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Key Points:

- Valley floor aeolianites are detected on Mars
- Potential source of cement is locally exposed carbonates
- Potential source of moisture is impact-induced hydrothermal circulation of water in vadose zone

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Valley floor aeolianite in an equatorial pit crater on Mars

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Abstract High and low albedo lineations in a valley entering a pit in Lucaya crater are overlain by a currently immobile dune field. We propose that they are an aeolianite that formed as the overlying dunes migrated. Implicit in this is the suggestion that available water promoted early cementation of evaporitic minerals. We propose that the deposit likely resulted from a combination of locally sourced carbonate minerals and transient groundwater, both of which were made available after the formation of the pit crater. We do not exclude other aerial or subsurface sources of soluble minerals. We report on a pilot regional reconnaissance of images that finds the alternating albedo of dune sediments in Lucaya crater is found elsewhere on Mars. This suggests a regional sediment source at the time of dune activity. We examine a coastal interdune site in Namibia as an analogue for early geochemical cementation and interdune microtopography similar to the features observed on Mars. We find that the curvilinear interdune strata at the field site in Namibia are the preserved lee slope facies deposited by the dune as it migrated. Early cementation occurs in the interdune vadose zone due to precipitation of salts from groundwater. The formation of aeolianite in Lucaya crater supports suggestions by others that moisture is available for a significant period following crater formation. Moreover, it suggests that groundwater flow is sustained near the surface as well as in the deeper subsurface.

1. Introduction

On Earth, cement for the formation of aeolianite (cemented dune sand) may be sourced from dune sediment, airborne dust fallout, bedrock, and/or groundwater [McClaren, 2004]. The majority of terrestrial aeolianites are carbonate-cemented and located in coastal regions with an abundant source of biogenetic carbonate. There are also examples sourced from carbonate-rich bedrock (e.g., the Northern Wahiba dunes are derived from wadis that drain limestones in the Hajar Mountains [Pease and Tchakerian, 2002]). Terrestrial aeolianite is generally of Quaternary age and often displays characteristics that differ from the modern dunes (e.g., orientation). They have multiple strata orientations, are often well indurated, and can display significant relief due to erosion.

The availability of liquid water in some locations on Mars has led to sediment diagenesis and the formation of aeolianite early in Mars history. One example is located in Meridiani Planum where it is suggested that high groundwater altered the aeolian sediments (e.g., at Meridiani Planum [Grotzinger et al., 2005]).

Here we identify a valley floor aeolianite, located in an equatorial crater on Mars. We propose that the deposit likely resulted from a combination of locally sourced hydrated minerals and transient groundwater, both of which were made available by an impact event.

2. Methods

Lucaya crater (11.611°S, 51.930°E) is a 34 km diameter crater situated on the rim of the larger Huygens basin. It has several “pit valleys” (in the sense of Peel and Fassett [2013]) that drain into a 5 km wide central pit (Figure 1a). Aeolian dunes cover the crater floor and are aligned transverse along the pit valley floors (Figure 1b). Geomorphological observations were made using High Resolution Imaging Science Experiment (HiRISE) images (ESP_013319_1685 and ESP_023024_1685). The HiRISE stereo pair (ESP_12897_1685 and ESP_013319_1685) was processed in ISIS and imported into BAE Systems SocetSet software to build a digital elevation model (DEM) of the study area. Multi-Sensor Triangulation was used to solve for relative and absolute horizontal orientation (by measuring tie points), and the image pair was then controlled to a Mars Orbiter Laser

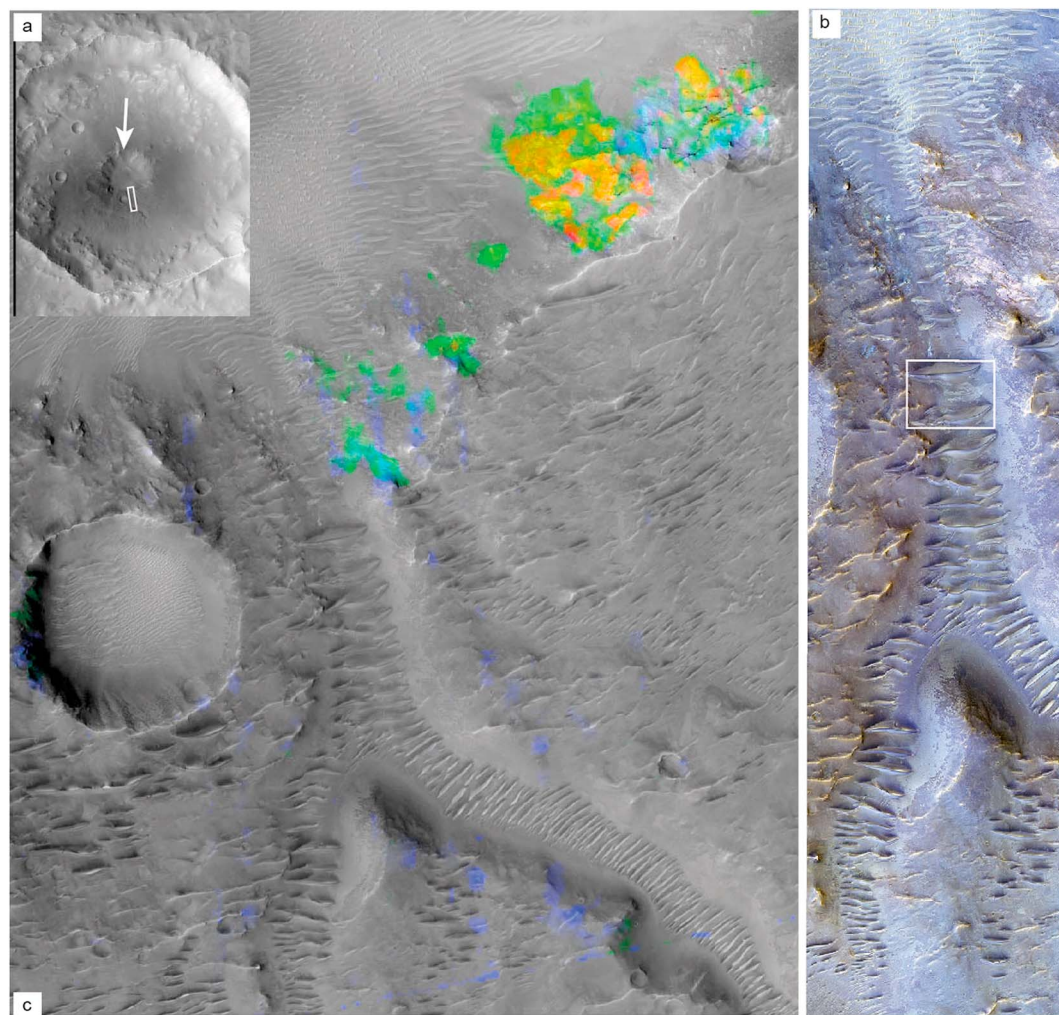


Figure 1. (a) Lucaya crater located on the rim of Huygens crater, Mars. Image is a subset of CTX image B09_013319_1684_XN_115308W. Crater diameter is approximately 34 km. Arrow points at central pit formation. White box shows location of Figure 1b. (b) Aeolian dunes along the floor of a valley in Lucaya crater. Section from HiRISE image PSP_013319_1685 (infrared, red, blue-green bands, IRB). North is to the top of the image. Location of Figure 2 is indicated by the white box which is approximately 400 m wide. (c) Compact Reconnaissance Imaging Spectrometer for Mars data overlain on HiRISE image. Color indicates assigned spectra as follows: phyllosilicate (orange) and carbonate (blue/green). See Figure 5c in *Wray et al.* [2016] for further information.

Altimeter (MOLA) digital elevation model (DEM) and MOLA track points for vertical orientation. We extracted morphometric data (dune wavelength, height, and width) from the DEM in ArcMap Geographic Information System.

A pilot analogue study was conducted near Walvis Bay, Namibia ($23^{\circ}1'25.19''\text{S}$, $14^{\circ}28'5.31''\text{E}$). In the field, shallow (30 cm depth) pits were excavated on a dune and within an interdune area. For two representative pits, grab samples were taken from approximately 20 cm depth. In addition two samples were taken from a high and a low albedo layer exposed in an interdune pit. Sediments were analyzed for moisture content, grain size, conductivity, and salt species. Sample conductivity was determined with a benchtop conductivity meter following standard calibration, analysis, and cleaning methodology. Soluble salt species (anions and cations) were determined using a Dionex ion chromatograph following dissolution of samples in deionized water. Grain size was established using a Malvern Mastersizer 2000 laser diffraction particle size analyzer set at 3000 rpm. The results are presented in Table 1. Moisture content of two grab samples was determined using the gravimetric method. Dune migration was estimated using image data from Google Earth (2009–2013).

Table 1. Sediment Analysis Results From Walvis Bay, Namibia

Sample	Location (Depth, cm)	Median Grain Size (μm)	Mean Conductivity ($\mu\text{S/cm}$)	Ranked Cation Content	Ranked Anion Content	Moisture Content (%)
1	Interdune (20)	367.0 (medium sand)	953.5	Na \gg Mg, Ca $>$ K	Cl \gg SO ₄ \gg NO ₃ , PO ₄	16.5
2	Dune crest (20)	408.3 (medium sand)	101.75	Na $>$ Ca $>$ Mg, K	Cl $>$ SO ₄ $>$ NO ₃	2
6	Pit 3: High albedo	398.8 (medium sand)	76.5	Na \gg Ca $>$ Mg, K	Cl \gg SO ₄ $>$ NO ₃	na
7	Pit 3: Low albedo	183.4 (fine sand)	4095.5	Na \gg Ca \gg K, Mg	Cl \gg SO ₄	na

3. Results

3.1. Geomorphology and Stratigraphy

3.1.1. Mars

We focus our study on the largest pit valley in Lucaya crater. It is 6 km long, 600–800 m wide, and attains a maximum depth of 35 m. Elevations along the channel floor range from 1298 m to 1665 m. The channel long profile indicates a convex shape and suggests that formative fluid flows ceased before an equilibrium valley profile was attained. Dunes on the valley floor are <5 m high, 300–400 m wide, and are spaced approximately 200 m apart. Small impact craters on the dunes and the erosion of the windward slope suggest that they are immobile at present (Figure 2).

The HiRISE false color images (Figure 2) indicate contrasting sediment albedo on windward (dark) and lee (brighter) slopes. In addition, eroded slopes expose the internal dune stratigraphy to show that they comprise alternating high and low albedo lineations. We refer to these dunes as “Zebra Dunes.” These lineations are both dune-parallel and curvilinear in planform and appear to truncate adjacent sediment layers (e.g., Figure 2a). If we assume that the surface expression of the layers in the image indicates the approximate deposit thickness, then the layers are between 0.5 and 1.5 m thick.

The dunes overlie a higher albedo surface along a significant length of the pit valley floor. The exposures in the interdune show alternating high and low albedo lineations (Figure 2b) which are detected a farther 3 km up from the valley mouth. They are similar in scale to the features exposed in the eroded dune slopes, they are curvilinear in planform and display similar crosscutting relationships. Overall, they appear to parallel the

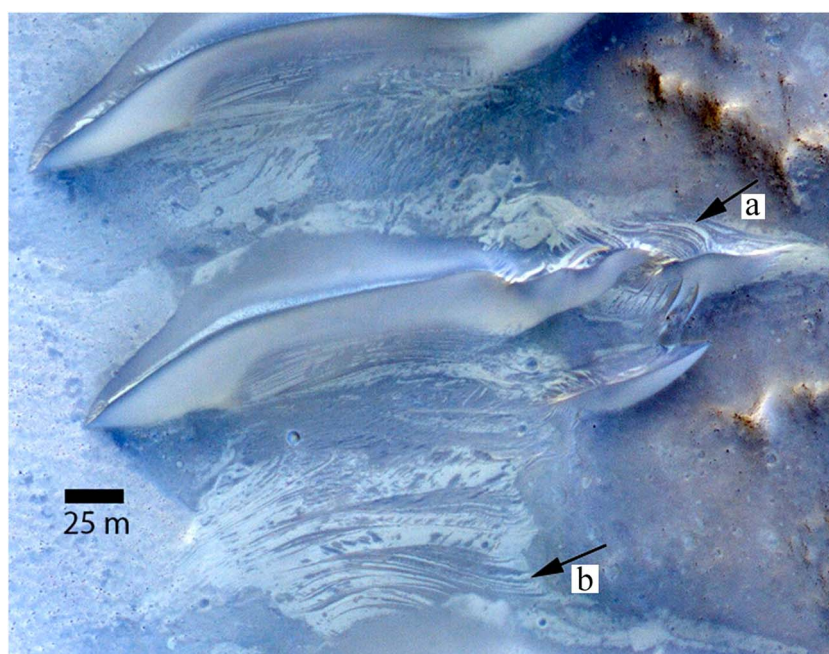


Figure 2. Image showing (a) exposure of putative crossbeds on windward slope of dunes, (b) interdune strata exposed in planform showing contrasting albedo and cross-cutting relationships similar to that exposed in the dune. Subset of false color (IRB) HiRISE image ESP_013319_1685.

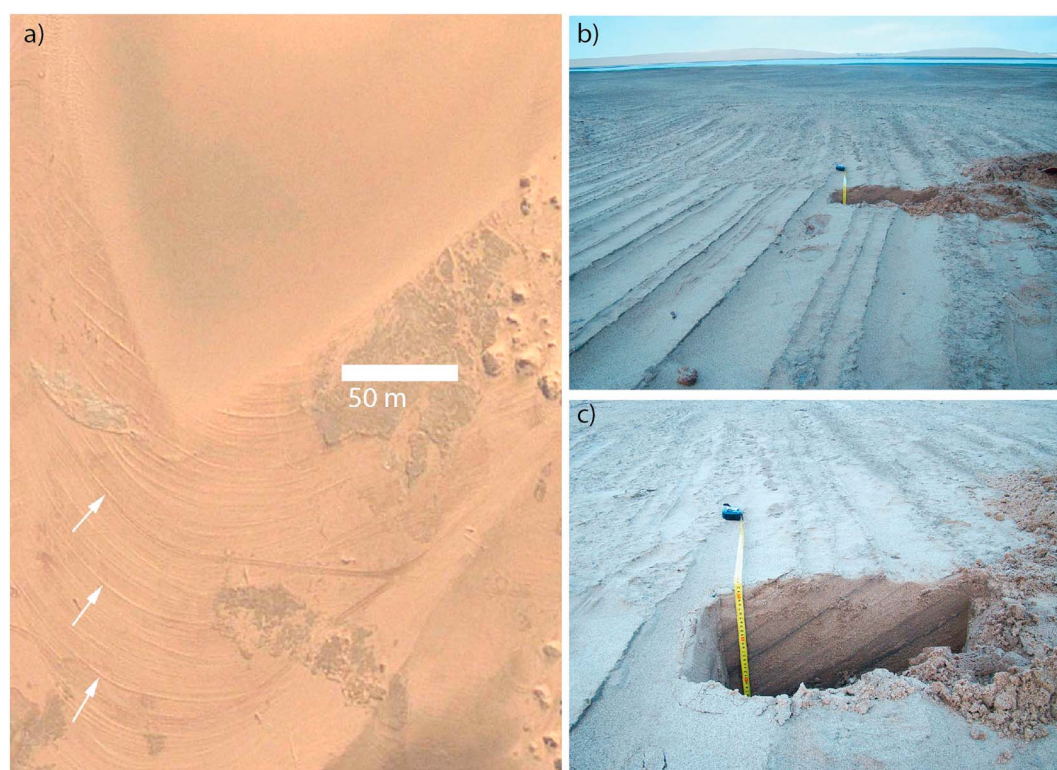


Figure 3. Example of crusted cross-bed strata in the interdune near Walvis Bay, Namibia. (a) Google Earth image of cross beds upwind of the windward slope of a barchan. White arrows highlight particularly prominent examples. (b) Ground image of cross beds showing general relief of interdune (<10 cm). (c) Wall of pit excavated in interdune (location seen in Figure 3b) shows dipping sediment layers in subsurface are contiguous with protruding layers on the surface. Alternating high and low albedo layers have different salt composition and grain size (Table 1). The darker layer forms the more pronounced microridges.

transverse dune orientation. Local relief in the interdune is on the order of 1 m and the DEM data indicate that the lineations in Figure 2 are at a Mars elevation between 1459 m and 1478 m.

3.1.2. Namibia

The field site is located in a barchan dune field south of Walvis Bay, Namibia. The dunes are mobile and measurements from Google Earth images suggest that the sampled dune migrated to the north an average of 18.25 m/yr between 2009 and 2013. The interdune consists of a series of curvilinear features (Figure 3a). A pit exposure in the low relief interdune topography (Figure 3b) indicates that the interdune layers display contrasting high and low albedos. These layers extend into the subsurface (see exposure on pit wall in Figure 3c). Their facies and dip suggests that they are aeolian cross beds formed on the avalanche face of an advancing dune. The darker interdune layer displayed more resistance to manual pressure, suggesting higher induration and as a consequence protrudes more from the surface. An excavation pit (30 cm deep) on the barchan dune windward slope did not expose any low albedo layers.

A comparison of the two grab samples from the dune and the interdune (Samples 1 and 2, Table 1) indicates similar grain sizes and sorting (poorly sorted, medium sand), similar ionic composition (commonly Na, Ca, Mg, Cl, SO_4 , suggesting NaCl and CaSO_4 as the dominant salts), but the interdune sample has a significantly higher moisture content and a higher conductivity than the dune sample. The samples from the high and low albedo layers exposed in the pit (Figure 3c) (Samples 6 and 7, Table 1) indicate that the low albedo layer has significantly higher conductivity and is finer grained (poorly sorted, fine sand). The high albedo layer in the interdune has similar conductivity and sediment size distribution to the dune crest sample. Both low and high albedo samples have similar ionic compositions to the interdune and dune crest samples. There is a good correlation between total measured ionic contents and conductivity ($R^2 = 0.99$) demonstrating that the measured ions are the major contributors to the observed conductivities.

Unlike the dunes on Mars, the contrasting albedo layers were not detected in the main dune body, suggesting that the dark layers are formed in situ in the vadose zone.

4. Discussion

On Earth, interdune lineations form in several ways. First, they may be arcuate ridges of remnant stoss slope sands stabilized by vegetation (e.g., the NE Brazilian Coast [Jimenez *et al.*, 1999; Maia *et al.*, 2005]). Second, they may be frozen dune strata found in cold climate dune fields such as Antarctica [Lindsay, 1973; Selby *et al.*, 1974]. Third, they may be the exposure of aeolianite underlying a dune system (e.g., in the Wahiba Sand Sea [Robinson *et al.*, 2007]). The first mechanisms require vegetation as binding agents and so is not a relevant mechanism for Mars. The second mechanism requires ice to be stable at the surface. This condition is not met under current equatorial latitudes on Mars. On Earth, aeolianites are lithified under vadose, mixed, and or phreatic conditions. Those cemented in the vadose zone form in wet aeolian systems where the availability of pore water through high or fluctuating groundwater leads to cementation of aeolian cross strata by soluble minerals. The facies, the high moisture content at shallow depth, and the high conductivity of the interdune sediments at the Namib site suggest that the interdune sediments are geochemically cemented. The ionic compositions imply that the cementing agents are a mixture of NaCl and CaSO₄ as is commonly found in many salt pan environments.

The absence of similarly cemented layers in the dune exposure pit confirms that early cementation is restricted to dune sediments that are periodically saturated by groundwater that is highly saline in this environment. The nature of the low albedo layer (highly saline, fine grained sand, and dark color) may be a result of microbial activity under reducing conditions. The low albedo layer occurs several times in the interdune sediments, suggesting that the formative process is repeated across the interdune.

We propose that the curvilinear interdune strata at the field site in Namibia are preserved avalanche face facies that were deposited by the dune as it migrated. Early cementation occurred in the interdune vadose zone due to precipitation of salts from groundwater saturation. Low albedo layers might reflect changing oxidation states accompanied by microbial activity within the vadose zone. As the dunes continue to migrate downwind, they leave remnant cemented cross strata that form microridges and troughs in their wake. These microtopographies are the differentially eroded cemented forests. These interdune deposits are buried beneath the prograding slope of the next advancing dune. An example of another somewhat similar system is the White Sands National Monument dune field, New Mexico [Kocurek *et al.*, 2007; Schenk and Fryberger, 1988]. These systems are sustained by continuous and varying groundwater conditions that allow for wetting and drying of sediment. They are not reported in locations dominated by surface flow.

In these wet interdune systems, the scale and orientation of the interdune lineations resemble those of the overlying migrating dunes. Therefore, the formation of aeolianite in the vadose zone seems a reasonable analogue for the deposits at our study site on Mars.

The dune-parallel and curvilinear planform lineations observed on the eroded dune slopes on Mars are typical of aeolian dune stratigraphies that typify the progradation and growth of the aeolian dunes. Changes in wind direction can cause dune erosion and reaggradation and the formation of cut and fill structures. The reactivation of dune sediment in this way is reflected in the curvilinear planforms and truncated layers. These cut and fill patterns are observed in both the dune and interdune sediments on Mars. The interdune lineations on Mars are similar to the structures exposed in the overlying dunes in their scale, orientation, planform, and albedo (Figures 2a and 2b). This suggests coeval formation of the interdune strata and the dunes in the pit valley.

We therefore propose that the features reported here are an aeolianite that formed as the overlying dunes migrated. Implicit in this is the suggestion that available pore water promoted early cementation by soluble minerals. We will now discuss a possible source of water and a potential source of soluble minerals for the Lucaya crater site.

4.1. The Source of Soluble Minerals

Wray *et al.* [2016] have mapped Fe/Ca carbonate outcrops in Lucaya crater. The strongest spectral signature for the crater is located on the central pit wall, 400 m to the NE of the interdune lineations (Figure 1c) [see

Wray *et al.*, 2016, Figure 5c]. Elevations of this exposed carbonate, as measured from the DEM, range from 1396 m to 1473 m. This is similar to the elevation of the interdune strata (1459 and 1478 m). Unfortunately, the spectra at the precise location of the cross strata and dunes are ambiguous (J. Wray, personal communication, 2015), and carbonate at the precise location of the interdune lineations cannot be confirmed. Nevertheless, this local source of carbonate could be the cementing agent if a source of water was available. We note that Fe and Ca carbonates are relatively insoluble, so an effective volume of liquid water for an adequate duration may have been required for dissolution to occur. The dissolved minerals are then proposed to reprecipitate as cements in the interdune.

4.2. Source of Moisture

Pit valleys are found in approximately 5% of pit craters on Mars, and liquid water is required for their formation [Peel and Fassett, 2013]. There is still ongoing discussion as to the mechanism for the formation of central pit craters. A leading hypothesis suggests that liquid water may be generated by the crater-forming impact event that would release the volatiles from an ice-rich impact target [Wood *et al.*, 1978]. For such targets, the extreme temperatures underlying the transient cavity are sufficient to vaporize the volatiles which are released once pressure thresholds are reached [Pierazzo *et al.*, 2005]. Whether these volatiles can stabilize as liquids during or after the impact has yet to be modeled.

A second hypothesis suggests that a groundwater source is possible due to postimpact hydrothermal activity [Abramov and Kring, 2005]. The initiation of the pit valley on the crater floor (and not on the rim) lends weight to this model. In addition, a groundwater source would provide a potential pathway for carbonate-enriched water to reach the dune sediment along the valley floor. An alternative hypothesis is direct atmospheric precipitation (fog, rain, or snow) [Peel and Fassett, 2013] that would locally raise groundwater.

4.3. Proposed Model

Our conceptual model for the formation of the interdune strata in the pit valley in Lucaya crater is as follows:

1. A period of pit valley incision following the formation of the pit crater.
2. Cessation of surface flow to permit the initiation of aeolian transport of (fluvial) sediments to form aeolian dunes along the valley floor.
3. The migration of dunes coincided with a phase/phases of fluctuating groundwater that led to cementation of aeolian sediments in the vadose zone similar to the Namibian analogue.

We propose that a potential source of hydrated minerals is the local exposure of carbonate in the pit wall. However, we do not exclude other aerial or subsurface sources. The carbonate may have reached the interdune site via enriched groundwater or could have been blown up valley as a carbonate-rich dust from the exposure. It is also possible that the valley floor has incised into a carbonate layer, although this is not detected in the spectral data.

4.4. Alternating Albedo of Dune Sediment

The alternating dark and bright albedo layers exposed on the eroded windward dune slopes are similar to some terrestrial dunes. On Earth, this can result from the differentiation and concentration of a heavy mineral or differential diagenetic alterations. Alternatively, the albedo difference may reflect the deposition from different sediment sources. On Mars the cause of difference in albedo detected in the dunes and interdune sediments is currently unknown.

Some insight is gained from a pilot examination of HiRISE images in the region. A reconnaissance of available HiRISE images in an E-W oriented ellipse centered around Lucaya crater (an area of 4.81×10^6 km²) finds that Zebra Dunes occur frequently elsewhere in the region. The alternating albedo of the layers in the Martian dunes could be the result of a frequent and cyclical process on Mars at the time of dune activity. The distribution of Zebra Dunes over such a large area suggests that the process is regional in nature, and an air fall source of dust or ash may be a relevant analogue. A potential Earth analogue may be the Mount Saint Helens eruption which deposited bright layers of ash on the dark basaltic Moses lake dunes, Washington, USA [Bandfield *et al.*, 2002].

5. Summary

Examination of lineation patterns along a pit valley floor in Lucaya crater suggests that they formed due to transient moisture availability at the time of valley dune migration. The crater-forming impact generated a suite of conditions that (1) excavated a source of hydrated minerals from deep in the Martian crust [Wray *et al.*, 2016] and (2) provided transient water that formed the pit valleys and provided sufficient moisture to allow aeolian sediment to be cemented in the vadose zone as the dunes migrated.

The volume and duration of moisture generated during and after pit crater formation is not known; however, our study suggests that it may have been substantive. We find that the duration of moisture availability was sufficient for significant geomorphic work to be done. It allowed the pit valleys to be eroded (35 m deep and 6 km long), sand-sized fluvial sediments were produced and likely mobilized (along with impact sediment). These sediments were subsequently transported by winds, and dune fields were formed and mobilized. While it is unknown how long this geomorphic landscape would have taken to form, it is certainly longer than the instantaneous crater-forming process. The estimated lifetime of impact-induced hydrothermal systems for 30 km diameter craters are suggested to be 67,000 years [Abramov and Kring, 2005].

Cemented aeolian sandstone (aeolianite) has been detected at several locations on Mars. It is formed under a myriad of conditions including that as a result of surface water and groundwater. The requirement of shallow subsurface water and hydrated minerals make aeolianite an important and perhaps niche geological target for detecting past life forms on planetary surfaces.

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