Salt deliquescence along boulder cracks in the Antarctic Dry Valleys: An overlooked source of moisture for rock weathering processes

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Abstract

Cracking is a primary rock-weathering mechanism in arid environments, where dry conditions typically limit the efficacy of water-driven weathering processes. Here, we present results from a field-based experiment in the hyper-arid and frigid Antarctic Dry Valleys (ADV) that documented recurring periods of transient accumulation of liquid water along rock cracks during otherwise dry conditions. This moisture was likely sourced from the deliquescence of hygroscopic salts during sub-saturated humidity conditions. Analysis of meteorological data from 17 stations scattered throughout the ADV revealed that near-surface atmospheric conditions across one of Earth's driest environments can annually support tens of such deliquescence-efflorescence cycles of hygroscopic salts, e.g., $CaCl_2$, $NaNO_3$, NaCl, and $MgCl_2$. This deliquesced moisture may have an important role in the cracking processes of ADV rocks. In a broader context, the results from the ADV suggest that deliquesced atmospheric humidity may be an overlooked source of moisture available for rock weathering processes in otherwise extremely dry deserts on Earth and possibly Mars.

1 Introduction

1.1 Rock weathering in hyper-arid environments

Rock weathering is broadly regarded as a key and often rate-limiting process in the subsequent evolution of terrestrial landscapes. In hyperarid environments, physical disintegration, i.e., the breakup of rocks through cracking, is typically a dominant mode of weathering because the characteristic dry conditions in such settings limit the efficacy of water-dependent chemical, biological, and frost weathering mechanisms (Cooke, 1981; Cooke & Smalley, 1968). When rocks or other brittle materials are subjected to low stresses, cracks can propagate subcriticaly (Anderson, 2005; Atkinson, 1984). Natural stresses in arid climates are likely dominantly subcritical in magnitude and commonly attributed to repeated cycles of thermal expansion/contraction in response to diurnal insolation dynamics (e.g., McFadden et al., 2005) or salt weathering (Desarnaud et al., 2016; Sperling & Cooke, 1985; Steiger et al., 2008; Winkler & Wilhelm, 1970). Nonetheless, laboratory, as well as field-based studies, have shown that even a slight increase in moisture can significantly increase the rates at which these otherwise 'dry' rock-cracking mechanisms can operate (Eppes et al., 2020; Eppes & Keanini, 2017; Meredith & Atkinson, 1985; Yoshitaka Nara et al., 2010, 2012; Waza et al., 1980). Here, we present field-based evidence from one of Earth's driest and coldest deserts that the deliquescence of atmospheric humidity by hygroscopic salts is an effective pathway for water delivery to rock cracks. This moisture delivery pathway to rock cracks may have an important and previously overlooked pace-setting role in the cracking process of rocks in hyper-arid environments.

1.2 The Antarctic Dry Valleys

The Antarctic Dry Valleys (ADV) (Fig. 1) are amongst the coldest and driest 'ice-free' regions on Earth (Doran et al., 2002; Fountain et al., 2010; Obryk et al., 2020). The mean annual air temperatures on the valleys floors range between −15°C and −30°C, depending on the location (Obryk et al., 2020), and precipitation is limited to less than 50 mm/yr that occurs primarily as snowfall (Fountain et al., 2010). These hyperarid and frigid conditions have prevailed in the ADV since the Plio-Pleistocene (Fielding et al., 2011; Scopelliti et al., 2013), resulting in one of the slowest eroding landscapes on Earth with estimated bedrock erosion rates below 1 m/m.y. (Balco & Shuster, 2009; Brook et al., 1995; Margerison et al., 2005; Marrero et al., 2018; Staiger et al., 2006; Sugden et al., 1999; Summerfield et al., 1999). As such, the ADV environment is also regarded as a prime analog site for the present-day hyperarid and cold surface conditions on Mars (Head & Marchant, 2014; Sletten et al., 2003; Tamppari et al., 2012). Rock weathering processes in the ADV have been previously attributed to thermal stress mechanisms (Campbell & Claridge, 1987; Hall, 1999; Lamp et al., 2017) or to hygroscopic salts (Campbell & Claridge, 1987; Johnston, 1973; Selby & Wilson, 1971; Wellman & Wilson, 1965), that accumulate at or near the ADV surface due to the extremely dry conditions (Bisson et al., 2015; Keys, 1979; Keys & Williams, 1981). The presence of up to ~30 salt phases was previously reported in the ADV soils, including hygroscopic salts, such as NaCl, $MgCl_2$, $NaNO_3$, and $CaCl_2$ (Bisson et al., 2015; Claridge & Campbell, 1977; Goudie & Cooke, 1984; Keys, 1979; Keys & Williams, 1981; Miotke & von Hodenberg, 1983; Tamppari et al., 2012; Wilson, 1979).

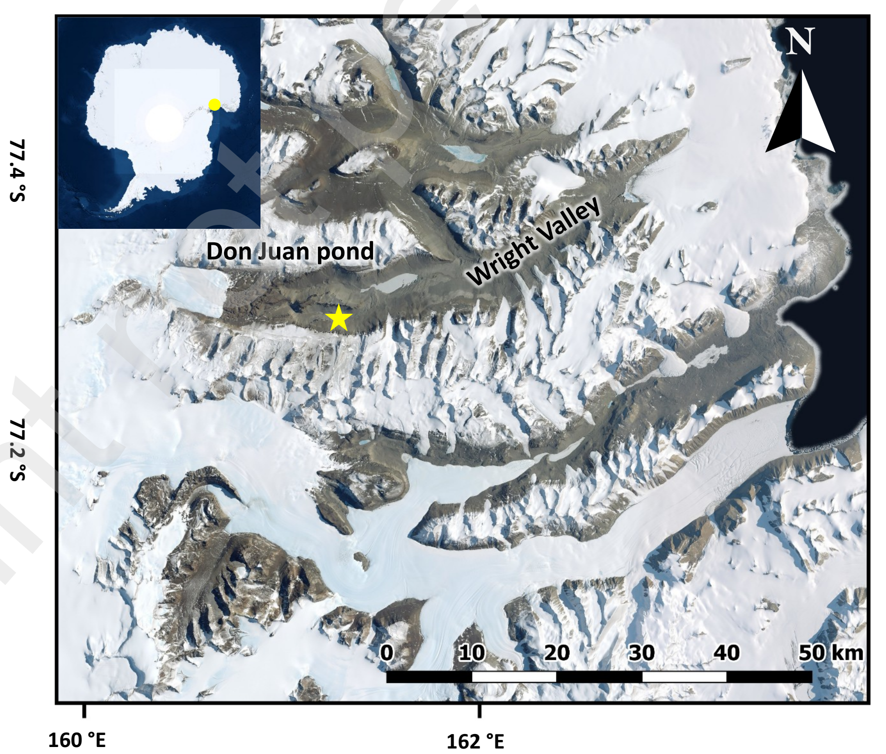

Figure 1: Annotated satellite image of the Antarctic Dry Valleys. Yellow star marks the field site near Don Juan pond in Wright valley. The satellite image was obtained through the QuickMapServices QGIS plugin, from ESRI server (ArcGIS/World_Imagery).

1.3 Salt deliquescence in the ADV

Deliquescence occurs when the relative humidity (RH) of the air mass exceeds the deliquescence relative humidity (DRH) of a specific salt or a salt mixture, and atmospheric water is absorbed and forms a brine that can further adsorb water. Efflorescence is the reverse process that occurs when relative humidity is reduced below the efflorescence relative humidity (ERH) and recrystallization occurs. Salt deliquescence/efflorescence dynamics have been previously documented in the ADV soils as the appearance of transient 'wet patches' (Gough et al., 2016; Harris & Cartwright, 1981; Head et al., 2007; Levy, 2021; Toner et al., 2022) or 'wet slope streaks' (Toner et al., 2022) during events of increased atmospheric humidity. The present study tests whether and how such deliquescence/efflorescence dynamics can facilitate rock-cracking processes in the ADV.

2 Methods

2.1 Field experiment and laboratory analyses

A field-based 10-day experiment was performed using local meteorological measurements (Kestrel 5500), time-lapse photography (Brinno TLC 200), and thermal imaging (FLIR SC430) of a Ferrar Dolerite boulder with incipient cracks near the Don Juan pond in Wright Valley (Fig. 1, 2). After the experiment, extraction of the boulders revealed light-toned salts along the rock cracks that were embedded in the soil during the experiment (Fig. 2b, c). Mineralogical and chemical analyses of the salts were performed at the Geological Survey of Israel. Salts samples taken from a crack in the boulder were dissolved in distilled water, and chemical analysis for major cations was conducted using inductively coupled plasma-optical emission spectrometry (Perkin Elmer, Optima 5300) and major anions using ion chromatography (Dionex ICS-2000). Mineralogic analysis was performed using bulk X-ray diffraction. Mineral phase identification and semi-quantification were performed using HighScore Plus® software based on the ICSD database.

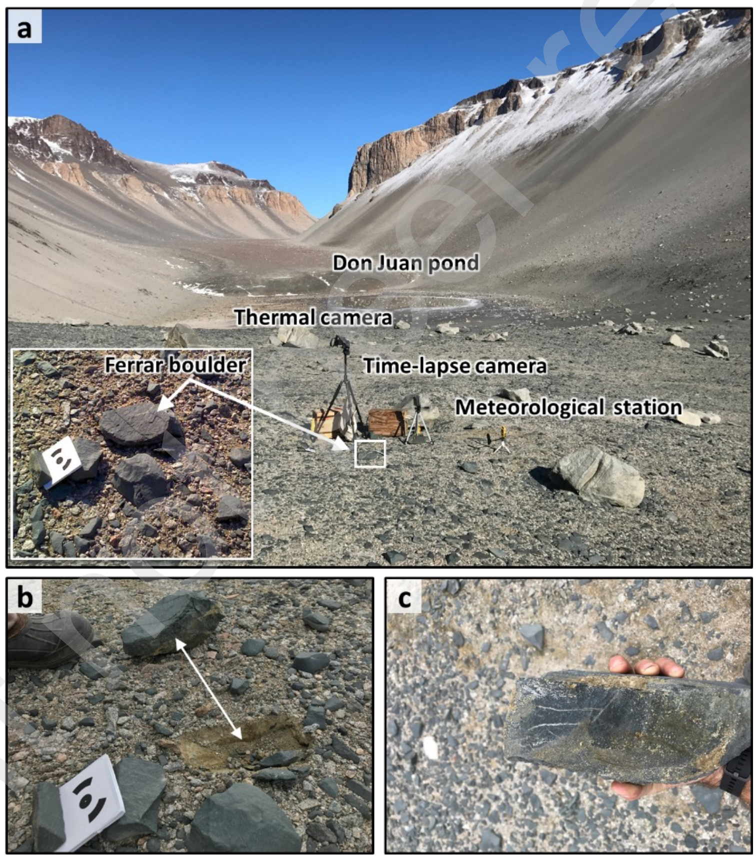

Figure 2: a) Field experiment setup near Don Juan pond (in the background, west of the experiment site) in Wright Valley. White arrows mark the imaged boulder. The length of the boulder is 25 cm. Monitoring equipment includes: a time-lapse optical camera used to detect wetting events, a mobile meteorological

station, and a thermal camera. b) Image of the Ferrar dolerite boulder removed from the soil after the experiment (white arrow). c) The underside of the Ferrar dolerite boulder showing accumulation of salts in cracks.

2.2 Meteorological data

Meteorological data from 17 weather stations scattered throughout the ADV were used to examine the occurrence of deliquescence-efflorescence conditions for $NaNO_3$, $CaCl_2$, NaCl, and $MgCl_2$. The weather stations are part of the McMurdo Long Term Ecological Research Project (MCM LTER) in the ADV. Most stations (11 out of 17) have been operating for over 20 years at 1-hour temporal recording resolution. Analysis of these data was conducted to quantify the occurrence of supra-DRH conditions for these salt phases in the ADV environment through time. Deliquescence conditions were defined as the durations in a year when RH values exceed the DRH of the specific salt phase. A Deliquescence/efflorescence cycle was defined as a period between the increase of RH above DRH to when RH decreases below DRH. A minimum duration threshold of 3 hours and a minimum of 5% excess humidity above DRH were used to filter out short events and those with marginal excess RH. The DRH value of $CaCl_2$ used in the analysis refers to the hexahydrate phase - $CaCl_2 \cdot 6H_2O$ ('Antarcticite'), which was first described in the ADV (Torii & Ossaka, 1965).

3 Results

3.1 Salt deliquescence during the field experiment

Time-lapse photography revealed an accumulation of moisture along cracks in the imaged boulder (identified visually by the darkening of the rock, Fig. 3a) during three discrete periods spanning between approximately 6-12 hours each (Fig. 3a, supp. Time-lapse video). Since no precipitation was observed during the experiment, we can overrule snow melt as a potential source, although it is a recognized source of water for rocks and soils during the austral summers (Hagedorn et al., 2010; Liu et al., 2015). These periods of moisture stability along the boulder cracks coincided exclusively with RH values that exceeded 35~40% but did not reach the dew point and included sub-zero air temperatures (Fig. 3c, d). During these moisture accumulation events, RH values coincided with supra DRH conditions for chloride salts, such as $CaCl_2$ and $MgCl_2$ (Fig. 3b, d). Chemical analysis of the salts samples taken from a crack in the boulder shows that the major anions are Cl^-, SO_4^{-2}, and (55%, 45%, respectively) and that the major cations are Ca^{+2}, Na^+, K^+, Mg^{+2}, SiO_2, and Sr^{+2} (71%, 23%, 3%, 2%,1%, 1% respectively). Excess of Cl^- and Ca^+ after accounting for the complete precipitation of halite and gypsum, which were the dominant salt phases found in X-ray diffraction, points to the presence of $CaCl_2$ and possibly other chlorides, which is not unexpected considering the proximity of the experiment site to the Don Juan pond – a saline lake rich in $CaCl_2$ (Dickson et al., 2013; Toner et al., 2017). Therefore, the most likely explanation for the observed wetting events in the experiment appears to be the deliquescence of such salts. Altogether moisture sourced from deliquesced atmospheric humidity was found to be stable along the boulder cracks for ~25% of the otherwise ‘dry’ 10-day span of the experiment.

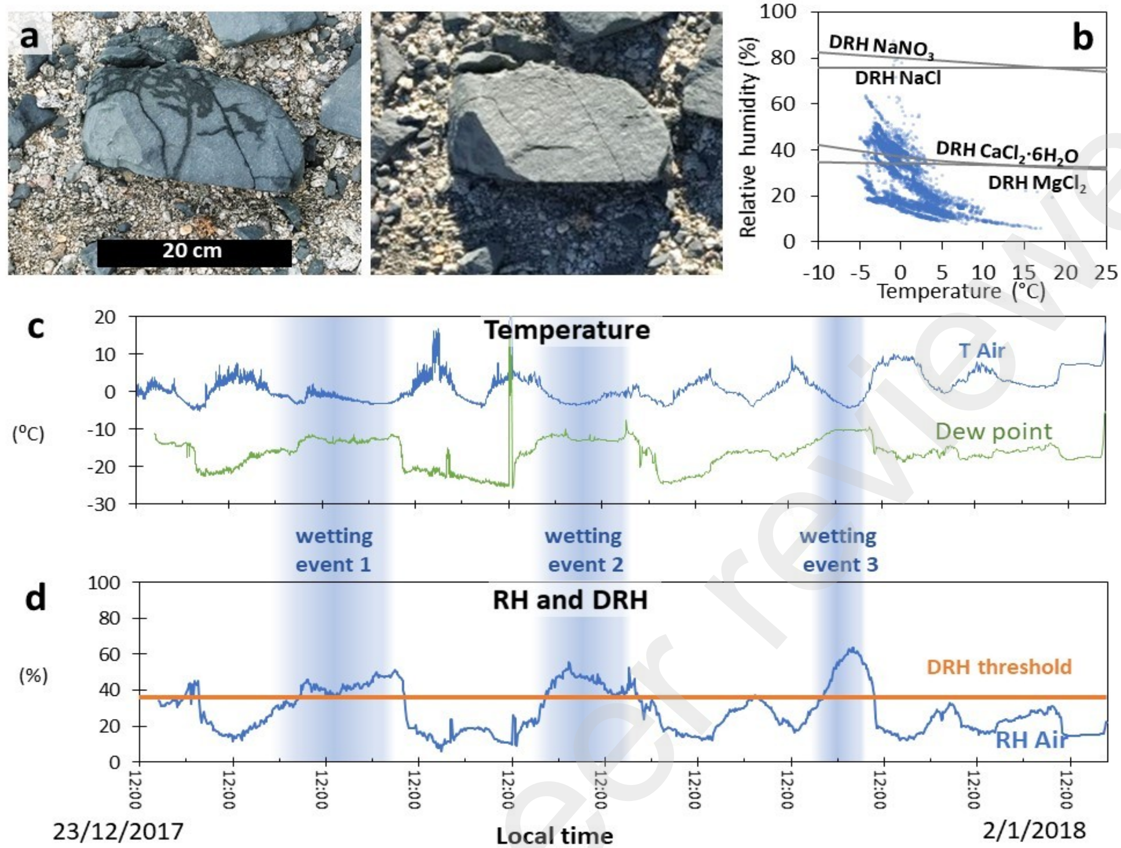

Figure 3: Moisture delivery to rock cracks via salt deliquescence. a) Images of a Ferrar dolerite boulder during (left) and between (right) wetting events. b) Data from field measurements of air temperature vs. relative humidity during the 10 days experiment. Black lines indicate the DRH of $CaCl_2 \cdot 6H_2O$, $NaNO_3$, NaCl, $MgCl_2$ salts as a function of temperature. c) Ambient air T (blue), and dew point (green) through time. Note that air T does not reach the dew point during observed wetting events and that wetting events (blue shading) persist through sub-zero temperatures. d) Relative humidity (blue) and the DRH threshold of 35%~40% (orange). All three wetting events were initiated after supra-DRH conditions were achieved and ended when RH declined below the DRH threshold.

3.2 Analysis of meteorological data

Results from analysis of 17 meteorological stations in the ADV show that the conditions for deliquescence of the salt phases that were examined, i.e., $CaCl_2$, $NaNO_3$, NaCl, and $MgCl_2$, prevail on average for 69% (range 43%-85%), 16% (range 4%-25%), 32% (range 10%-51%) and 83% (range 43%-85%) of the year, respectively (Fig. 4, Fig. supp. S1-3). In addition, the conditions for discrete deliquescence events happen on average 55 (range 25-83), 30 (range 12-48), 50 (range 20-76), and 39 (range 15-36) times per year, respectively (Fig. 4, Fig. supp. S1-3). For simplicity, deliquescence conditions for single-phase salt-brine systems were assumed. However, laboratory experiments show that the DRH of salt mixtures is expected to be even lower than that of the same single salts (e.g. Yang et al., 2002). Thus, the duration of deliquescence conditions is potentially longer than calculated herein.

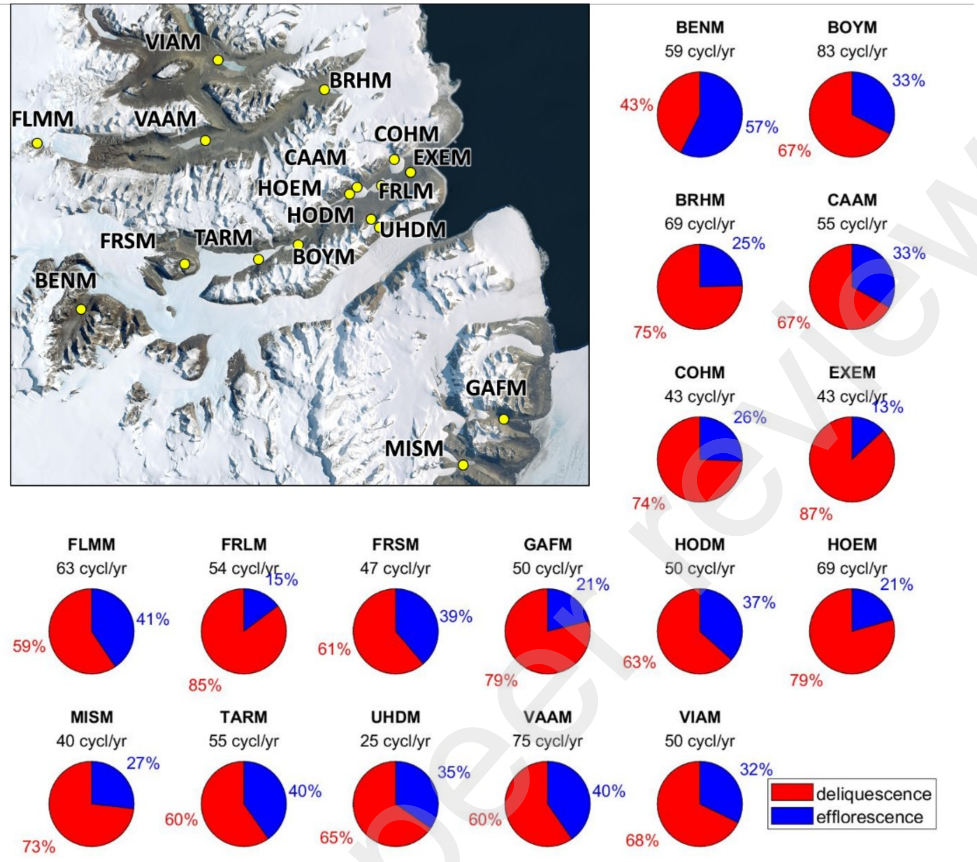

Figure 4: Results of deliquescence conditions of $CaCl_2$ in 17 meteorological stations in the ADV. The pie plots show the time fraction of deliquescence conditions (red). The number of estimated deliquescence-efflorescence cycles per year is marked below the station name. A full description of the stations is found at https://mcm.lternet.edu/meteorology-data-sets#met-15.

4 Discussion

The results of the field-based experiment show evidence that salt deliquescence is an effective mechanism of moisture delivery to the rock surface and cracks in the hyper-arid and frigid conditions of the ADV. Deliquescence/efflorescence cycles such as those observed during the experiment (Fig. 3) are expected to promote rock cracking by 'salt shattering', which is regarded as an important weathering mechanism in arid soils (Amit et al., 1993; A. Goudie & Viles, 1997; Andrew S. Goudie, 2013; Rodriguez-Navarro & Doehne, 1999), including the ADV (Johnston, 1973) and Mars (Jagoutz, 2006; Malin, 1974). Salt shattering requires that the amount of water is low enough to limit the leaching of the salts from the surface/soils, and yet sufficient for salt-water interactions that support cycles of dissolution and crystallization of salts that can exert local stress when confined within rock pores or fractures (Amit et al., 1993; Desarnaud et al., 2016; Sperling & Cooke, 1985). In addition, recent studies have demonstrated that even the rates of 'dry' mechanical weathering processes, such as those induced by salt hydration or cyclic thermal stress-loading (Lamp et al., 2017; McFadden et al., 2005; Richter & Simmons, 1974; Viles et al., 2010), may accelerate by orders of magnitude in the presence of small amounts of moisture (Eppes et al., 2020; Eppes & Keanini, 2017). This acceleration is associated with the weakening of bonds by water molecules at the tip of cracks that propagate slowly in response to subcritical stresses (Atkinson, 1984; Eppes et al., 2020; Meredith & Atkinson, 1985; Nara & Kaneko, 2006; Voigtländer et al., 2018). The delivery of moisture to the tips of cracks, via salt deliquescence, can thus also accelerate crack propagation under external subcritical stress. The analysis of data obtained from permanent ADV meteorological stations (Fig. 4) shows that the atmospheric conditions that enabled the deliquescence events in our field site near the Don Juan pond are prevalent throughout the ADV and therefore suggest that deliquesced moisture during otherwise 'dry' conditions can be an important moisture delivery pathway for rock weathering throughout the ADV soil.

Laboratory experiments show that ERH can be lower than DRH for a given salt and temperature due to a kinetic barrier for the nucleation of a crystalline phase (Gough et al., 2016; Martin, 2000). In our experiment, there is no evidence for the reported hysteresis between DRH and ERH. This could be because of the heterogeneity and impurity of natural brines that can readily facilitate the nucleation of salt crystals. Furthermore, the onset and termination of the deliquescence events that were documented during the field experiment were not driven by diurnal oscillations in air temperature and resulting changes in RH and instead appeared to be more closely associated with pulses of increased vapor pressure (Fig. Supp. S4).

We thus propose that deliquescence/efflorescence cycles may be an important driver of rock weathering in the ADV and potentially other hyper-arid regions where an accumulation of hygroscopic salts is observed. This includes Mars, where the presence of deliquescent salts was previously suggested (Gough et al., 2019; Toner et al., 2015).

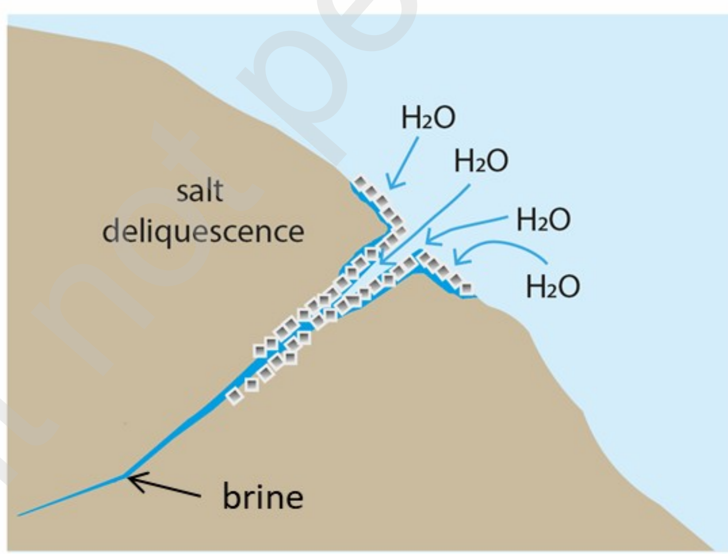

Figure 5: illustration of moisture delivery into rock cracks by salt deliquescence. Deliquesced moisture (brine) within rock cracks can accelerate the propagation of cracks by weakening rock chemical bonds by

water molecules at the tip of cracks that propagate slowly in response to subcritical stresses. Such stresses can originate from cycles of salt crystallization (deliquescence/efflorescence cycles) and/or thermal expansion/contraction in response to diurnal insolation dynamics.

5 Conclusion

Based on our results from a field experiment that show discrete wetting events of a rock surface in sub-saturated air and sub-freezing conditions, following an increase in air RH, we conclude that salt deliquescence may be an effective and overlooked mechanism of water delivery into rock cracks in hyper-arid and cold conditions on Earth and possibly Mars as well. An analysis of data from 17 permanent meteorological stations shows that conditions for the deliquescence of several salt phases that are found in the ADV prevail throughout the region and that such moisture delivery may be widespread in the ADV. We suggest a dual role that salt deliquescence plays in the acceleration of rock cracking in arid regions. The first is a source of stress load, as cycles of dissolution and crystallization of salts exert local stress when confined within rock pores or fractures (Sperling and Cooke, 1985; Desarnaud et al., 2016; Amit et al., 1993). The second is the acceleration of subcritical rock cracking in the presence of even small amounts of water at the tip of cracks (Eppes et al., 2020; Eppes & Keanini, 2017; Meredith & Atkinson, 1985; Yoshitaka Nara et al., 2010, 2012; Waza et al., 1980).

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References

Amit, R., Gerson, R., & Yaalon, D. H. (1993). Stages and rate of the gravel shattering process by salts in desert Reg soils. *Geoderma*, *57*(3), 295–324. https://doi.org/10.1016/0016-7061(93)90011-9

Anderson, T. L. (2005). *Fracture Mechanics: Fundamentals and Applications*. CRC Press.

Atkinson, B. K. (1984). Subcritical Crack Growth in Geological Materials. *Journal of Geophysical Research*, *89*(B6), 4077–4114. https://doi.org/10.1029/jb089ib06p04077

Balco, G., & Shuster, D. L. (2009). Production rate of cosmogenic 21Ne in quartz estimated from 10Be, 26Al, and 21Ne concentrations in slowly eroding Antarctic bedrock surfaces. *Earth and Planetary Science Letters*, *281*(1–2), 48–58. https://doi.org/10.1016/j.epsl.2009.02.006

Bisson, K. M., Welch, K. A., Welch, S. A., Sheets, J. M., Lyons, W. B., Levy, J. S., & Fountain, A. G. (2015). Patterns and Processes of Salt Efflorescences in the McMurdo region, Antarctica. *Arctic, Antarctic, and Alpine Research*, *47*(3), 407–425. https://doi.org/10.1657/AAAR0014-024

Brook, E. J., Brown, E. T., Kurz, M. D., Ackert, R. P., Raisbeck, G. M., & Yiou, F. (1995). Constraints on age, erosion, and uplift of Neogene glacial deposits in the Transantarctic Mountains determined from in situ cosmogenic 10 Be and 26 Al. *Geology*, *23*(12), 1063–1066. https://doi.org/10.1130/0091-7613(1995)023<1063:COAEAU>2.3.CO;2

Campbell, I. B., & Claridge, G. G. C. (1987). Antarctica: Soils, Weathering Processes and Environment. *Develop*, *16*.

Claridge, G. G. C., & Campbell, I. B. (1977). The salts in Antarctic soils, their distribution and relantionship to soil processes. *Soil Science*, *123*(6), 377–384. https://doi.org/10.1097/00010694-197706000-00006

Cooke, R. U. (1981). Salt weathering in deserts. *Proceedings of the Geologists' Association*, *92*(1), 1–16. https://doi.org/10.1016/S0016-7878(81)80015-6

Cooke, R. U., & Smalley, I. J. (1968). Salt weathering in deserts [10]. *Nature*, *220*(5173), 1226–1227. https://doi.org/10.1038/2201226a0

Desarnaud, J., Bonn, D., & Shahidzadeh, N. (2016). The Pressure induced by salt crystallization in confinement. *Scientific Reports*, *6*(1), 30856. https://doi.org/10.1038/srep30856

Dickson, J. L., 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. *Scientific Reports*, *3*(4), 1–8. https://doi.org/10.1038/srep01166

Doran, P. T., McKay, C. P., Clow, G. D., Dana, G. L., Fountain, A. G., Nylen, T., & Lyons, W. B. (2002). Valley floor climate observations from the McMurdo dry valleys, Antarctica, 1986-2000. *Journal of Geophysical Research Atmospheres*, *107*(24), ACL 13-1-ACL 13-12. https://doi.org/10.1029/2001JD002045

Eppes, M. C., & Keanini, R. (2017). Mechanical weathering and rock erosion by climate-dependent subcritical cracking. *Reviews of Geophysics*, *55*(2), 470–508. https://doi.org/10.1002/2017RG000557

Eppes, M. C., Magi, B., Scheff, J., Warren, K., Ching, S., & Feng, T. (2020). Warmer, Wetter Climates Accelerate Mechanical Weathering in Field Data, Independent of Stress-Loading. *Geophysical Research Letters*, *47*(24), 1–11. https://doi.org/10.1029/2020GL089062

Fielding, C. R., Browne, G. H., Field, B., Florindo, F., Harwood, D. M., Krissek, L. A., et al. (2011). Sequence stratigraphy of the ANDRILL AND-2A drillcore, Antarctica: A long-term, ice-proximal record of Early to Mid-Miocene climate, sea-level and glacial dynamism. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *305*(1–4), 337–351. https://doi.org/10.1016/j.palaeo.2011.03.026

Fountain, A. G., Nylen, T. H., Monaghan, A., Basagic, H. J., & Bromwich, D. (2010). Snow in the McMurdo Dry Valleys, Antarctica. *International Journal of Climatology*, *30*(5), 633–642. https://doi.org/10.1002/joc.1933

Goudie, A.S, & Viles, H. A. (1997). *Salt weathering hazard*. wiley.

Goudie, A. S., & Cooke, R. U. (1984). Salt efflorescences and Saline lakes; a distributional analysis. *Geoforum*, *15*(4), 563–582. https://doi.org/10.1016/0016-7185(84)90025-3

Goudie, A. S. (2013). *Arid and semi-arid geomorphology*. Cambridge university press.

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. *Planetary and Space Science*, *131*, 79–87. https://doi.org/10.1016/j.pss.2016.07.006

Gough, R. V., Primm, K. M., Rivera-Valentín, E. G., Martínez, G. M., & Tolbert, M. A. (2019). Solid-solid hydration and dehydration of Mars-relevant chlorine salts: Implications for Gale Crater and RSL locations. *Icarus*, *321*(July 2018), 1–13. https://doi.org/10.1016/j.icarus.2018.10.034

Hagedorn, B., Sletten, R. S., Hallet, B., McTigue, D. F., & Steig, E. J. (2010). Ground ice recharge via brine transport in frozen soils of Victoria Valley, Antarctica: Insights from modeling δ18O and δD profiles. *Geochimica et Cosmochimica Acta*, *74*(2), 435–448. https://doi.org/10.1016/j.gca.2009.10.021

Hall, K. (1999). The role of thermal stress fatigue in the breakdown of rock in cold regions. *Geomorphology*, *31*(1–4), 47–63. https://doi.org/10.1016/S0169-555X(99)00072-0

Harris, H. J. H., & Cartwright, K. (1981). Hydrology of the Don Juan Basin, Wright Valley, Antarctica. In L. D. McGinnis (Ed.), *Antarctic Research Series* (Vol. 33, pp. 161–184). Washington, D. C.: American Geophysical Union. https://doi.org/10.1029/AR033p0161

Head, J.W, Marchant, D., Dickson, J., Levy, J., & Morgan, G. (2007). Slope streaks in the Antarctic Dry Valleys: Characteristics, candidate formation mechanisms, and implications for slope streak formation in the Martian environment. *Lunar Planet. Sci., XXXVIII*.

Head, J. W., & Marchant, D. R. (2014). The climate history of early Mars: Insights from the Antarctic McMurdo Dry Valleys hydrologic system. *Antarctic Science*, *26*(6), 774–800. https://doi.org/10.1017/S0954102014000686

Jagoutz, E. (2006). Salt-induced rock fragmentation on Mars: The role of salt in the weathering of Martian rocks. *Advances in Space Research*, *38*(4), 696–700. https://doi.org/10.1016/j.asr.2005.07.070

Johnston, J. H. (1973). Salt weathering processes in the McMurdo Dry Valley regions of South Victoria Land, Antarctica. *New Zealand Journal of Geology and Geophysics*, *16*(2), 221–224. https://doi.org/10.1080/00288306.1973.10431454

Keys, J. R. (1979). Distribution of salts in the McMurdo region, with analyses from the saline discharge area at the terminus of Taylor Glacier. *Publication of the Geology Department, Victoria University of Wellington*, *14*.

Keys, J. R., & Williams, K. (1981). Origin of crystalline, cold desert salts in the McMurdo region, Antarctica. *Geochimica et Cosmochimica Acta*, *45*(12), 2299–2309. https://doi.org/10.1016/0016-7037(81)90084-3

Lamp, J. L., Marchant, D. R., Mackay, S. L., & Head, J. W. (2017). Thermal stress weathering and the spalling of Antarctic rocks. *Journal of Geophysical Research: Earth Surface*, *122*(1), 3–24. https://doi.org/10.1002/2016JF003992

Levy, J. (2021). Episodic basin-scale soil moisture anomalies associated with high relative humidity events in the McMurdo Dry Valleys, Antarctica. *Antarctic Science*, *33*(5), 533–547. https://doi.org/10.1017/S0954102021000341

Liu, L., Sletten, R. S., Hagedorn, B., Hallet, B., McKay, C. P., & Stone, J. O. (2015). An enhanced model of the contemporary and long-term (200 ka) sublimation of the massive subsurface ice in

Beacon Valley, Antarctica. *Journal of Geophysical Research: Earth Surface*, *120*(8), 1596–1610. https://doi.org/10.1002/2014JF003415

Malin, M. C. (1974). Salt weathering on Mars. *Journal of Geophysical Research*, *79*(26), 3888–3894. https://doi.org/10.1029/jb079i026p03888

Margerison, H. R., Phillips, W. M., Stuart, F. M., & Sugden, D. E. (2005). Cosmogenic 3He concentrations in ancient flood deposits from the Coombs Hills, northern Dry Valleys, East Antarctica: Interpreting exposure ages and erosion rates. *Earth and Planetary Science Letters*, *230*(1–2), 163–175. https://doi.org/10.1016/j.epsl.2004.11.007

Marrero, S. M., Hein, A. S., Naylor, M., Attal, M., Shanks, R., Winter, K., et al. (2018). Controls on subaerial erosion rates in Antarctica. *Earth and Planetary Science Letters*, *501*, 56–66. https://doi.org/10.1016/j.epsl.2018.08.018

McFadden, L. D., Eppes, M. C., Gillespie, A. R., & Hallet, B. (2005). Physical weathering in arid landscapes due to diurnal variation in the direction of solar heating. *Bulletin of the Geological Society of America*, *117*(1–2), 161–173. https://doi.org/10.1130/B25508.1

Meredith, P. G., & Atkinson, B. K. (1985). Fracture toughness and subcritical crack growth during high-temperature tensile deformation of Westerly granite and Black gabbro. *Physics of the Earth and Planetary Interiors*, *39*(1), 33–51. https://doi.org/10.1016/0031-9201(85)90113-X

Miotke, F. D., & von Hodenberg, R. (1983). *Salt fretting and chemical weathering in the darwin mountains and the dry valleys, victoria land, antarctica*. *Polar Geography and Geology* (Vol. 7, p. 122). Taylor & Francis Group. https://doi.org/10.1080/10889378309377191

Nara, Y., & Kaneko, K. (2006). Sub-critical crack growth in anisotropic rock. *International Journal of Rock Mechanics and Mining Sciences*, *43*(3), 437–453. https://doi.org/10.1016/j.ijrmms.2005.07.008

Nara, Y., Hiroyoshi, N., Yoneda, T., & Kaneko, K. (2010). Effects of relative humidity and temperature on subcritical crack growth in igneous rock. *International Journal of Rock Mechanics and Mining Sciences*, *47*(4), 640–646. https://doi.org/10.1016/j.ijrmms.2010.04.009

Nara, Y., Morimoto, K., Hiroyoshi, N., Yoneda, T., Kaneko, K., & Benson, P. M. (2012). Influence of relative humidity on fracture toughness of rock: Implications for subcritical crack growth. *International Journal of Solids and Structures*, *49*(18), 2471–2481. https://doi.org/10.1016/j.ijsolstr.2012.05.009

Obryk, M. K., Doran, P. T., Fountain, A. G., Myers, M., & McKay, C. P. (2020). Climate From the McMurdo Dry Valleys, Antarctica, 1986–2017: Surface Air Temperature Trends and Redefined Summer Season. *Journal of Geophysical Research: Atmospheres*, *125*(13). https://doi.org/10.1029/2019JD032180

Richter, D., & Simmons, G. (1974). Thermal expansion behavior of igneous rocks. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *11*(10), 403–411. https://doi.org/10.1016/0148-9062(74)91111-5

Rodriguez-Navarro, C., & Doehne, E. (1999). Salt weathering: Influence of evaporation rate, supersaturation and crystallization pattern. *Earth Surface Processes and Landforms*, *24*(2–3), 191–209. https://doi.org/10.1002/(sici)1096-9837(199903)24:3<191::aid-esp942>3.0.co;2-g

Scopelliti, G., Bellanca, A., Monien, D., & Kuhn, G. (2013). Chemostratigraphy of the early Pliocene diatomite interval from MIS AND-1B core (Antarctica): Palaeoenvironment implications. *Global and Planetary Change*, *102*, 20–32. https://doi.org/10.1016/j.gloplacha.2013.01.001

Selby, M. J., & Wilson, A. T. (1971). The origin of the Labyrinth, Wright Valley, Antarctica. *Bulletin of the Geological Society of America*, *82*(2), 471–476. https://doi.org/10.1130/0016-7606(1971)82[471:TOOTLW]2.0.CO;2

Sletten, R. S., Hallet, B., & Fletcher, R. C. (2003). Resurfacing time of terrestrial surfaces by the formation and maturation of polygonal patterned ground. *Journal of Geophysical Research E: Planets*, *108*(4), 1–10. https://doi.org/10.1029/2002je001914

Sperling, C. H. B., & Cooke, R. U. (1985). Laboratory simulation of rock weathering by salt crystallization and hydration processes in hot, arid environments. *Earth Surface Processes and Landforms*, *10*(6), 541–555. https://doi.org/10.1002/esp.3290100603

Staiger, J. W., Marchant, D. R., Schaefer, J. M., Oberholzer, P., Johnson, J. V., Lewis, A. R., & Swanger, K. M. (2006). Plio-Pleistocene history of Ferrar Glacier, Antarctica: Implications for climate and ice sheet stability. *Earth and Planetary Science Letters*, *243*(3–4), 489–503. https://doi.org/10.1016/j.epsl.2006.01.037

Steiger, M., Linnow, K., Juling, H., Gülker, G., Jarad, A. E., Brüggerhoff, S., & Kirchner, D. (2008). Hydration of $MgSO_4 \cdot H_2O$ and Generation of Stress in Porous Materials. *Crystal Growth & Design*, *8*(1), 336–343. https://doi.org/10.1021/cg060688c

Sugden, D. E., Summerfield, M. A., Denton, G. H., Wilch, T. I., McIntosh, W. C., Marchant, D. R., & Rutford, R. H. (1999). Landscape development in the Royal Society Range, southern Victoria Land, Antartica: Stability since the mid-Miocene. *Geomorphology*, *28*(3–4), 181–200. https://doi.org/10.1016/S0169-555X(98)00108-1

Summerfield, M. A., Sugden, D. E., Denton, G. H., Marchant, D. R., Cockburn, H. A. P., & Stuart, F. M. (1999). Cosmogenic isotope data support previous evidence of extremely low rates of denudation in the Dry Valleys region, southern Victoria Land, Antarctica. *Geological Society Special Publication*, *162*(1), 255–267. https://doi.org/10.1144/GSL.SP.1999.162.01.20

Tamppari, L. K., Anderson, R. M., Archer, P. D., Douglas, S., Kounaves, S. P., McKay, C. P., et al. (2012). Effects of extreme cold and aridity on soils and habitability: McMurdo Dry Valleys as an analogue for the Mars Phoenix landing site. *Antarctic Science*, *24*(3), 211–228. https://doi.org/10.1017/S0954102011000800

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 and Planetary Science Letters*, *474*, 190–197. https://doi.org/10.1016/j.epsl.2017.06.039

Toner, J. D., Sletten, R. S., Liu, L., Catling, D. C., Ming, D. W., Mushkin, A., & Lin, P.-C. (2022). Wet streaks in the McMurdo Dry Valleys, Antarctica: Implications for Recurring Slope Lineae on Mars. *Earth and Planetary Science Letters*, *589*, 117582. https://doi.org/10.1016/j.epsl.2022.117582

Toner, J D., Catling, D. C., & Light, B. (2015). Modeling salt precipitation from brines on Mars: Evaporation versus freezing origin for soil salts. *Icarus*, *250*, 451–461. https://doi.org/10.1016/j.icarus.2014.12.013

Torii, T., & Ossaka, J. (1965). Antarcticite: A new mineral, calcium chloride hexahydrate, discovered in Antarctica. *Science*, *149*(3687), 975–977. https://doi.org/10.1126/science.149.3687.975

Viles, H., Ehlmann, B., Wilson, C. F., Cebula, T., Page, M., & Bourke, M. (2010). Simulating weathering of basalt on Mars and Earth by thermal cycling. *Geophysical Research Letters*, *37*(18), 1–5. https://doi.org/10.1029/2010GL043522

Voigtländer, A., Leith, K., & Krautblatter, M. (2018). Subcritical Crack Growth and Progressive Failure in Carrara Marble Under Wet and Dry Conditions. *Journal of Geophysical Research: Solid Earth*, *123*(5), 3780–3798. https://doi.org/10.1029/2017JB014956

Waza, T., Kurita, K., & Mizutai, H. (1980). The effect of water on the subcritical silicate rocks crack growth in silicate rocks. *Tectonophysics*, *1967*, 25–34.

Wellman, H. W., & Wilson, A. T. (1965). Salt Weathering, a Neglected Geological Erosive Agent in Coastal and Arid Environments. *Nature*, *205*(4976), 1097–1098. https://doi.org/10.1038/2051097a0

Wilson, A. T. (1979). Geochemical problems of the Antarctic dry areas. *Nature*, *280*(5719), 205–208. https://doi.org/10.1038/280205a0

Winkler, I. M., & Wilhelm, E. J. (1970). Salt Burst by Hydration Pressures in Architectural Stone in Urban Atmosphere. *Geological Society of America Bulletin*, *81*, 567–572.

Yang, L., Pabalan, R. T., & Browning, L. (2002). Experimental determination of the deliquescence relative humidity and conductivity of multicomponent salt mixtures. *Materials Research Society Symposium - Proceedings*, *713*, 135–142. https://doi.org/10.1557/proc-713-jj11.4