First in-situ analysis of dust devil tracks on Earth and their comparison with tracks on Mars

Journal Item

GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L14203, doi:10.1029/2010GL044016, 2010

First in-situ analysis of dust devil tracks on Earth and their comparison with tracks on Mars

D. Reiss,[1] J. Raack,[1] A. P. Rossi,[2,3] G. Di Achille,[4] and H. Hiesinger[1]

Received 17 May 2010; revised 14 June 2010; accepted 17 June 2010; published 22 July 2010.

[1] In this study we report about the first in-situ analysis of terrestrial dust devil tracks (DDTs) observed in the Turpan depression desert in northwestern China. 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). This erosional process changes the photometric properties of the upper surface causing the albedo differences within the track to the surroundings. Measurements imply that a removal of an equivalent layer thickness of ~2 μm is sufficient to form the dark dust devil tracks. Our terrestrial results are in agreement with the mechanism proposed by Greeley et al. (2005) for the formation of DDTs on Mars. **Citation:** Reiss, D., J. Raack, A. P. Rossi, G. Di Achille, and H. Hiesinger (2010), First in-situ analysis of dust devil tracks on Earth and their comparison with tracks on Mars, *Geophys. Res. Lett.*, *37*, L14203, doi:10.1029/2010GL044016.

1. Introduction

[2] Dust devils are low pressure vortices formed from unstable near surface warm air generated by insolation and they can be visible due to the entrainment of dust and possibly sand (for further details, see *Balme and Greeley* [2006]). On Mars, dark filamentary streaks were first observed in Mariner 9 imagery [*Veverka*, 1976] and active dust devils were first observed by *Thomas and Gierasch* [1985] in Viking Orbiter imagery. In the same data set, *Grant and Schultz* [1987] observed tracks on Mars, which they interpreted as "tornado tracks". Later, with higher resolution imagery it was shown that these tracks are formed by dust devils [*Malin and Edgett*, 2001]. Active dust devils have been observed leaving tracks, which are mostly darker than their surroundings, although some are brighter [*Malin and Edgett*, 2001]. The albedo differences can be explained by the removal of a thin layer of bright dust by dust devils exposing an underlying darker surface [*Grant and Schultz*, 1987]. Image data of the Microscopic Imager (MI) [*Herkenhoff et al.*, 2003] onboard of the Mars Exploration Rover (MER) Spirit in Gusev crater showed that surfaces consisting of sand grains within dust devil track zones are relatively free of finer grained dust compared to the bright regions outside the tracks [*Greeley et al.*, 2005]. It has been suggested that the albedo difference is caused by the different grain sizes because the brightness is photometrically inversely proportional to grain size [*Greeley et al.*, 2005]. The thickness of removed material by dust devils on Mars was estimated to be in the range of 2–40 μm [*Balme et al.*, 2003] based on the results of *Metzger et al.* [1999] at the Mars Pathfinder landing site. Dust devil track simulations with the Mars Regional Atmospheric Modeling System (MRAMS) indicate removal thicknesses of 1–8 μm [*Michaels*, 2006]. *Greeley et al.* [2006] estimated removal thicknesses of about 8 μm from active dust devil observations in Gusev crater.

[3] On Earth, dust devil tracks (hereafter referred to as DDTs) are rare. *Rossi and Marinangeli* [2004] observed DDTs in ASTER satellite imagery in the Ténéré desert, Niger. These low albedo tracks have been identified on different terrain types as transverse dune fields, sand sheets and interdune zone of seif dunes. The average width of the tracks is a few tens of meters and the average length about 3 km. The orientation of the tracks is orthogonal to the prevailing wind direction in this region. The track patterns change over a time span of 2 years indicating their ephemeral characteristics. Their formation might be due to the bimodal sand characteristics of the soil, with a layer of fine sands overlying coarser sand. The removal of the fine sand by the passage of a dust devil would expose the coarser sands, which increases the surface roughness causing the albedo contrast of the tracks to the surroundings in satellite imagery [*Rossi and Marinangeli*, 2004].

[4] Here, we report results from the first in-situ study of terrestrial DDTs which was performed in the Turpan depression desert in northwestern China. The aim of the study is 1) to assess whether the albedo differences are caused by photometric properties due to the removal of finer grained material overlying coarser grained particles and/or compositional differences due to the removal of brighter material exposing a darker surface, 2) what grain sizes and how much material is needed to be removed for the formation of tracks and entrained into the atmosphere, and 3) to compare the terrestrial in-situ analysis of DDTs to the results obtained by MI of the MER mission.

2. Methods

[5] Soil samples were taken inside and outside of DDTs for grain size analyses. However, because dust devils only affect the first millimeters of a surface, the soil samples, were only used to characterize the general grain size distribution of the study region. For the analysis of the upper surface of DDTs and their surroundings we took microscopic images with a Bresser Digital Eyepiece MD130 handheld microscope. The microscopic imagery in two enlargements has a

[1]Institut für Planetologie, Westfälische Wilhelms–Universität, Münster, Germany.
[2]International Space Science Institute, Bern, Switzerland.
[3]Department of Earth and Space Sciences, Jacobs University Bremen, Bremen, Germany.
[4]Research and Scientific Support Department, ESTEC, European Space Agency, Noordwijk, Netherlands.

0094-8276/10/2010GL044016

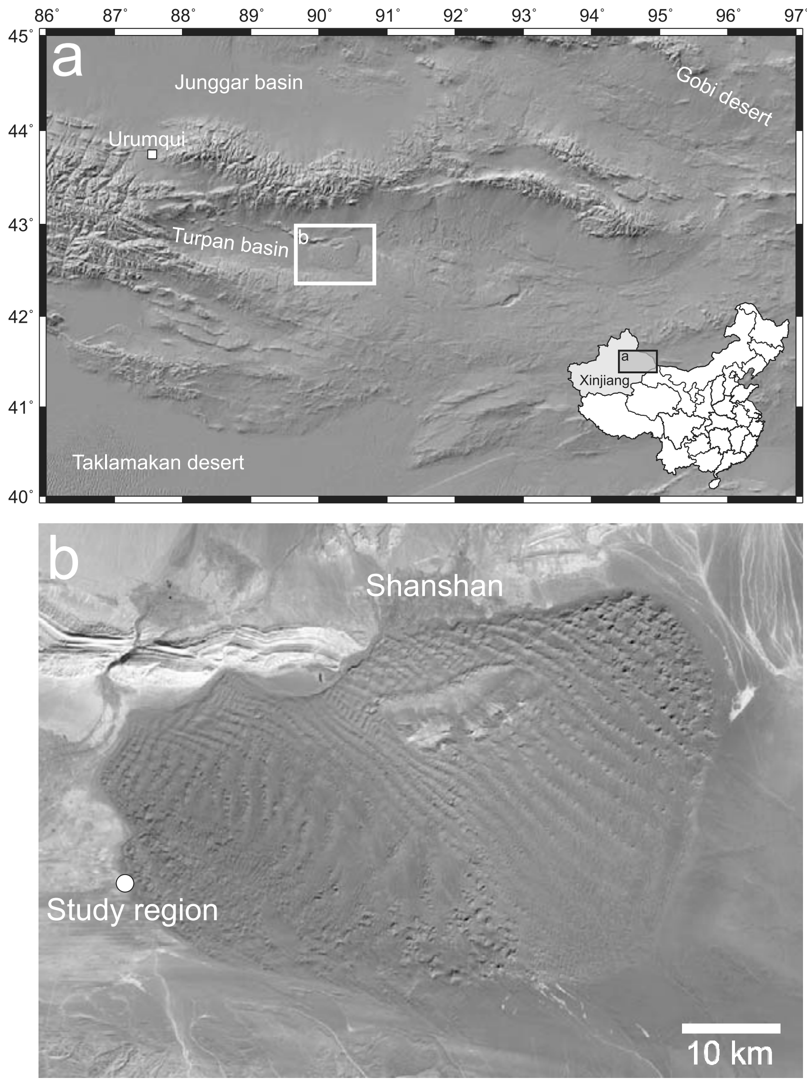

Figure 1. (a) The Turpan depression desert (white box) is located in the Xinjiang province of China, northeast of the Taklamakan and southwest of the Gobi deserts at the eastern part of the Turpan basin. (Shaded relief derived from Aster GDEM data.) (b) Context image showing the Turpan depression desert, south of the city Shanshan. The study region is located at the western margin of the dune field (Landsat 7 image L72141030_03020021112_B80).

resolution of ~7μm/pxl and ~1.5 μm/pxl. The advantage of the microscopic imagery is that the uppermost surface affected by dust devils can be analyzed without disruption. The radii of fine particles (<~63 μm) were measured in high resolution microscopic imagery with the software package "Analysis" to estimate an equivalent layer thickness needed to create the albedo differences. In a second step we compare our terrestrial results to the observations made by the microscopic imager onboard the MER rover Spirit.

3. Study Area

[6] The Turpan depression dune field is located in the Xinjiang province of northwestern China (Figure 1a) south of the city of Shanshan (Figure 1b) and covers an area of approximately 2500 km^2. There is some confusion in naming deserts in the region because the Turpan depression dune field is also called Kumtag desert, which can be mistaken for the officially named Kumtag desert (Kumutage shamo) further south. However, in the Uygur language "kum tagh" or "kumtag" literally means "sand mountain".

[7] Based on the identification of dust devil tracks in satellite images accessed trough Google Earth we decided to study the tracks at the western edge of the dune field because this region shows a frequent distribution of DDTs and is relatively easy to access. Figure 2a shows the study region located at 42.63°N and 89.86°E. The high resolution Quickbird satellite image (60 cm/pxl) acquired on 5 April 2005 shows several linear and curvilinear DDTs (Figure 2a). Active dust devils were frequently observed in the field and several of them left dark tracks compared to their surroundings. It was relatively easy to see DDTs from some distance (>10 m). In this study we focus on a curvilinear DDT observed on 15 April 2010 with a width of ~1.3 m and a length of about 70 m (Figure 2b). The track was relatively fresh, in fact it was not identified in the field

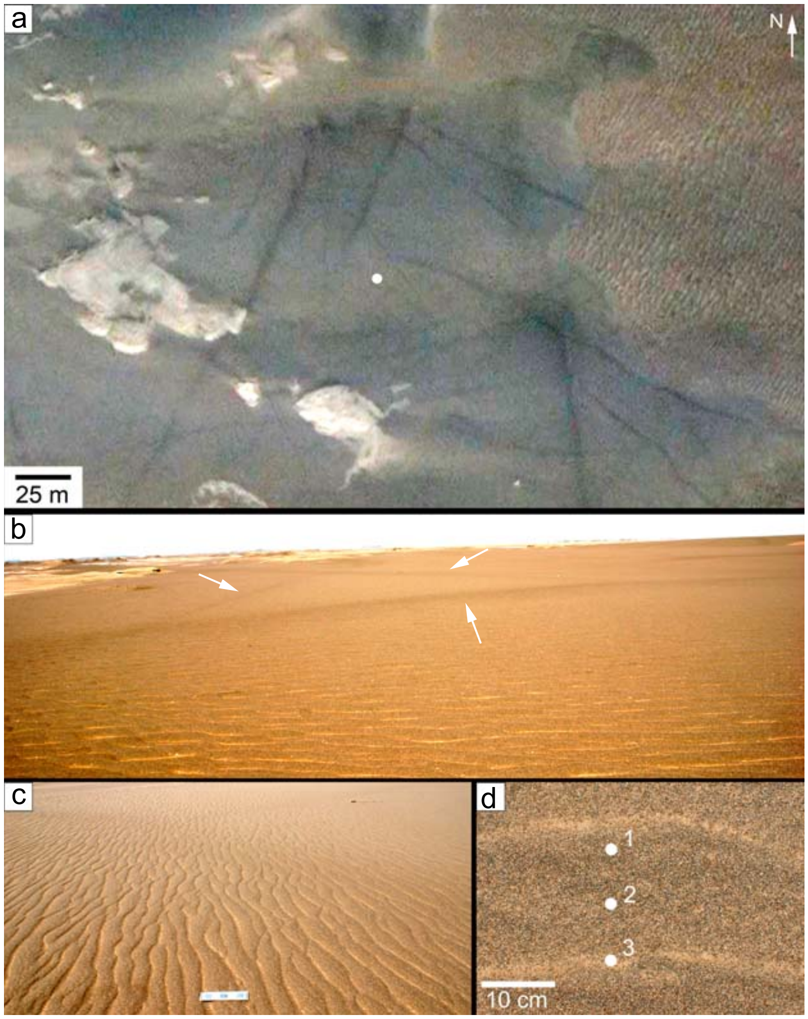

Figure 2. (a) High resolution satellite image of the study region acquired at 03 April 2005 (Quickbird image (catalog id 10100100004247600) with a resolution of ~0.6 m/pxl, from Google Earth) showing several linear and curvilinear dust devil tracks. White dot in the middle of the image marks the location of the dust devil track in b as well as the area where the microscopic images (Figure 3) were taken. (b) View of the study region from northeast. Three dust devil tracks (arrows) were identified on 14 April 2010. The DDT in front was analyzed with the microscopic imager shown in Figure 3. (c) The study region is characterized by a ripple surface. Scale bar has a width of 25 cm. (d) Image of the ripple surface from above. Microscopic images were taken from (1) the ripple crest, (2) an intermediate area and (3) the ripple troughs.

during a survey performed in the late afternoon of the day before.

4. Results

4.1. Grain Size Analysis

[8] The flat plain of the study region is characterized by a wind ripple surface (Figure 2c). Individual ripples are 1–3 cm high and the ripple wavelength varies by 10–30 cm. The vertical grain size distribution is bimodal. The largest grain sizes occur on the ripple surface and smaller grain sizes below. The grain size analyses show that the ripple surface is dominated by coarse sand (0.5–1 mm), whereas the surface layer below is dominated by very fine to fine sand (0.063–0.25 mm). Smaller grain sizes (≤0.063 mm) of silt and clay are intermixed. The grain size distribution on the ripple surfaces is inhomogeneous. The abundance of coarse sand increase on the wind- and leeward slopes to the ripple crest, within the ripple troughs fine sand grain sizes dominate. These morphologic characteristics are also known from granule ripples on Earth [*Sharp*, 1963] and coarse sand ripples on Mars [*Greeley et al.*, 2004].

4.2. Microscopic Imagery

[9] Based on the morphologic characteristics of the ripples, we sampled three different parts of the ripple surface with the microscopic imager (Figure 2d); the ripple crest, an intermediate area with small fine sand patches and the ripple trough. The microscopic imagery of the surface is shown in Figure 3. Lower resolution imagery outside the DDT (Figures 3a, 3e, and 3i) shows a relatively higher abundance of finer particles (<63 μm) than inside the DDT (Figures 3b, 3f, and 3j) in all areas. The difference in abundances is also clearly visible in the high resolution microscopic imagery inside (Figures 3c, 3g, and 3k) and outside (Figures 4d, 4h, and 4l) the DDT. However, not all fine particles are removed

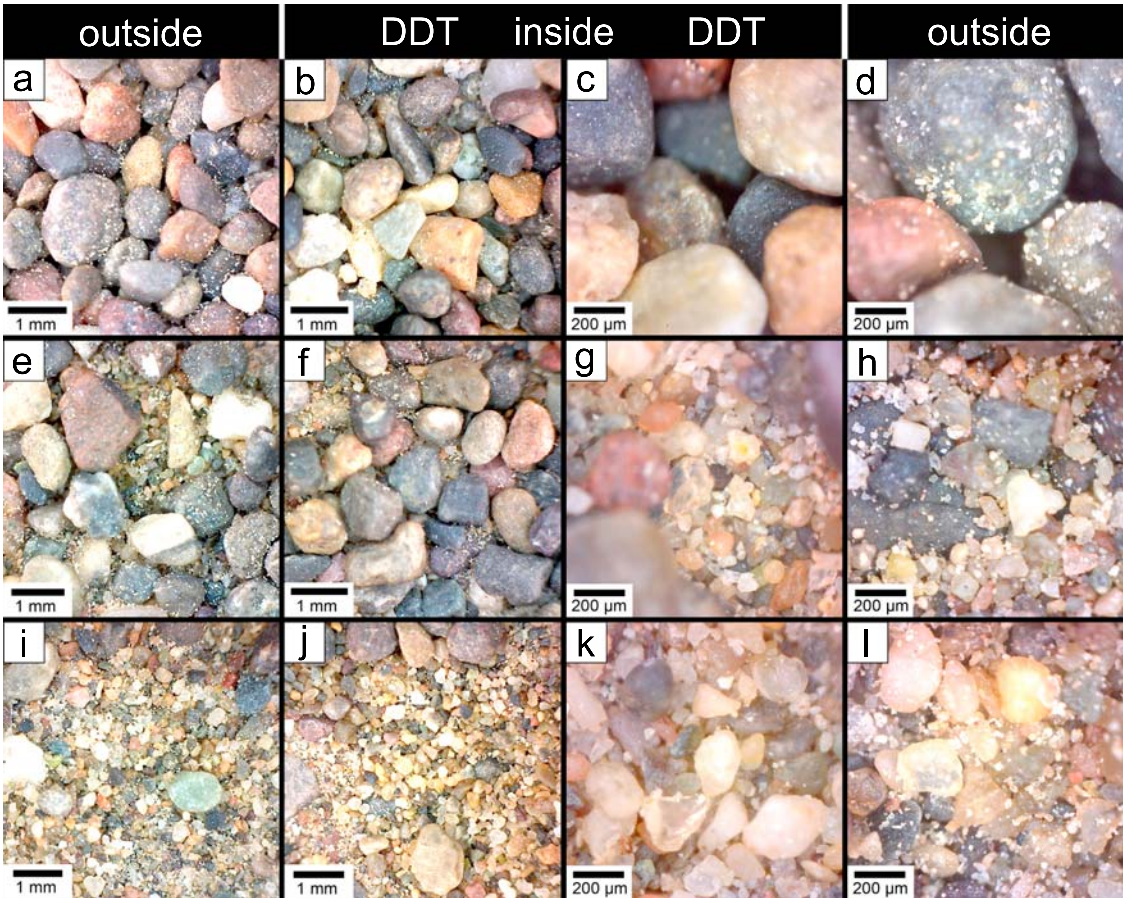

Figure 3. Microscopic imagery (a, e, i, d, h, and l) outside and (b, f, j, c, g, and k) inside the DDT in two image resolutions. Figures 3a–3d are taken on the ripple crest, Figures 3e–3h on the intermediate area, and Figures 3i–3l on the trough.

within the DDT. The upper surfaces of the coarse sand material are nearly free of fine grained material, but larger amounts of finer particles remain within the pore volume of the coarse sand (Figures 3b and 3c).

4.3. Layer Thickness Estimation

[10] Estimates of the layer thickness were made by measuring the radius of fine particles (diameter of <~63 μm) in high resolution microscopic images outside the track region on top of coarse sand grains (n = 890; A = ~0.57 mm^2). The measured grain sizes ranged from ~4 to <70 μm with a median diameter of ~6 μm. Smaller particles could not be measured due to the limitations in image resolution. Assuming an average material density of 2500 kg m^{-3}, our measurements imply a removal of an equivalent layer of ~4 μm. This value does not change significantly if we assume a larger amount - based on the grain size distribution statistics in the range of ~4–<70 μm - of smaller grain sizes (1–≤4 μm). However, the loosely packed coarse sand enhances the pore space between the grains. Based on the observations most of the fine grained material, which can be removed by a dust devil passage, rests on top of the coarse sand grains. Fine grained material located within the pore spaces is not much affected by removal. Therefore, we assume a pore space for the coarse sand areas of 50%, which would lower the maximum equivalent layer thickness to ~2 μm.

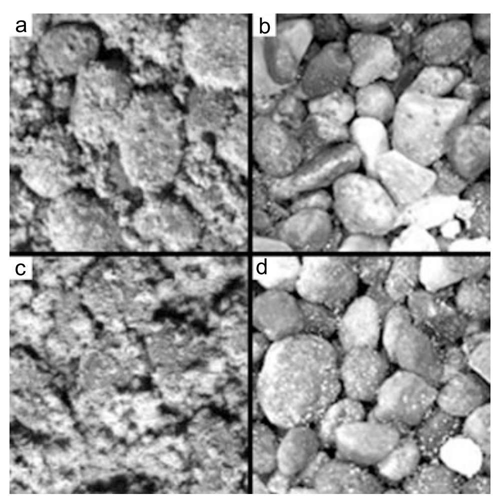

Figure 4. Comparison of microscopic images of ripple crests (a) inside and (c) outside of dust devil tracks on Mars [see also *Greeley et al.*, 2005] and (b) inside and (d) outside of dust devil tracks on Earth. Resolution of Earth images is lowered to 30 μm/pxl for direct comparison with Mars. All images have a scale of 4 × 4 mm.

4.4. Comparison to Mars

[11] Figure 4 shows a comparison of microscopic images of ripple crests on Mars and Earth inside and outside of DDTs. For a direct comparison we down-sampled the image resolution of the terrestrial images to 30 μm/pxl. When compared to the DDT investigated by the microscopic imager onboard the rover Spirit at the Gusev landing site [*Greeley et al.*, 2005] the terrestrial DDT show the same effect of a removal of finer particles with the subsequent unveiling of a coarser grained substrate. The grain size of the underlying material is in about the same range (coarse sand). However, the amount of dust mantling on the surfaces, at the boundary and outside the dark track [see also *Greeley et al.*, 2005, Figures 2c–2e] seems to be much higher on Mars compared to our terrestrial study region, regardless of the different image resolution of the microscopic imagers. In contrast to the terrestrial images, the underlying material of coarse sand is not completely cleaned. There are still large amounts of dust embedded within the coarse sands. In addition, the grain size of the dust on Mars seems to be in general much finer than on Earth. Although, it is not resolvable due to the image resolution of the microscopic imager, various calculations imply a diameter of Martian dust of ~2–~3 μm [e.g., *Pollack et al.*, 1995; *Lemmon et al.*, 2004].

5. Discussion and Conclusion

[12] Our terrestrial results of the formation of DDTs are in agreement with the proposed mechanism by *Greeley et al.* [2005] of the removal of a thin layer of dust by suspension as well as downward infiltration and therefore a greater exposure of coarser grain sizes that result in a lower-albedo surface. Dust devils represent localized areas of vortical wind action and are more efficient to lift dust into the atmosphere due to the low pressure core and higher tangential wind speeds than boundary layer winds alone [*Greeley et al.*, 2003; *Balme and Hagermann*, 2006], which enhances the atmospheric dust mobilization where the dust devil passes over the sediment (i.e., the track). The morphologic characteristics of ripple bedforms consisting of coarse to very coarse sand grain sizes as the underlying material show a striking similarity. From visual inspection, the amount of the overlying material fine grained material, which is removed by the passage of dust devils, seems to be lower on Earth than on Mars. The removed grain size diameters on Earth range from ~4 to <70 μm with a median of ~6 μm. It is probable that smaller grain sizes (<4 μm) are also present and removed, but this can not be confirmed due to the limited spatial resolution of the microscopic imager. The exact grain size distribution of removed fines on Mars is unknown, again due to the limited spatial resolution of the microscopic imager. However, it is probable that most of the fines are around ~2–~3 μm [e.g., *Pollack et al.*, 1995; *Lemmon et al.*, 2004], but larger grain sizes can not be ruled out. Calculations of the removed maximum equivalent layer of fine grained material on Earth based on measurements are around 2 μm. This is at the lower end of proposed removed equivalent layer thicknesses by dust devils on Mars, which are in the range of 2–40 μm [*Balme et al.*, 2003], 1–8 μm [*Michaels*, 2006], and about 8 μm [*Greeley et al.*, 2006]. However, our results strongly imply and also confirm the Martian results that even a very low removal of overlying fines is able to unveil enough of the underlying coarser material to cause albedo differences and thus the observed DDTs. Based on the results of our in-situ study and their comparison with the Martian results [*Greeley et al.*, 2005] we suggest that dark DDTs might be formed on Earth and Mars only in regions, where relatively fine grained material ($\ll$~63 μm) is removed by the passage of dust devils exposing much coarser grain sizes ($\gg$~500 μm). The albedo difference caused by photometric changes due to the geometric properties of the particles might be visible only if the grain size differences are strong enough. For example, DDTs were not observed on the Turpan depression dune field composed of fine sand grain sizes and also superposed by fine grained material, whereas DDTs were identified only in areas where coarse sand material occurs. This effect might also be responsible for the rarity of DDT observations on Earth. The process might also work if fine sands are removed and underlying coarse sands are exposed as suggested by *Rossi and Marinangeli* [2004]. However, in-situ and representative grain size measurements in the Ténéré desert are lacking.

[13] **Acknowledgments.** Many thanks to our taxi driver in Shanshan, who brought us relatively safe and efficient into the field and back. We still do not know his name due to language problems, although each of us was firm to speak two different languages.

References

Balme, M., and R. Greeley (2006), Dust devils on Earth and Mars, *Rev. Geophys.*, *44*, RG3003, doi:10.1029/2005RG000188.
Balme, M., and A. Hagermann (2006), Particle lifting at the soil-air interface by atmospheric pressure excursions in dust devils, *Geophys. Res. Lett.*, *33*, L19S01, doi:10.1029/2006GL026819.
Balme, M. R., P. L. Whelley, and R. Greeley (2003), Mars: Dust devil track survey in Argyre Planitia and Hellas Basin, *J. Geophys. Res.*, *108*(E8), 5086, doi:10.1029/2003JE002096.
Grant, J. A., and P. H. Schultz (1987), Possible tornado-like tracks on Mars, *Science*, *237*, 883–885, doi:10.1126/science.237.4817.883.
Greeley, R., M. R. Balme, J. D. Iversen, S. Metzger, R. Mickelson, J. Phoreman, and B. White (2003), Martian dust devils: Laboratory simulations of particle threshold, *J. Geophys. Res.*, *108*(E5), 5041, doi:10.1029/2002JE001987.
Greeley, R., et al. (2004), Wind-related processes detected by the Spirit Rover at Gusev Crater, Mars, *Science*, *305*, 810–813, doi:10.1126/science.1100108.
Greeley, R., et al. (2005), Martian variable features: New insight from the Mars Express Orbiter and the Mars Exploration Rover Spirit, *J. Geophys. Res.*, *110*, E06002, doi:10.1029/2005JE002403.
Greeley, R., et al. (2006), Active dust devils in Gusev Crater, Mars: Observations from the Mars Exploration Rover Spirit, *J. Geophys. Res.*, *111*, E12S09, doi:10.1029/2006JE002743.
Herkenhoff, K. E., et al. (2003), Athena Microscopic Imager investigation, *J. Geophys. Res.*, *108*(E12), 8065, doi:10.1029/2003JE002076.
Lemmon, M. T., et al. (2004), Atmospheric imaging results from the Mars Exploration Rovers: Spirit and Opportunity, *Science*, *306*, 1753–1756, doi:10.1126/science.1104474.
Malin, M. C., and K. S. Edgett (2001), Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission, *J. Geophys. Res.*, *106*, 23,429–23,570, doi:10.1029/2000JE001455.
Metzger, S. M., J. R. Carr, J. R. Johnson, T. J. Parker, and M. T. Lemmon (1999), Dust devil vortices seen by the Mars Pathfinder camera, *Geophys. Res. Lett.*, *26*, 2781–2784, doi:10.1029/1999GL008341.
Michaels, T. I. (2006), Numerical modeling of Mars dust devils: Albedo track generation, *Geophys. Res. Lett.*, *33*, L19S08, doi:10.1029/2006GL026268.
Pollack, J. B., M. E. Ockert-Bell, and M. K. Shepard (1995), Viking Lander image analysis of Martian atmospheric dust, *J. Geophys. Res.*, *100*, 5235–5250, doi:10.1029/94JE02640.
Rossi, A. P., and L. Marinangeli (2004), The first terrestrial analogue to Martian dust devil tracks found in Ténéré Desert, Niger, *Geophys. Res. Lett.*, *31*, L06702, doi:10.1029/2004GL019428.
Sharp, R. P. (1963), Wind ripples, *J. Geol.*, *71*, 617–636, doi:10.1086/626936.

Thomas, P. C., and P. J. Gierasch (1985), Dust devils on Mars, *Science*, *230*, 175–177, doi:10.1126/science.230.4722.175.
Veverka, J. (1976), Variable features on Mars. VII. Dark filamentary markings on Mars, *Icarus*, *27*, 495–502, doi:10.1016/0019-1035(76)90165-2.

G. Di Achille, Research and Scientific Support Department, ESTEC, European Space Agency, Keperlaan 1, NL-2200 AG Noordwijk, Netherlands.
H. Hiesinger, J. Raack, and D. Reiss, Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm−Klemm-Str. 10, D-48149 Münster, Germany. (dennis.reiss@uni-muenster.de)
A. P. Rossi, Department of Earth and Space Sciences, Jacobs University Bremen, Campus Ring 1, D-28759 Bremen, Germany.