FORMATION OF CYCLOIDAL DUST DEVIL TRACKS BY REDEPOSITION OF COARSE SANDS IN SOUTHERN PERU: IMPLICATIONS FOR MARS.

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Background: On Earth, dust devil tracks (hereinafter DDTs) are rarely observed in satellite imagery [1-4] and in situ studies were so far only performed in China [3;5]. First in situ investigations of DDTs on Earth showed that passages of active dust devils remove a thin layer of fine grained material (< ~63 μm), cleaning the upper surface of coarse sands (0.5 – 1 mm) [3]. This erosional process changes the photometric properties of the upper surface causing the albedo differences within the track to the surroundings [3]. This process is consistent with the formation mechanism proposed by [6] for DTTs on Mars. [4] reported about long- and short lived DDTs in southern Peru. They show a different morphology than usual continuous, low albedo DDTs on Earth and Mars. They have a low albedo cycloidal pattern which is in some areas accompanied by bright margins [4]. Low albedo cycloidal DDTs accompanied by bright lateral areas are still visible after 5 years (long-lived), whereas DDTs without bright lateral areas disappear in less than six months (short-lived) [4]. Based on satellite imagery, their formation was suggested to be due to exposed coarse surface materials (dark cycloidal central track) and fallout of sand-sized material along the edges (bright margins) [4], whereas the formation of shorter-lived DDTs was ascribed to erosion of dust exposing coarse sand sized material [4] equivalent to the previously described formation mechanism [3,6]. Based on our in situ investigations of the DDTs in southern Peru we will show that these proposed formation mechanisms for the Peruvian DDTs and the hypothesis of the longevity of DDTs [4] are not valid. Long- and short-lived DDTs were analyzed in southern Peru in two different study areas: 1) Southwest of the city of Ica at 14.45°S and 75.84°W (long-lived DDTs), and 2) West of the city of Ica at 14.19°S and 75.88°W (short-lived DDTs).

Long-lived DDTs: Based on satellite imagery more than 20 well defined DDTs can be observed in study area 1. Multitemporal images (from 2003, 2005 and 2010) together with our field survey in 2012 reveals that DDTs remain visible for more than 9 years. In plan view the DDT is characterized by a low albedo cycloidal pattern which is accompanied by bright lateral areas (Fig. 1A-C). The alluvial fan surface where the long-lived DDTs are found can be classified as a desert pavement. Grain size analysis shows that the upper surface layer is dominated by very coarse sand grains (1 – 2 mm). Aeolian landforms such as ripples cannot be found indicating a stable surface with no or low aeolian transport processes. This is in agreement with the angular to subangular grain shape of the very coarse sands resting on top of a fine grained substrate composed of clay, silt and fine sand (< 0.25 mm). Fig. 1D-F shows example surface areas from the low albedo DDT, from the high albedo lateral area of the DDT, and from the undisturbed desert pavement outside the DDT, respectively. The low albedo surface area inside the DDT exhibits a higher abundance of very coarse sands compared to the nearby desert pavement. In contrast, the high albedo lateral area of the DDT shows a very low abundance of very coarse sands compared to the low albedo DDT area as well as to the undisturbed desert pavement outside the DDT area. This implies that very coarse sand material from the desert pavement was eroded by the outer regions of the vortex of a passing dust devil and deposited within the dust devil center. The long lifetime of the DDTs can be explained by their occurrence on aeolian inactive desert pavements. Field experiments on desert pavements showed that the recovery of areas cleared from stones and granules happens at a rate of about 1 % per year on a 40 cm² plat, thus implying a full recovery within 80 years [7].

Short-lived DDTs: In study area 2, DDTs are abundant in high-resolution satellite images (Fig. 2A). In contrast to study area 1, multi-temporal satellite imagery reveals that their lifetime is less than about one year. Similar to the described long-lived DDTs they show a low albedo cycloidal pattern, but in most cases no bright lateral areas. During our field work several dust devils were observed, some of them leaving tracks (Fig. 2B). The study area consists of a sand sheet characterized by coarse-grained ripples ~3 cm high and with a wavelength of ~75 cm. Grain size analyses show that the ripples are dominated by coarse to very coarse sand (0.5–2 mm). Within the ripple troughs bright patches of underlining fine grained substrate composed of clay, silt and fine sand (< 0.25 mm) are exposed (Fig. 2C). Detailed views of the surfaces outside and within the DDT (Fig. 2C and D) shows that the bright patches are covered by coarse sands; hence exhibiting a lower albedo. This implies that the formation of these short-lived DDTs is caused by the redeposition of coarse sands from the outer regions of the vortex towards the dust devil center as it is the case in study area 1. The lack of bright lateral areas can be explained by the much larger amounts of coarse sand grains of the sand sheet compared to the desert pavement in study area 1. The shorter lifetime of DDTs can be explained by their occurrence on an active aeolian sand sheet leading to obliteration when the ripples within the low albedo zone are reorganized and bright patches reoccur.
produce dark cycloids surrounded by a brighter region (due to exposed desert pavement), consistent with the field observations described herein.

**Laboratory studies:** Our DDT formation hypothesis is also consistent with laboratory work of [13]. The laboratory dust devils (eroded sand material (0.2 mm) from a zone which was 1 to 4 times the diameter of the vortex [13]. The unique cycloidal DDTs were formed by deposition of the eroded sand material in an annular pattern within the dust devil center [13].

![Figure 3](image.png) Simulated net deposition by a dust devil vortex with high swirl ratio $\text{Sc}=9.3$, moderate intensity $A_a=2.2$, translation parameter $At=0.15$, and debris type (a) $A_v=22.7$ (1 mm diameter / mass density 666 kg m$^{-3}$) and (b) $A_v=6.8$ (1 mm / 5200 kg m$^{-3}$). The vortex has moved from left to right across the surface (toward $+x$). The y-coordinate is measured with respect to the vortex center far aloft. Max dep/rem. corresponds to ~one monolayer of 1 mm debris.

**Implications for Mars:** Most DDTs on Mars are characterized by continuous low albedo tracks (Fig. 4 A and B) and do not show the distinctive cycloidal pattern observed in southern Peru. In situ analyses of this type of DDTs by the MER Spirit implies a formation due to dust removal exposing darker coarse grained sands [6], a formation process which was also observed on Earth [3]. However, several DDTs on Mars show a low albedo cycloidal pattern (Fig. 4 C and D) which indicates - based on our field observations and model results - that they are formed by redeposition of sand-sized material instead of dust removal.

![Figure 4](image.png) Examples of different martian DDT patterns. (A) Continuous low albedo DDTs in Gusev crater (PSP 006524_1650). (B) Continuous low albedo DDTs (ESP 013751_1115). (C) Cycloidal DDT, note the similarity to the terrestrial DDT 1 in Fig. 2A (PSP 006477_1745). (D) Cycloidal DDT, note the similarity to the terrestrial DDT 2 in Fig. 2A and the bright lateral area on the southern edge of the dark track (HiRISE image PSP 005910_1745).

**References:**