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A deep groundwater origin for recurring slope lineae on Mars

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The recurring slope lineae on Mars have been hypothesized to originate from snow melting, deliquescence, dry flow or shallow groundwater. Except for the dry flow origin, these hypotheses imply the presence of surficial or near-surface volatiles, placing the exploration and characterization of potential habitable environments within the reach of existing technology. Here we present observations from the HiRISE (High Resolution Imaging Science Experiment), heat-flow modeling and terrestrial analogs, which indicate that the source of recurring slope lineae could be natural discharge along geological structures from briny aquifers within the cryosphere, at depths of approximately 750 m. Spatial correlation between recurring slope lineae source regions and multi-scale fractures (such as joints and faults) in the southern mid-latitudes and in Valles Marineris suggests that recurring slope lineae preferably emanate from tectonic and impact-related fractures. We suggest that deep groundwater occasionally surfaces on Mars in present-day conditions.

Understanding groundwater flow and its interaction with the surface is crucial for assessing the potential for recent or ancient habitability on Mars. The recently discovered recurring slope lineae (RSL) [1, 2] indicate the presence of seasonal brine water flow today on the Martian surface [3]. RSL emanate from bedrock outcrops and progressively lengthen during warm seasons and fade during cooler seasons preferably on equatorial- and west-facing slopes [1–3]. Slopes (25° to 40°) that encompass active RSL in the southern Martian hemisphere range in temperature from 250 to above 273 K [2], whereas the partial pressure of water vapor at the surface of Mars is below 1 Pa. It is unlikely that pure liquid water could be responsible for the relatively long-lasting flow of liquids observed in RSL locales. Unlike brines, which can sustain a liquid phase at temperatures lower than 210 K and saturation vapor pressure in the range of 0.1 to 0.2 Pa [4], pure water can exist only under triple point conditions of water temperature (i.e., 273.16 K) and vapor pressure (i.e., 611.73 Pa). The

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Author contributions

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origin of RSL has been debated between dry flows, deliquescence, subsurface melting of brines and ice and groundwater discharge [1, 4, 5–9]. Geomorphological analysis and numerical modeling of geologically recent gullies on Mars, which are commonly associated with RSL occurrences [1], suggest that these features are either formed by pure liquid water at high flow rates (15–60 m³/s) or by briny fluids at much lower rates to produce the observed short gully channels on Mars [10, 11]. The incremental lengthening of RSL throughout most of the year (up to 74% of the Martian year in Valles Marineris (VM) [12]) indicates continuous replenishment and relatively large volumes of water under cold temperature conditions (<<273 K) is inconsistent with pure water supply. The spectral identification of hydrated salts in four RSL locations [3] also supports a briny flow rather than pure water flow.

Except for the dry flow hypothesis, all current hypotheses for the origin of RSL suggest the presence of surface or near-surface source of volatiles that originated these features. Unfortunately, neither of the radar subsurface sounding experiments (MARSIS and SHARAD) identified any evidence of shallow groundwater within the first few hundred meters [13, 14] in the volcanic terrains in VM and the southern mid-latitudes, where the majority of RSL occurrences are reported [1, 2, 12] to support the shallow subsurface origin of these features. It is worth mentioning that the processing and interpretation of radar sounding data encounter significant challenges raised by the resemblance in time delay between surface clutter and potential subsurface echos [14]. Additionally, the absence of returned radar echos from subsurface aquifers could be attributed to high conductive crustal materials that attenuate the radar signal and obscure the subsurface aquifer [13, 15]. Theoretically, orbital sounders with an effective dynamic range of 24 and 30 dB (equivalent to that of MARSIS and SHARAD) would achieve a maximum penetration depth ranging from ~300 to 500 m in such volcanic terrain [16].

The recent discovery of a potential 20 -kilometers- wide zone of liquid water at the base of the Martian polar caps at depths exceeding 1.5 km below the surface [17] draw attention to the presence of deep aquifers on Mars in present-day conditions. Hence, alternative formation mechanisms associated with deep groundwater dynamics need to be explored, as the source of recharge of RSL remains largely unconstrained and poorly comparable with appropriate Earth analogs. The term “deep” groundwater in this study is assigned to potential aquifers that lie beneath the maximum theoretical penetration depth (~500 m) of orbital sounding radar sensors in the Martian volcanic terrains, and hence remained uncovered and required a geological interpretation rather than geophysical propping to demonstrate their existence.

Here, we investigate the possibility of a deep groundwater origin of the RSL by conducting a structural mapping of RSL source regions along the walls of three craters in the southern mid-latitudes and in VM. We describe the spatial correlation between tectonic and impact-related faults and RSL sources and we then use a heat-flow model and terrestrial analogs to constrain the ambiguities associated with the depth of RSL recharge. In what follows, we examine whether RSL are structurally controlled artesian discharge from deep sources rather than near-surface or surficial ones, as widely hypothesized.

Correlating RSL occurrences to structural features

Confirmed RSL in Palikir crater are reported as dark and low albedo streaks with 0.5 to 5 m width, and up to hundreds of meters long, which lasted three Martian years (i.e., 28, 29 and 30 MY) [1]. Based on multi-temporal High Resolution Imaging Science Experiment (HiRISE) images, we extend the unceasing recurring behavior into the 33rd MY (Suppl. Fig. 1). We also report RSL activity in two other craters in the southern mid-latitudes, including an unnamed crater to the south of Palikir crater inside Newton crater basin and Triolet crater. All the reported locations show RSL sources from highly deformed bedrocks (Fig. 1). General inspection of the HiRISE images indicates that the craters have impact-related fractures remarkably similar to those reported from terrestrial craters (e.g., Lonar and Meteor craters; see ref. 18, 19). The rims of these craters are dissected by concentric and radial fractures which can be seen from the plan view (Fig. 1). We map impact-related multiscale fractures (i.e., joints and faults) in the three craters using five main characteristics as described in [ref. 20], which include: (1) displacement of beds along linear planes, (2) subparallel alignment of topography, (3) presence of scarps, (4) triangular facets, and (5) linear streams (Suppl. Fig. 2).

Concentric fractures strike parallel to the impact rims and extend downslope. These fractures expose as resistant ridges along gullies and RSL-related channels. On the other hand, the radial fractures are generally vertical on the crater wall and intersect the concentric fractures at multiple locations. We note from the HiRISE images that the majority of RSL onsets emanate from concentric fractures where they intersect radial fractures along the free faces of the crater walls (Figs. 1). In Triolet crater, RSL source areas are located along the intersection of concentric fractures and the pre-impact radial grabens associated with the rise of Tharsis [21] (Fig. 1). Along fractured zones in the studied craters, varied numbers of RSL (i.e., range from 1 to more than 30 streaks) initiate and extend downslope for hundreds of meters before they terminate.

VM, where more than half of the RSL locations on Mars are reported [12], is a fault-controlled canyon that extends for 4,000 km and is associated with extensional tectonics [22] leading to one of the largest normal fault systems in the solar system (Fig. 2). The troughs of VM contain a series of erosion-resistant ridges that stretch over tens of kilometers and is known as fault trace ridges with a characteristic dog-leg offset [23]. These ridges are attributed to fault zone cementation by ascending groundwater circulations [23]. Superimposing the distribution of normal faults along the walls of VM, fault trace ridges and the confirmed and candidate occurrences of RSL on a Mars Orbiter Laser Altimeter (MOLA) and High-Resolution Stereo Camera (HRSC) blended DEM (Fig. 2A) indicates a strong spatial correlation between the locations of RSL and the faulted areas in VM. A close-up view using HiRISE imagery to an RSL occurrence in Coprates Chasma (Fig. 2B and C), where the highest areal density of RSL on Mars is reported, indicates that RSL emanate from a densely faulted zone near the top of a fault trace ridge. However, RSL emanate from a dusty-covered side that impedes the demonstration of the fault control in the RSL source region, yet the adjacent side of the ridge show a clear exposure of the same geological units from which RSL emanate (Fig. 2B). These geological units show a dense deformation and multiple displacement of bedding planes including the dog-leg offset (Fig.

2C) that characterizes the fault trace ridges in VM [23]. Evidence of artesian groundwater discharge is commonly reported near the locations of RSL in VM by using geomorphological and geological analyses [24] and experimental and numerical modeling [25].

Our observations from RSL locations demonstrate a high structural control on the emergence of these features. Such control implies a discharge of subsurface water/brines in the liquid phase from bedrock exposures and opposes previous hypotheses for the formation of RSL by deliquescence [7], slope destabilization by metastable boiling ice melts [8] or granular flow [9]. Nevertheless, the hypothesis of deep briny groundwater accessing the Martian surface as springs and seeps was challenged by the widespread occurrences of RSL along crater walls, ridges and central peaks in complex craters [1], rather than along the lowlands inside crater basins where groundwater discharge from regional flow in subsurface aquifers is most likely to occur. Yet, the structural control on the discharge of these subsurface brines, as described in this study, can provide a plausible explanation for this phenomenon.

Palikir crater as a case study

Because of the perfectly exposed bedrocks and minimal dust cover along the crater walls, availability of numerous multi-temporal HiRISE and surface temperature images and a high resolution (up to 1 m) digital terrain model (HiRISE DTM), in addition to the well-established recurrence of RSL activity for the last six Martian years, all make Palikir crater an optimal site to further examine the hypothesis of deep groundwater source of RSL along vertical faults and fractures. We derive a 20-m interval contour map from the HiRISE DTM over Palikir crater to determine the elevations of RSL onsets and concentric fractures. We consider fractures that intersect more than two contour lines as radial fractures. Superimposing the contour map over the orthogonal HiRISE image indicates that RSL onsets occur at different elevations (Fig. 3) ranging from -740 to 0 m with two peaks of preferential discharge at elevations from -200 to -280 m and at -360 m (Fig. 4A). We observe that concentric fractures are also abundant at the same elevations where RSL onsets are abundant and the frequencies of both RSL onsets and concentric fractures decrease significantly at lower elevations away from the crater rim. This decrease in frequency could either be attributed to the burial of rock exposures under the crater fill materials [26] or to the natural decrease of fault activity towards the crater center [27]. Moreover, the Pearson correlation coefficient (Fig. 4B) between the frequencies of concentric fractures and RSL onsets shows a significant positive correlation between the two datasets ($P \approx 0.67$).

Most importantly, RSL onsets originate at discrete and different elevations along the same vertical path downslope from the crater rim (Figs. 3). It is most likely that at specific locations when a set of concentric fractures at different elevations intersect the same radial fracture, RSL onsets initiate at each point of intersection, where the intensified structural deformation along the intersection between different fault sets provides a preferential pathway for subsurface liquid to surface on Mars.

Given the elevation range of mapped fractures along the crater walls in Palikir crater (i.e., –740 to 0 m), and if we consider that RSL represent discharge zones of groundwater along fractures, a localized aquifer that is deeper than the abovementioned elevation range beneath the crater should exist and groundwater should move upward from this aquifer and locally discharge along fractures.

Vertical groundwater flow and artesian discharge on Mars

The transient upward flow of a briny aquifer (q) is given by

$$q = -K \frac{\partial h}{\partial t} \quad (1)$$

where the hydraulic conductivity (K) and the negative hydraulic gradient ($\frac{\partial h}{\partial t}$) control the artesian upward flow of these brines. The briny aquifer is expected to be under positive pressure that has been exerted by the weight of the overlying impermeable crystalline rocks and the cryosphere. Though earlier hydrological models of Mars [28] indicate that the cryosphere must be thick enough (>1 km) to confine an aquifer, however recent models such as the cryovolcanic model [29] indicate that changes in surface temperature causes impingement of the cryosphere or freezing front onto liquid water aquifers confined within the cryosphere at depths of several hundred meters. Freezing of the aquifers increases pore pressures and allows buoyant water to rapidly ascend toward the surface. Moreover, artesian flow from confined aquifers several hundred meters below the surface of Mars was also modeled in [ref. 10, 30, 31].

The hydraulic conductivity of faults zones in crystalline rocks is several orders of magnitude higher than in the host rocks (e.g., 10^{-6} m s^{-1} along fault zones compared to $10^{-13} \text{ m s}^{-1}$ within the crystalline rocks in High Arctic [see ref. 32]). As the crater walls and central peaks represent areas with intensive faulting and impact-related deformation [27], fractures zones along faults will focus groundwater and artesian discharge of brines, and associated RSL formation will preferentially occur along these zones (Fig. 5). Similar observations were reported from the Yucatan Peninsula [33] where significant deep circulating groundwater preferentially discharges to the surface in correlation with the peak ring and crater rims of the buried Chicxulub crater. Similarly, in Lonar crater, India, which is formed in the Deccan trap basalts, active springs occur at different elevations (e.g., 574, 550 and 510 m) that are consistent with highly deformed and conductive horizons [34]. The phenomenon of preferential discharge of deep groundwater under high hydrostatic pressures along fault-related ridges and scarps are also well documented in the Sahara [35]. The conceptual model (Fig. 5) also suggests that seasonal melting and freezing of the shallow subsurface acts as a gauge controlling the RSL activity. The system shuts down during winter seasons, when the ascending near-surface water freezes within fault pathways and resumes during summer seasons when brine temperatures rise above the freezing point.

Heat-flow modeling of vertical groundwater flow

In order to evaluate whether deep brine groundwater discharge into the surface along impact-related fractures in Palikir crater is consistent with our observations, and to constrain the depth to the aquifer, we implement the combined heat-flow model developed by [36]. The model is described in details in the methods section.

The model results (Fig. 6) show that the flow parameters (i.e. the values of γ) do not affect the outflow temperatures of the discharge under present day geothermal gradient of Mars. On the other hand, the depth of the aquifer has the greatest effect on the outflow temperature. The outflow temperature during summer seasons attains 343 and 312 K for aquifer depths of ~ 4.5 km and ~ 750 m respectively, and α is given as $20^{\circ}\text{C km}^{-1}$. Using α as $15^{\circ}\text{C km}^{-1}$, the outflow temperatures yield 333 and 310 for aquifer depths of ~ 4.5 km and ~ 750 m respectively. The outflow temperatures of the previous case are higher than the freezing point of liquid brines in the subsurface (i.e., < 240 K; see ref. 5). On the other hand, the outflow temperature during winter seasons declines to 270 and 233 K and to 255 and 231 K for the same depths at α as 20 and $15^{\circ}\text{C km}^{-1}$, respectively. The predicted outflow temperature during winter seasons for an aquifer depth of ~ 750 m beneath RSL locales is slightly lower than the freezing point of brines (< 240 K; see ref. 5). On the other hand, a deeper aquifer (e.g., beneath the Martian cryosphere ~ 4.5 km) would produce outflow temperatures that are higher than the freezing point of brines and thus a continuous discharge of RSL should be expected. This scenario is not consistent with the reported seasonality and recurring characteristics of RSL. Therefore, a natural discharge of briny aquifer at depths of about ~ 750 m below the surface along geological structures is more consistent with our observations in the RSL locations and hence it could provide a likely potential source of recharge for RSL in Palikir crater and in Martian southern mid-latitudes. Subsurface intra-permafrost taliks within the Martian cryosphere could provide a recharge source for the deep brines as well as the case of continental Antarctica [37]. The modeled seasonal melting and freezing of the groundwater discharge is consistent with finding from hydrological modeling [38], which indicates that for shallow unconfined and confined semi-pervious (e.g. hydraulic conductivity of 10^{-6} m/s) briny aquifers will freeze under winter mid and high southern latitudes and discharge restarts in the summer favoring equator-facing slopes. All reported RSL source areas on Mars in VM [2, 12], northern mid-latitudes [6] and southern mid-latitudes [1, 39] are found on the slopes of crater walls and faulted canyons. It is not an accident that all reported RSL on Mars, however they are highly scattered, yet restricted to highly fractured and deformed zones. The spatial limitation of RSL to highly deformed areas indicates, by default, a global control of geological structures on the formation of RSL on Mars. However, the demonstrated role of deep groundwater discharge along faults and fractures in the formation of RSL does not rule out other mechanisms of formation of RSL that could be different for specific areas. The lack of global coverage of HiRISE imagery, the widespread geographic distribution of RSL [1, 2, 6] and their occurrence among diverse geologic settings and broad elevation ranges [40] make a sole mechanism for the formation of RSL out of reach.

Methods

For our investigation of RSL activity and fracture mapping along the crater walls of the three studied locations (i.e., Palikir crater, Triolet crater and an unnamed crater to the south of Palikir crater within the Newton crater basin) and in VM, we use multiple orthorectified and Reduced Data Record (RDR) HiRISE images. For Palikir crater, we only use orthorectified images (ESP_021555_1380, ESP_030614_1380 and ESP_022689_1380) to ensure coalignment with the topographic datasets derived from the high resolution DTM (DTEEC_005943_1380_011428_1380) at ~ 1 m pixel resolution and an estimated vertical precision of ~ 30 cm [41]. The DTM is downloaded from the Lunar and Planetary Laboratory at University of Arizona website (<https://www.uahirise.org/PDS/DTM/PSP>). For Triolet crater and the other unnamed crater and for VM we use Reduced Data Record (RDR) HiRISE images that show the recurring behavior of the RSL activity in these locations including (ESP_022808_1425, ESP_023586_1425, ESP_025168_1375, ESP_040491_1375, ESP_038285_1665, ESP_040171_1665). For the studied locations, both the 6-km-wide HiRISE visible-wavelength (RED) band-pass images and the 1-km-wide enhanced-color (infrared-red-blue/green or IRB) images are used to facilitate the investigation of RSL distribution and fault mapping. RDR HiRISE images are georeferenced and overlaid using ArcGIS version 10.5 to ensure the orthorectification of multiple images covering the same area. For regional spatial analysis in VM, we use a mosaic of blended digital elevation model (DEM) data derived from the Mars Orbiter Laser Altimeter (MOLA) and the High-Resolution Stereo Camera (HRSC). The mosaic is downloaded from the USGS Astrogeology Science Center website (https://astrogeology.usgs.gov/search/map/Mars/Topography/HRSC_MOLA_Blend/Mars_HRSC_MOLA_BlendDEM_Global_200mp_v2). We develop a systematic mapping approach of impact-related multi-scale fractures (joints and faults) using procedures described in [ref. 20] within a GIS environment. We derive a 20-m interval contour map from the HiRISE DTM over Palikir crater to determine the elevations of RSL onsets and concentric fractures and consider fractures that intersect more than two contour lines as radial fractures. We also consider a buffer zone of 20 m around the mapped RSL onsets to avoid user errors associated with visual interpretation of the initiation of RSL along the slopes of the crater walls. Hence all measured elevation values of RSL and faults have uncertainty of 20 m. We create point and polyline shapefiles to map the location of RSL onsets and fractures, respectively, where each shapefile includes the elevation values of each feature that are extracted from the DTM. The frequency of RSL onsets and fractures at elevation intervals of 20 m and the Pearson correlation coefficient between the two datasets are calculated in MATLAB R2013b. The Pearson correlation coefficient (PCC) is a measure of correlation between two variables following equation (2);

$$PCC = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (2)$$

where X and Y are the two variables, and $\bar{X}$ and $\bar{Y}$ are the variable means.

We calculated PCC between fault frequency and RSL frequency and we obtained a value of 0.67 indicating a significant positive correlation between fault presence and RSL detection.

We also use a combined heat-flow model [36] to simulate the outflow temperature of groundwater discharge along the walls of Palikir crater using MATLAB R2013b.

Description of the heat-flow model

The model was originally constructed to simulate the outflow temperature of groundwater discharge from different aquifer depths along faults cutting through the permafrost of Earth as an analog to Mars and to demonstrate that liquid water can reach the surface in regions of thick and continuous permafrost through a vertical conductive structure in the absence of volcanic heat sources. The Arctic springs which are studied in [ref. 36] show the exact temperature-dependence behavior that we report for the RSL, where springs are active when they discharge underneath wet-based parts of the ice and the system freezes when it is exposed to surface temperature with thinning ice [33, 36].

Assuming the impact-related faults in Palikir crater, along which ascending brines take place, are cylinders with symmetric temperature profiles, and considering time-averaged conditions, the mean temperature of the outflow of brines is given by

$$T_w(z) = T_0 - \alpha \gamma e^{\frac{z - z_b}{\gamma}} + \alpha(z + \gamma), \quad (3)$$

where T_w is the temperature of the liquid brines as it flows upward along the faults at depth z ; T_0 is the average seasonal surface temperature; α is the Martian geothermal gradient; z_b is the depth to the briny aquifer; and γ is a characteristic scale length for the spring outflow considering every RSL source area as a spring, which is calculated as

$$\gamma = \frac{\dot{m}c}{2\pi k} \ln(r_\infty/r_0) \quad (4)$$

where $\dot{m}$ is the mass flow rate, c is the specific heat of liquid brines, k is the thermal conductivity, r_0 is the radius of the spring, and r_∞ can be considered the distance between RSL elevation and the depth to the aquifer [36].

The values of T_0 were given as 298 and 220 K, which represent the average near-maximum surface temperature during summer and winter seasons respectively [39]. The geothermal gradient α is defined as 20°C km^{-1} [42] and 15°C km^{-1} [43] and the depth to the aquifer z_b were defined as 4.5 km and 750 m to represent deep conditions (i.e., beneath the Martian cryosphere) or relatively shallower conditions such as a layer of year-round unfrozen ground (i.e., taliks) inside the permafrost. The geothermal gradient provides the heat source of the deep groundwater at the designated aquifer depths (i.e. 4.5 km and 750 m). The depth value of 4.5 km corresponds to the expected aquifer depths beneath the cryosphere in the southern

mid-latitudes [42; 43] and the depth value of 750 m is consistent with the RSL observations in Palikir crater.

The values of γ were calculated as 3.21 km and 2.79 km for aquifer depths of 4.5 km and 750 m, respectively. These values are obtained by calculating the mass flow rate ($\dot{m}$) from the hydromorphic characteristics of RSL in Palikir crater as described in [ref. 44] as $\dot{m} = \rho v A$, where ρ is the briny fluid density ($\rho = 1400 \text{ kg/m}^3$), v is the velocity ($v = 8.6 \times 10^{-6} \text{ m/s}$) and A is the cross-sectional area of 72 m^2 . A value of $2.0 \text{ W m}^{-1} \text{ K}^{-1}$ is used for thermal conductivity [42] and $3400 \text{ J kg}^{-1} \text{ K}^{-1}$ is used for specific heat [45]. The value of r_∞ refers to the distance between the surface and the aquifer (i.e. 750 m and 4.5 km) and the value of r_0 , which represents the radius of the spring, is used as 0.5 cm, as suggested in [ref. 36].

Data availability

The authors declare that [the/all other] data supporting the findings of this study are available within the article [and its supplementary information files].

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

RSL locations along fractured crater walls in the southern mid-latitudes of Mars. (a) Palikir crater ESP_022689_1380, (b) Unnamed crater within Newton crater basin ESP_040491_1375, (c) Triolet crater ESP_022808_1425, blue arrows refer to concentric fractures and red arrows refer to the pre-impact radial grabens. Inset is a close-up view to the intersection area between the concentric fractures and the pre-impact grabens and is highlighted in (c) with a purple box (d) Schematic diagram of crater wall fractures showing the distribution of radial and concentric fractures within terrestrial basalts and sandstones (modified from ref. 18, 19).

Fig. 2.

RSL occurrences in VM. (a) The distribution of normal faults (ref. 22), fault trace ridges (ref. 23) and RSL occurrences (ref. 12) over a MOLA /HRSC mosaic of VM showing the spatial correlation between these features. (b) The emergence of RSL in Coprates Chasma along highly deformed zone (yellow dashed lines). The location of (b) is located on Fig. 2a as a red star. (c) Detail from B showing multiple displacements of a marker horizontal strata along faults (white arrows) also shown is a dog-leg offset along linear ridges (yellow arrows) indicating high deformation of RSL source regions.

Fig. 3.

Fault control on RSL emergence in Palikir crater. (a) The intersection of concentric and radial fractures along the wall of Palikir crater during winter seasons ESP_021555_1380 and (b) during summer seasons ESP_022689_1380. Note the emergence of RSL during the summer season along discrete elevations in concordance with the locations of fractures. RSL are indicated with black arrows and elevation values are in purple.

Fig. 4. Correlation between faults and RSL. (a) The frequencies of concentric faults and RSL onsets showing a strong correlation at different elevations along the crater walls. (b) Pearson correlation coefficient between the frequencies of RSL and concentric faults showing a positive correlation between the two datasets. The frequencies of RSL onsets and fractures are counted in fixed 20 m buffer zones and elevation values are obtained from a 20 m contour map, hence all the measurements have uncertainty of 20 m. The trendline and the line of perfect correspondence are presented in red line and black dashed line respectively.

Fig. 5.

The control of seasonal melting and freezing of shallow subsurface on RSL activity. (a) During winter seasons the system shuts down when ascending brines freezes within fault pathways in the near-surface, (b) during summer seasons the system resumes when brine temperature rise above the freezing point.

Fig. 6. Modeled outflow temperatures of groundwater discharge along the surface of Palikir crater fractured walls. The outflow temperature is modelled as a function of the flow parameter (Υ) during winter (black lines) and summer (red lines) seasons under aquifer depths (z_b) of 750 m as solid lines and 4.5 km as dashed lines. (a) and (b) are the outflow temperatures at geothermal gradient of 20 and 15°C km^{-1} respectively. Υ at values of 2.79 km and 3.21 km are expressed in solid blue and dashed blue lines for aquifer depths of 750 m and 4.5 km respectively.