internal filling of DJP from upwelling of a deep aquifer was not found during our imaging campaign. The only two liquid sources that provided measurable changes to DJP surface area from November 27, 2009 to January 22, 2010 were freshwater stream discharge from the west and active water track transport from the east. Evaporative mixtures of stream water and water track fluids can account for the chemistry of DJP and produce the observed filling and hydrograph patterns reported by Harris and Cartwright[13]. As this transport mechanism more effectively explains the abundance of $CaCl_2$ compared to other salts[11], it readily accounts for all of the geochemical measurements[11–14] in addition to the flow-direction observations documented in this study (Figure 3).

These results also provide a model in which it is possible to maintain ecosystem-sustaining hydrological systems in Earth's coldest and driest environments entirely through atmospheric interaction with the surface, without invoking deep groundwater resources. Therefore, this model may have broad implications, explaining why larger, ice-covered MDV lakes tend to have high basal salinity readings[14], including those with water tracks within their watershed[9]. Water tracks that drain into larger fresh-water lakes contribute $CaCl_2$-rich brines that are denser than the more-abundant freshwater[9]. Therefore, the brines should be concentrated at the base, a trend that is observed[14]. Furthermore, water circulation in the absence of a deep groundwater connection makes this a plausible model for a hydrologic system on present-day Mars, where extremely low temperatures (-55°C annual average, $+27^\circ$C maximum, -143°C minimum; in comparison with an annual average of -20°C, monthly average maximum of 11°C, and monthly average minimum of -54°C) at all latitudes and a global permafrost layer should largely preclude deep aquifer interaction with the surface, and for ancient Mars, when surface waters were more abundant.

The features that feed $CaCl_2$ to DJP, water tracks (Figure 1a,b), are similar in planform morphology to recently discovered Recurring Slope Lineae (RSL) in the southern mid-latitudes of Mars: low-albedo streaks of soil on steep ($\sim 30^\circ$) slopes that advance and recede each martian year, initiating when surface temperatures approach the melting point of H_2O[28]. Downslope propagation rates for RSL and Antarctic water tracks are consistent with each being formed by brine flow through a shallow regolith, based on remotely measured average permeability values of 10^{-8} to 10^{-9} cm^2 for RSL and 10^{-6} to 10^{-7} cm^2, which are consistent with fluid flow through sandy, unconsolidated sediments[29].

Could a DJP-like hydrological system be active on modern Mars? Chloride-bearing salts have been documented on Mars from both in-situ[30] and remote[31] observations, and peak daily temperatures on the warm, equator-facing slopes where RSL are observed frequently surpass 0°C[28]. Seasonal water frost is observed on the surface in hyperspectral data at latitudes as low as 12° in the southern hemisphere[32,33], such that sufficient atmospheric water vapor is available to initiate relative deliquescence at mid-latitudes, where RSL are found. Therefore, the essential conditions for a DJP-like hydrological system may be transiently achievable on contemporary Mars at RSL-bearing locations.

Chloride-bearing units exposed within topographic basin floors have also been mapped from orbit in the southern hemisphere of Mars[31]. Unlike RSL, which are active today, these units are primarily found within ~4 Gyr old Noachian terrain, suggesting that they were deposited early in Mars' history when conditions were more conducive to liquid water stability than today. The chemical separation and transport mechanisms that produced these units are not well understood, but the cold-desert model provided by DJP of humidity-induced relative deliquescence may be applicable, provided that they were formed in the absence of pluvial activity[14].

While the volumes of freshwater available to these hydrologic systems on Mars is unknown, recent work in the Atacama desert has provided in-situ documentation of cyanobacteria that are capable of subsisting entirely on the brines created from deliquescence in halite rocks[34], a very localized ecological model that has been proposed for Mars in the past[35]. Furthermore, work in the MDV has shown that certain organisms are capable of being preserved in a cryptobiotic state for decades, then flourish once exposed to stream waters[36]. Thus, if RSL and chloride-bearing basin floor units on Mars do represent DJP-like hydrologic systems, they may have significant potential for hosting resilient microbiota, and the most habitable places on Mars may mimic the least habitable places on Earth.

Methods

The color image in Figure 1a and 1c was acquired on February 1, 2009 and is composed of 4 m/pixel IKONOS multi-spectral data (Blue: 0.445–0.516 μm; Green: 0.506–0.595 μm; Red: 0.632–0.698 μm), pan-sharpened in ENVI to 1 m/pixel using 1 m/pixel panchromatic imagery (0.45–0.90 μm). The grayscale image in Figure 1b was acquired on January 31, 2003 and consists of 1 m/px panchromatic imagery (0.45–0.90 μm). Both images were orthorectified in ENVI using 200 m/pixel RADARSAT topography data and rendered in ArcMap in Lambert Conformal Conic projection (central meridian: 162°E; Standard Parallel 1: 76.66667°S; Standard Parallel 2: 79.33333°S; Latitude of Origin: 78.0°S).

The time-lapse imagery from December 2010 (Figure 2) was acquired at 2-minute intervals with a firmware-modified Canon PowerShot SX1 digital camera, located at 77.563°S, 161.256°E. Relative Humidity was measured using an Onset 12-bit Temperature/RH probe (S-THB-M002) inside a solar radiation shield, sampling every 3 minutes (averaged for one reading every 15 minutes) 2 m above the surface on the easternmost edge of the salt pan surrounding Don Juan Pond (77.563°S, 161.208°E). Data and time-lapse imagery were synchronized using proprietary software written by the authors that correlates timestamps on images with meteorological data tables, such that each image is no more than 7.5 minutes before/after the correlated measurement (which is logged every 15 minutes in an Onset HOBO Microstation).

The time-lapse imagery from January 2010 (Figure 3) was acquired at 5-minute intervals with a firmware-modified Canon Powershot a590 IS digital camera, located on the southern margin of the Dais (77.551°S, 161.176°E). Ground surface temperature was recorded at the surface of the easternmost edge of the salt pan surrounding Don Juan Pond (77.563°S, 161.208°E) with an Onset 12-bit Temperature probe (S-TMB-M002) located $<$2 cm below the surface logged by an Onset HOBO Microstation.

Figure 5 consists of portions of a high-resolution panorama of Don Juan Pond acquired from the southern edge of the Dais (77.551°S, 161.176°E).

Soil moisture measurements from Figure 6 were acquired using two identical Decagon ECH$_2$O soil moisture probes placed on the surface of a water track ($<$2 cm below the surface) and 1 m off the surface of the water track (77.564°S, 161.221°E), logged by a single Onset HOBO Microstation.

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Author contributions

Conceived and designed the time-lapse experiments: JD. Conceived and designed the meteorological experiments: JD, JH and JL. Performed the experiments: JD, JH and JL. Wrote the paper: JD, JH, JL and DM.

Additional information

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