Open Journal of Modern Hydrology, 2017, 7, 245-256
http://www.scirp.org/journal/ojmh
ISSN Online: 2163-0496
ISSN Print: 2163-0461

Weathering Processes on Martian Craters: Implications on Recurring Slope Lineae and the Location of Liquid Water

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How to cite this paper: Garcia-Chevesich, P., Bendek, E., Pizarro, R., Valdes-Pineda, R., Gonzalez, D., Bown, H., Martínez, E. and Gonzalez, L. (2017) Weathering Processes on Martian Craters: Implications on Recurring Slope Lineae and the Location of Liquid Water. *Open Journal of Modern Hydrology*, 7, 245-256.
https://doi.org/10.4236/ojmh.2017.74014

Received: November 10, 2016
Accepted: September 9, 2017
Published: September 12, 2017

Abstract

Recent attention has been put into recurring slope lineae (RSL), after the discovery that water is present in them. It is assumed that RSL are due to flowing water. However, even though that might be the case, the general characteristics of RSL as well as their seasonal and spatial distribution in Mars, and their occurrence within craters, suggest that RSL correspond to the weathering of frozen aquifers, which coincides with slope stability processes occurring in impact craters and scree slopes from Earth. In this study, we associated RSL with similar weathering processes occurring on impact craters and hydrogeological processes occurring on Earth (including ice, water, and wind erosion and natural aquifer recharge processes). We were able to create a conceptual model on how RSL develop, why are they found mostly in mid latitudes around craters, why are they present in more frequency in one side of crates in high latitudes, and why are there more RSL in the Martian southern hemisphere. Considering the whole hydrogeological processes occurring in craters that experience RSL, we were able to predict where large quantities of liquid water are most likely to be present in the red planet.

Keywords

Mars, Recurring Slope Lineae (RSL), Weathering Processes, Craters, Groundwater

1. Introduction

For decades, mankind has been exploring our solar system with the hope of finding suitable conditions for life, as well as useful natural resources, among many other things. Furthermore, most attention has been placed on Mars, because of its similarity to Earth and the short astronomical distance between both planets. Despite the above, extra attention has gained the red planet after the recent discovery of hydrated salts in recurring slope lineae (RSL), an evidence that suggest the presence of liquid water flowing over the Martian surface [1]-[8]. Liquid water in Mars not only would help sustain life forms [9]; the vital element is also crucial for future human expeditions to our neighboring planet.

In fact, there is enough evidence to suggest that Mars was actually a planet with plenty of water, with rivers, lakes, and even oceans [10] [11]. Mars's current surface topography, characterized by the presence of countless rills, gullies, and channels, is a clear indication of some types of fluid (most likely water) eroding the surface of the planet, a condition that occurred billions of years ago [12] [13]. Many studies support the existence of liquid water flowing in Mars in the past. For example, based on water-derived erosion formations in tectonic faults, Treiman [14] suggested that liquid groundwater near the Martian surface was present about 3500 - 1800 Myr ago. Similarly, Williams *et al.* [13] developed a model that provided a simple explanation for the latitudinal distribution of Martian gullies, suggesting that the gullies were formed when water migrated away from the present poles to the mid-latitudes.

Thus, almost four billion years ago the planet lost most of its liquid water and atmosphere due to solar winds [15] [16]. It is believed that only "modest atmospheric loss" has occurred ever since and that the Martian atmosphere's water content hasn't changed much for the last 165 million years [17]. In addition, not having an atmosphere means extremely low temperatures, *i.e.* everything that was exposed to the planet's thin atmosphere froze, including crater and canyon walls [18].

As for the presence of liquid water in current days, besides the RSL reports previously mentioned, recent research suggests that there might be thin liquid water layers in the surface of the planet in present times, after condensation and for short periods [19] Moreover, Kereszturi and Appéré [20] suggested that "good chance exists for the presence of liquid interfacial water in the warmest part of the day in the northern hemisphere of Mars at extended areas—although firm evidence requires better targeted future observations".

Despite the above, and most likely not associated with flowing water, erosion and sedimentation processes continue to be active in Mars [21]-[28], though it has been suggested that gully formation is not necessarily restricted to a single hydrological process [29]. Moreover, erosion processes in Mars are strictly associated with gravity erosion and, according to recent RSL foundlings, with short periods of liquid water flows [2].

It is now known that RSL are concentrated in equatorial latitudes, with higher occurrences in the southern hemisphere of the planet, and being relatively absent, with less numbers within craters, and with smaller dimensions in northern latitudes [2] [3] [30]. Additionally, RSL occur mostly during summer months, being higher in number in north-facing slopes of craters located in southern latitudes and in south-facing slopes on craters from the northern hemisphere. Also, equatorial craters have a relatively homogeneous distribution of RSL along their circumference, or slopes, suggesting all together that they are correlated with sun exposure [3]. In other words, RSL have a tendency to occur on the most unstable slopes of Martian craters, *i.e.* those receiving more direct sunrays during summers. Typically, one would expect the more stable slopes of a crater to have more vertical slopes (since they are not as affected by weathering processes as the slopes located in front of them). Thus, this study focuses on the relationship between RSL and latitudinal slope stability distribution within Martian craters, as related to terrestrial impact craters' latitudinal slope stability. Additionally, based on natural aquifer recharge processes occurring on Earth, we developed a conceptual model indicating where liquid water might be abundant in the red planet, based on the presence of RSL.

2. Research Methods

Based on Google Earth images and slope profile applications, we evaluated Earth's slope stability within impact craters at different latitudes. Thus, we evaluated slope stability based on visual characteristics and elevation profiles, comparing north and south slopes within each crater. We compared terrestrial slope stability tendencies with RSL locations within craters and latitudes on Mars. Our intention was to find out whether RSL might be related to Mars' rock weathering processes (*i.e.* slope stability), following the findings by McEwen *et al.* [7], with the purpose of searching a possible explanation for their appearance and their geographical distribution within craters at different latitudes.

Additionally, we analyzed current knowledge on Mars's orbit around the sun, specifically its eccentricity, to see if that could explain why RSL are less abundant in the northern hemisphere, that is if they are actually related to rock weathering processes.

Finally, after finding the above relationships and assuming that RSL correspond to a weathering process occurring mostly on slopes that experience more sun exposure during Martian summers, we followed similar Earth's natural water cycles and created a simple conceptual hydrological model, leading us to where liquid water might be abundant in the red planet.

3. Results and Discussion

Unfortunately, just a few terrestrial impact craters were intact enough to see differences between north and south slopes; many craters simply have too much vegetation, human constructions, or wind-driven sand deposits to be able to evaluate slope stability differences just based on areal views and digital north-to-south elevation profile transects. The relationship between slope stability within qualified impact craters and their general location on Earth is shown in **Table 1**.

Table 1. Location of some impact craters on Earth and spatial distribution of their more unstable slopes around them.

Impact crater's name and location	Hemisphere	Location of more unstable slope
Amguid, Algeria	Equatorial	No visible differences
Aorounga, Chad	Equatorial	No visible differences
Aouelloul, Mauritania	Equatorial	No visible differences
Bosumtwi, Ghana	Equatorial	No visible differences
Lonar, India	Equatorial	No visible differences
Meteor, Arizona	Northern	North
Monturaqui, Chile	Southern	South
Roter Kamm, Namibia	Southern	South
Tenoumer, Mauritania	Equatorial	No visible differences
Tswaing, South Africa	Southern	South
Vredefort, South Africa	Southern	South
Wolfe Creek, Australia	Southern	South

Considering the 12 qualified terrestrial impact craters found, there is a clear tendency to have more differences in slope stability on craters located in higher latitudes.

As shown in **Table 1**, terrestrial craters located in northern latitudes have a clear tendency to be gentler (*i.e.* more geologically unstable) in the north portion of the crater's circumference (*i.e.* the south-facing slopes). In southern latitudes, on the other hand, the south slopes (or north-facing slopes) of craters are usually more unstable, compared to slopes located in the north side. Additionally, craters located near our planet's equator tend to show no differences in slope stability around their edges. According to our results, this latitudinal effect on crater's slope stability distribution tends to be clearer on craters located in desert areas of our planet, where none or little plant protection exists since none or little rainfall occurs, and where temperature oscillations are broader. Finally, the most reasonable explanation for these differences in slope stability within craters is the angle in which sunrays heat the slopes of the craters. Thus, craters located in the northern hemisphere (e.g. Meteor Crater in Arizona, **Figure 1**, left) receive more direct sunrays during summers in their south-facing slopes, whereas the opposite happens in craters at the southern hemisphere (e.g. Monturaqui Crater in Chile, **Figure 1**, center). Additionally, craters near the equator receive sunrays at similar angles, all year round (e.g. Tenoumer Crater in Mauritania, **Figure 1**, right).

Coincidentally, RSL follow similar latitudinal slope distributions than that from terrestrial craters' stability [2] [31] [32], which is an indication that such phenomenon is probably part of a weathering process in the red planet [7]. The occurrence of RSL in Mars is stronger in craters' slopes receiving more direct sunrays, as previously mentioned [2] [3].

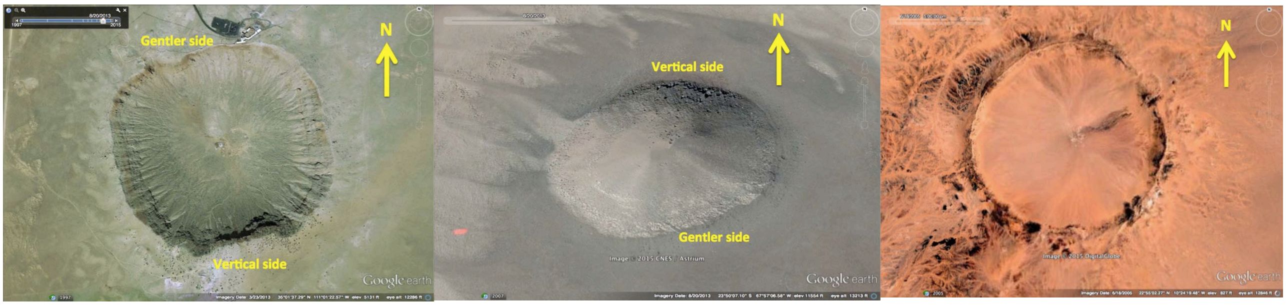

Figure 1. Left: Meteor Crater in Arizona (northern hemisphere, Northern Arizona desert), an example of the effects of latitude on the spatial distribution of a crater's geological slope stability. As one can see, the most unstable slopes are located in the northern side of the crater, whereas the southern slopes are more vertical. Center: Monturaqui Crater, Chile (southern hemisphere, Atacama Desert), where more unstable slopes are located in the southern portion of the crater's edges. Right: Tenoumer Crater located in Mauritania (Equatorial latitude, Saharan desert), showing no differences on slope stability around the crater. Source: Google Earth.

Recent discoveries indicate that RSL contain significant amounts of hydrated salts [2] [31] [32], suggesting that such dark pathways might be the reminding of a frozen aquifer [5]. Even though the presence of fluid water in RSL has been confirmed [2], it is unclear whether RSL move downslope under fluid conditions. It is known that RSL move downslope by gravity, on a relatively viscous way, and in a relatively concentrated form [3] (**Figure 2**). However, liquid flows on Earth, more specifically liquid debris flows (which is the most similar liquid process associated with rock weathering on steep rocks similar to Martian craters) get more concentrated as the flow travels down the slope, ending up in a semi-circular, tongue-shaped form [33], not being the case for RSL, in which the bottom ends get wider and in different directions, a behavior associated with dry rock flows on Earth, or "scree avalanches", which are loose rock sliding down the slope as they break apart by the action of gravity, weathering processes, and occasional liquid flows, as shown in **Figure 3** [34]. Scree slopes are characteristic of Andean or Alpine rock weathering processes on steep slopes, among other sites on Earth [35] [36] [37], similar to those experiencing RSL in Mars [7].

The absence of liquid following water on RSL was also confirmed by Edwards and Piqueux [38], who analyzed temperature data and a numerical heat transfer model. Similarly, Heinz *et al.* [39] concluded that RSL might not be associated with flowing liquid water, suggesting that their association with gullies may be the result of ancient flowing water.

In addition to the above, RSL material's downslope traveling speed has been estimated to be between 5.8×10^{-7} and 3.2×10^{-5} m/s [40], being that too slow to be attributed to permanent liquid water in such steep slopes, though consideration must be taken into the lower gravitational forces on Mars' surface, compared to our planet [41]. However, Mangold *et al.* [42] documented RSL velocities of 1 - 7 m/s, suggesting that the moving mass should carry between 10 and 40% of liquid water. Moreover, based on available RSL images, no rills or gullies are formed when this interesting phenomenon occurs, also an indication that no

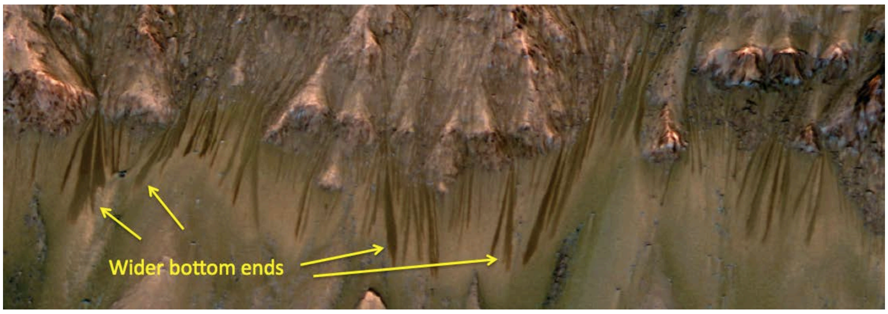

Figure 2. Wider bottoms are an indication that gravity might be the main factor for the transportation of RSL downslope. Image taken by the Mars Reconnaissance Orbiter. NASA/JPL/University of Arizona.

Figure 3. Dry rock flows at an unstable slope in north-facing slopes of Chilean Andes. The flows follow similar paths as those from RSL in Mars. Source: Google Earth.

liquid water is flowing down the slope. As a consequence, in order to better understand RSL in Mars, it is strictly necessary to study scree slope processes on Earth.

The above suggests that RSL might be some form of solid rock material that travels downslope by both, gravity and intermittent fluid water during summer days, when surface temperatures can reach 20˚C [43] and melting of the water contained in the broken, frozen geologic material can flow down the slope, eroding the remaining material for short distances ("material" refers to either frozen sediments or frozen rocks, a currently unknown composition). This agrees the finding by Ojha *et al.* [2], since liquid water is likely to be present on the crater's slopes; however, based on the geomorphological characteristics of scree slopes (mostly rocks and gravels), one could expect that most of the melted water infiltrates into the coarse media located underneath [32], rather than flowing down the slope.

Thus, RSL are able to travel so far down with most of their liquid water being infiltrated into the ground, as it occurs with scree slopes on Earth, by the action of gravity, as the material breaks down, probably on a daily base [44] [45] [46]. Since the darker material (RSL) is apparently the one that degrades at the fastest rates within the crater's rock walls, it is an indication that water might be involved in the form of, for example, frozen, saturated sediments or rocks, as previously mentioned.

Mars is a cold planet with a dry atmosphere [18] [43] in which physical weathering occurs at much higher rates, as a result of its extremely cold temperatures, and wide temperature oscillations during summers, when compared to planet Earth [29]. Thus, the constant freezing and thawing occurring between day and night on the Martian surface during summers is probably enough to quickly break down the remaining RSL material. As summer goes on, RSL material continues to be broken apart into smaller pieces, after being exposed to nearly 100˚C temperature oscillations [43], a difference that can be reached only during summers, which explains the seasonal occurrence of RSL reported by McEwen *et al.* [7]. Eventually, the RSL material most likely releases all of its water contents, since all of their water was either evaporated or melted. The process repeats itself until the frozen rocks are likely to be reduced into smaller and smaller pieces, ending up in small, dry sediment particles, which are probably either eroded by the Martian winds [47], buried by wind-driven sediments being carried from elsewhere, as it occurs in scree slopes on high mountains of Iceland [48], or the material is simply oxidized, a common process on Martian surface, which is the responsible for the planet's characteristic red color [49]. Despite the above, the reason why RSL vanish by the end of summers continues to be unknown and more research is needed to find out what is really happening.

The existence of those saturated, frozen materials (aquifers) is supported by the findings of Kurokawa *et al.* [50] and Chen *et al.* [51], among others, who suggested that significant amounts of underground water/ice should exist at present days in Mars. In addition, since RSL contain water [2], future attention should be taken to find out how much of the frozen water contained in RSL actually melt, drain, and percolate into the ground underneath, at the crater's piedmonts, most likely resulting in aquifer recharge with liquid water [52], as it happens in similar conditions on Earth [53]. Even if a small portion of the ice-melted water contained in the RSL material is able to infiltrate into the media located below it, it is an indication of the existence of abundant liquid groundwater under the crater's surface. Thus, melted RSL percolated water is likely to remain freeze-free thanks to the great insulating properties of the soil layers located above the water table, just like occurs in cold regions of our planet [54].

Finally, as previously mentioned, RSL episodes are larger in quantity in the southern hemisphere compared to those occurring in northern latitudes. Such differences are probably a result of Mars's trajectory around the sun. As the red planet follows its trajectory around our star, its hemispheres get exposed to solar radiation at different angles (*i.e.* winter and summer). However, just like on

Earth and Milankovic's theory about the relationship between solar radiation and eccentricity [55], one of the main responsible factors for terrestrial ice ages, Mars has the highest orbital eccentricity of any planet within our solar system [56] [57], resulting in summers with less solar radiation in the northern hemisphere, *i.e.* less RSL. With this information we can now suggest that, considering the highly eccentric orbit of Mars, the southern hemisphere is where more aquifer recharge might be occurring on craters experiencing RSL.

4. Conclusions and Recommendations

Based on all the above, we suggest that RSL are part of weathering processes, similar to those occurring on Earth's impact craters and on Andean and Alpine scree slopes, in which the constant freezing and thawing of frozen rocks during Martian summer nights and days, respectively, quickly break down the material, releasing its water through melting and evaporation processes. We are well aware that Earth and Mars cannot be compared directly; vegetation and gravitational forces make the above comparisons somewhat uncertain. Nevertheless, we believe the processes, and not the magnitudes, to be the same.

Based on RSL hydrologic characteristics, it is most likely that liquid water is produced during summer days, agreeing with the finding by Ojha *et al.* [2], when temperatures can reach 20˚C and day-night oscillations are nearly 100˚C. However, based on terrestrial hydrological processes occurring in similar conditions, it is possible that such liquid water percolates into the ground below the RSL, rather than flowing downslope. Moreover, we conclude that in order to better understand RSL processes, it is strictly necessary to study scree slope processes occurring on upland Andes and Alps.

The above conclusion suggests that abundant liquid water is likely to exist in the form of groundwater underneath craters experiencing RSL, as melted water produced during this fascinating hydrological process recharges the crater's aquifer.

Based on our perspectives, future research should focus on answering questions like 1) How much of the RSL's liquid water infiltrate into the ground below it? 2) What is the textural composition of the piedmonts over which RSL moves over? 3) Are there aquifers with liquid water below the craters experiencing RSL? 4) What is the composition of RSL material: frozen sediments or frozen rocks with high water contents?

In addition to the above, since probabilities for finding living organisms in Mars are strictly associated with liquid water, life is likely to be located beneath craters, where sufficient soil layers protect the ice-melted RSL percolated water from freezing, as it occurs on cold regions of Earth.

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