Martian variable features: New insight from the Mars Express Orbiter and the Mars Exploration Rover Spirit

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[1] Linear, low-albedo patterns (termed dark wind streaks) formed on the floor of Gusev crater between September 2003 and February 2004, as seen on High Resolution Stereo Camera images taken on board the Mars Express Orbiter. Pancam images from the Mars Exploration Rover Spirit show that the rover crossed a dark streak during its traverse to Bonneville crater. Spirit Microscopic Imager data reveal that sand grains within the dark wind streak are relatively free of dust, whereas grains outside the streak are mantled with dust. During the September 2004 solar conjunction, Spirit remained in one location from sol 240 to sol 260. Comparison of images taken before and after the conjunction shows that patches of soil beneath the rover darkened with respect to the adjacent soils, suggesting removal of relatively bright material. Two MI mosaics taken 18 sols apart of the surface within 0.5 m of the nearest dark patch show that some larger (1–2 mm) sand grains moved as far as 0.7 mm. These observations support the hypothesis that some dark surface patterns result from the removal and/or repositioning of fine-grained material by winds, exposing a relatively lower albedo substrate, such as coarse sand grains. Other variable features on the Gusev floor seen from orbit faded between September 2003 and February 2004 and are interpreted to represent settling of dust from the atmosphere, consistent with the accumulation of dust observed on Spirit. The observation of dark streaks fading with time, while some dark streaks were newly formed, is consistent with local wind gusts or the passage of dust devils that locally sweep dust from the surface or cause a redistribution of fine grains among larger particles.

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1. Introduction

[2] Variable features, first seen on Mariner 9 images, were defined by *Sagan et al.* [1972] for albedo patterns that change with time. They are considered to represent sand (62.5–2000 μm), silt (4–62.5 μm), and dust (<4 μm) particles redistributed by winds. As such, variable features serve as local wind vanes that indicate the near-surface wind patterns at the time of their formation. Dark wind streaks were suggested to form by the removal of bright dust and the exposure of a lower-albedo substrate [*Sagan et al.*, 1972]. Dark wind streaks have a variety of planforms, including fan shapes that occur in association with craters, and linear to meandering streaks that could represent the passage of atmospheric vortices [*Grant and Schultz*, 1987], such as dust devils [*Malin and Edgett*, 2001].

[3] The floor of Gusev crater, landing site for the Mars Exploration Rover (MER) Spirit, exhibits numerous variable features [*Greeley et al.*, 2003a]. The most common variable features are dark wind streaks of fan-shaped and linear form (Figures 1 and 2a), including a linear feature on which Spirit landed [*Squyres et al.*, 2004; *Greeley et al.*, 2004]. Prior to Spirit landing on 3 January 2004, the site was imaged on 26 September 2003 from orbit by the Thermal Emission Imaging Spectrometer (THEMIS) instrument (Figure 1a) on board Mars Odyssey [*Christensen et al.*, 2004]. After the landing, the same general area was imaged by the High Resolution Stereo Camera (HRSC) [*Neukum et al.*, 2004] on board the Mars Express orbiter on 16 January and 1 February 2004 (Figures 1b and 1c). Combined with ground-truth data from Spirit, these images (Table 1) allow evaluation of the pro-

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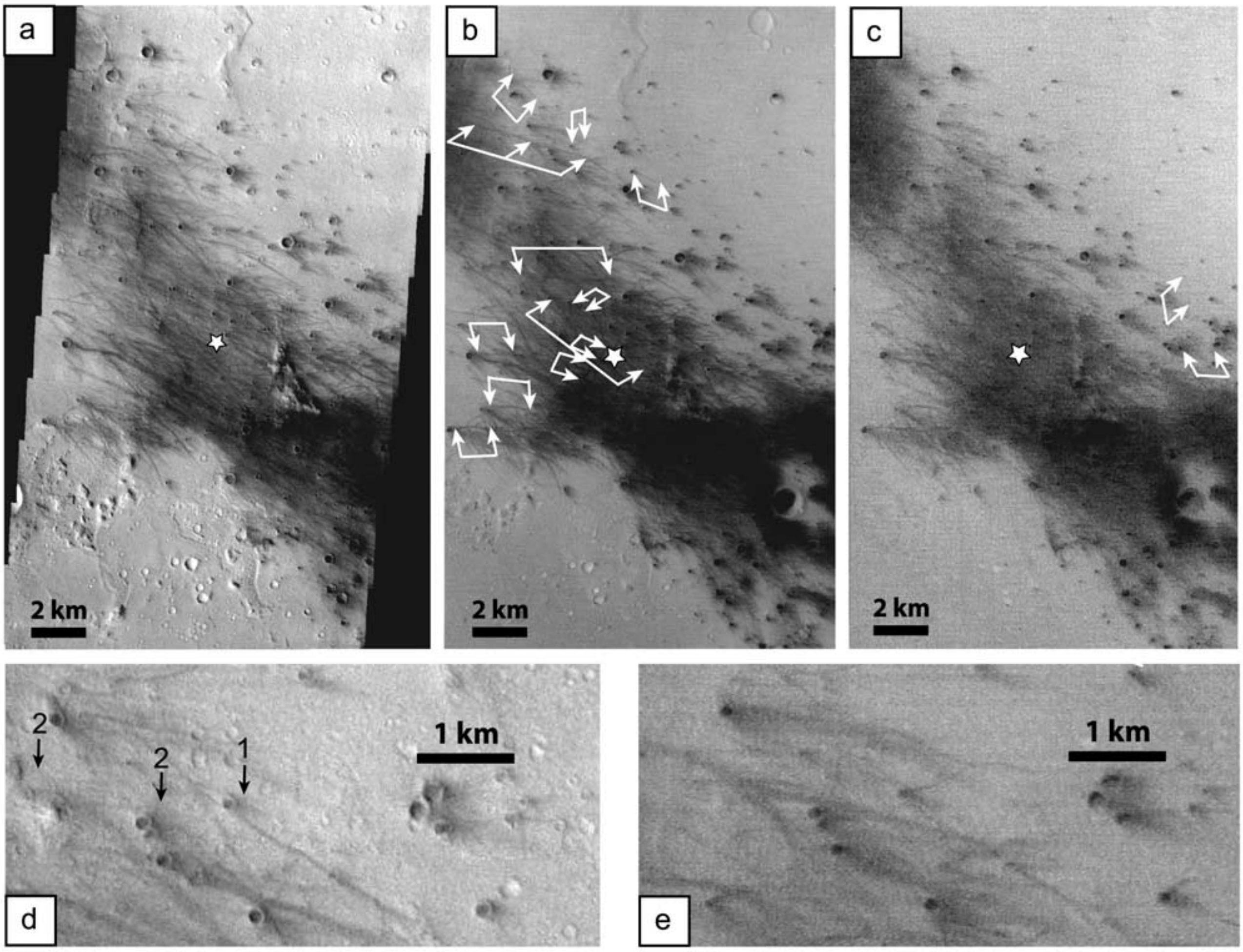

Figure 1. Comparisons of dark wind streak formation and evolution seen from orbit in the vicinity of the Spirit landing site at the Columbia Memorial Station (CMS, indicated by a star): (a) THEMIS image taken 26 September 2003, (b) HRSC image taken 16 January 2004, two weeks after the landing; white lines indicate the location and length of newly formed dark streaks since the THEMIS image, (c) HRSC image taken 1 February 2004 showing additional dark streaks since the previous HRSC image was taken; (d) detail between the THEMIS image and (e) January HRSC image showing the formation of a new crater-associated dark streak (1) and the formation of a new linear dark streak (2). Table 1 shows image parameters. North is to the top in all images.

cesses involved in the formation and evolution of some classes of variable features.

2. Dark Wind Streaks

[4] Figure 1 illustrates the dark wind streaks in the Spirit landing site vicinity, and the changes that occurred between September 2003 and early February 2004. Changes included the formation of linear-to-curvilinear dark streaks and a general fading of dark wind streaks that were visible in the September 2003 image but not in the vicinity of Spirit operations. The atmosphere in this period, which includes the landing time of Spirit, is characterized as being dusty [*Squyres et al.*, 2004]. Dust has accumulated on the rover solar panels since landing, and we attribute the fading of some dark streaks to dust settling on the surface, mantling a darker substrate; such a mechanism was suggested previously for albedo changes in other areas [*Sagan et al.*, 1972]. For example, analyses of the evolution of linear dark streaks in Argyre and Hellas over two Martian years [*Balme et al.*, 2003] show that they tend to fade or disappear with time, presumably as dust settles from the atmosphere [*Cantor and Edgett*, 2002]. Experiments by *Wells et al.* [1984] show that the addition of only a few micrometers of dust on the surface can increase the reflectance.

[5] The formation of new dark wind streaks in the same period of general fading of existing dark streaks suggests that local erosion of dust occurred in the area of observations. Previously, dark linear streaks in other areas of Mars were imaged in the process of formation by active dust devils [*Malin and Edgett*, 2001], suggesting that the vortex within the dust devil injects fine-grained material into the atmosphere where it is removed in suspension. Lower-albedo material, such as larger grains or material of darker compositions, is then exposed beneath the path of the vortex. Studies by *Thomas et al.* [1984] and *Edgett and Malin* [2000] suggested that the removal of as little as a few micrometers of dust from the surface could account for the

differences in reflectance seen in many variable features. Thus it seems likely that, although the general area of the Spirit landing site was experiencing net deposition of dust in the three month period of orbiter observations, the formation of dust devils and their passage over the terrain, and/or local wind gusts led to local dust-lifting and removal, leading to a relatively darker surface and the formation of dark wind streaks.

[6] Although several attempts were made to observe active dust devils from Spirit, none were captured [*Whelley et al.*, 2004]. However, Spirit images provide new information on the characteristics of dark streaks, including the streak at the landing site. Figure 2b is a Pancam image [*Bell et al.*, 2004] taken from the rover on its traverse to Bonneville crater, viewed back toward the landing site. Clearly visible is the boundary between the dark streak within which the rover landed and the zone outside the dark streak [*Greeley et al.*, 2004]. Although some of the differences in brightness in the Pancam view can be attributed to the local terrain and the viewing geometry from the rover, the boundary coincides with the boundary of the streak seen in orbiter views. The Spirit Microscopic Imager (MI) has a spatial resolution of 31 μm per pixel [*Herkenhoff et al.*, 2004]. MI images of the soil on the crest of ripples inside the dark streak zone show coarse sand grains ∼1 mm in diameter that are relatively "clean" of finer grained material (Figure 2c), while MI of ripple crests outside the dark streak zone (Figures 2d and 2e) show sand grains set in a matrix of finer grains, inferred to be dust.

[7] Numerous studies based on theory [e.g., *Sagan and Pollack*, 1969] and wind tunnel experiments [e.g., *Greeley et al.*, 1980; *Iversen and White*, 1997] show that smooth beds of dust-sized particles require a higher wind surface shear stress for particle entrainment than smooth beds of sand-sized particles. However, wind tunnel experiments also show that dust particles mantling rougher surfaces are more vulnerable to entrainment [*White et al.*, 1997]. Local wind gusts, winds within dust devils, and the "vacuum cleaner" effect of lower atmospheric pressure beneath the core of dust devils [*Greeley et al.*, 2003b] also facilitate lifting of dust from the surface. Once lifted, dust is easily transported in suspension. Thus we suggest that dust grains that settle on the tops of sand grains are relatively easily swept away by gusts or the passage of a dust devil, leaving

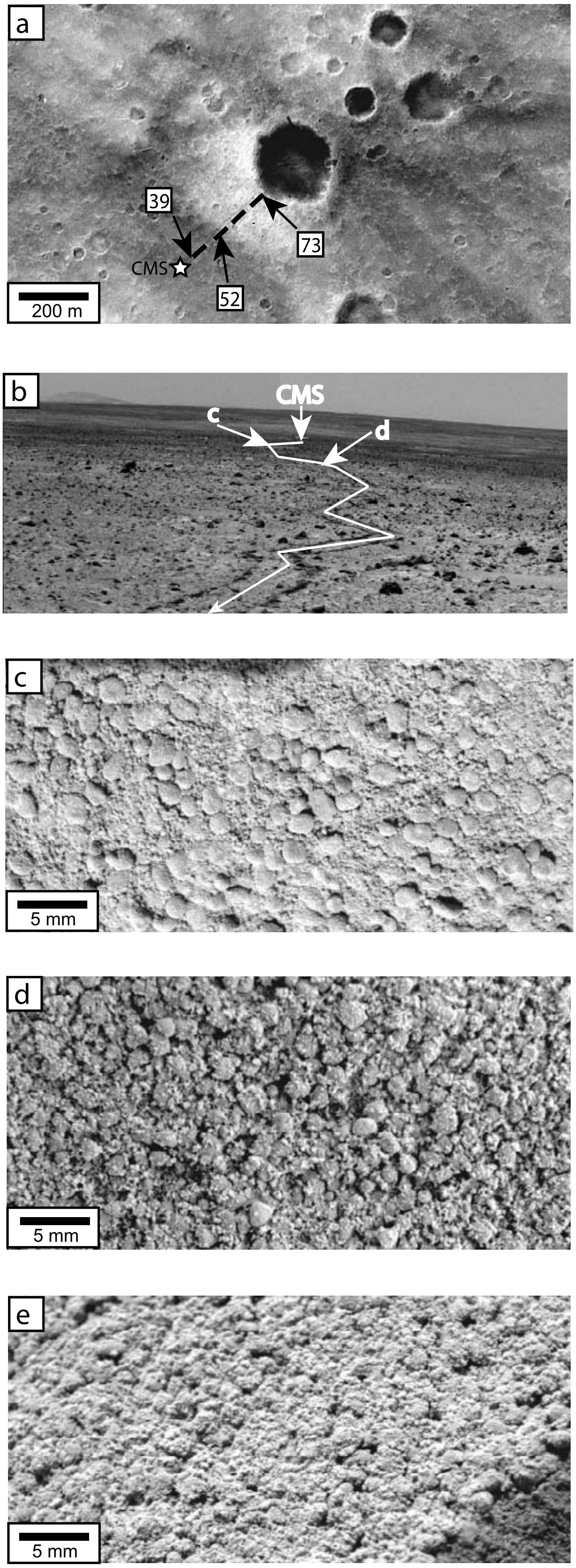

Figure 2. (a) Mars Orbiter Camera image showing the landing site for Spirit (CMS; star) within a dark linear streak and the traverse to Bonneville crater (dashed line); (b) Pancam image viewed from near the rim of Bonneville crater back toward the landing site and the traverse path of the rover; the boundary between the dark streak and the bright ejecta is visible. Figures 3c, 3d, and 3e show the locations of Figures 2c, 2d, and 2e: (c) MI image taken on sol 39 of soil on the crest of a bedform within the dark streak showing coarse sand that appears relatively "cleaner" of fine dust; (d) MI image taken on sol 52 of soil on the crest of a bedform within the bright zone near the dark streak boundary, showing coarse sand grains and a texture indicative of fine dust coating the grains, and (e) MI image taken on the crest of a bedform near the rim of Bonneville crater in the bright zone, showing "dusty" appearance of the sands.

Table 1. Mars Express HRSC, Mars Odyssey THEMIS, and MER Spirit Images Used in the Analysis

Figure	Orbiter; MER Sol	Date	Image ID	Ls, °	Resolution per Pixel	Filter, nm	Incidence Angle, °	Emission Angle, °	Phase Angle, °
1a, 1d	THEMIS	26 Sept. 2003	V07909002	268	19 m	654	67	0	67
1b, 1e	MEx 0024	16 Jan. 2004	h0024_0000.nd3	334	13 m	675 ± 90	40	16	52
1c	MEx 0072	1 Feb. 2004	h0072_0000.nd3	343	18 m	675 ± 90	28	56	31
2a	MOC	30 March 2004	R15-02643	12	1.47 m		33	11	41
2b	MER A Sol 66	10 March 2004	2P132219261FFL16000P2283L2M1	3	600 micron (center of mosaic)	750, 530, 480, 980	24	87	63
2c	MER A Sol 39	12 Feb. 2004	2M129820106EFF0400P2943M2M1	349	31 micron	400–700	na	0	na
2d	MER A Sol 52	25 Feb. 2004	2M130974187EFF1100P2953M2M1	356	31 micron	400–700	na	0	na
2e	MER A Sol 73	18 March 2004	2M132840805EFF2000P2937M2M1	6	31 micron	400–700	na	0	na
3h	MER A Sol 258	24 Sept. 2004	2M149275148EFF8800P2976M1	92	31 micron	400–700	na	0	na
3b, 3d, 3f	MER A Sol 239	4 Sept. 2004	2P147585044FFL8702P2408L2M1	83	400 micron (center of mosaic)	430, 530, 750	47	38	36
3c, 3e, 3g	MER A Sol 261	27 Sept. 2004	2P149536842FFL8815P2411L2M1	93	400 micron (center of mosaic)	430, 530, 750	45	39	40

the coarser grains behind. Because the brightness of a surface is partly a function of particle size, in which brightness is qualitatively inversely proportional to grain size, the resulting surface would appear dark.

[8] During the solar conjunction from 5 to 26 September 2004, Spirit was placed in a stand-down mode and did not move (Figures 3a, 3b, and 3c). Prior to conjunction, Pancam imaged the surface where the rover was to be placed during the stand-down. The rover was then moved into position for the stand-down where it remained for 20 sols. After conjunction, the rover was moved to the previous position and a second set of Pancam images was obtained under nearly identical illumination and viewing conditions as the first set of images. As shown in Figures 3d–3g, several patches became darker with respect to the surrounding soils. Wind tunnel experiments simulating Martian conditions using a 1/6th scale model of the rover showed that these zones correspond to higher wind surface shear stresses (Figure 4) that result from the acceleration of winds beneath the body of the rover [*Neakrase et al.*, 2004].

[9] MI images (Figure 3h) were taken of the area where the Spirit Robotic Arm placed the Mössbauer Spectrometer, which indented the soil surface a few millimeters. Images taken 18 sols apart during the solar conjunction of the area show that some of the larger grains moved as far as 0.7 mm. None of the grains were seen to be removed, but were simply repositioned. Although vectors of the directions of movement show much scatter (Figure 3i), there is a general trend for movement toward the southeast. This direction of motion is consistent with the orientation of various wind-related features in the area [*Greeley et al.*, 2004], such as dune forms, and with stronger afternoon winds predicted by atmospheric models [*Rafkin and Michaels*, 2003].

[10] As suggested in Figure 5, dust perched on the tops of larger grains is more easily removed by wind than from a flat surface composed entirely of dust, similar to wind tunnel results for dust mantles on gravel [*White et al.*, 1997]. In addition, the movement of sand grains by winds can cause the finer dust to infiltrate downward among the sands with neither the sand nor the dust being removed by the wind. In an inactive bedform, dust would eventually fill the interstices among the sand grains. In both cases, the exposure of the coarser-grained sands would lead to a relatively darker surface.

3. Conclusions

[11] MER Spirit data and THEMIS and HRSC images taken from orbit indicate that dark wind streaks and other dark variable features can form by the removal of dust from larger grains, and perhaps during minor repositioning of these larger (e.g., sand) grains provide new data on the formation of dark wind streaks on Mars. HRSC images show the development of dark wind streaks in the general time-frame and place of rover operations. Microscopic Imager data from the rover suggest that bright areas are

Figure 3. Changes seen on the surface from Spirit during the solar conjunction stand-down from sol 240 to sol 260: (a) diagram showing the position of the rover on sol 239 before the stand-down and sol 261 after the stand-down and its location during the stand-down, where it remained for 20 sols; dashed lines indicate approximate footprints of the Pancam images; (b) Pancam mosaic taken on sol 239; (c) Pancam mosaic taken on sol 261, showing the dark surface markings where soil was disturbed by the rover wheels; (d) Pancam image taken on sol 239 of site A compared to (e) image taken on sol 261 showing the development of dark spots; (f and g) similar comparisons for site B; (h) mosaic of MI images of the depression in the soils from the Mössbauer spectrometer showing individual sand grains; and (i) vectors of the movements of individual grains tracked in the MI images taken on sol 240 compared to those taken on sol 258. No grains were seen to be removed, suggesting that winds were able to move them only short distances.

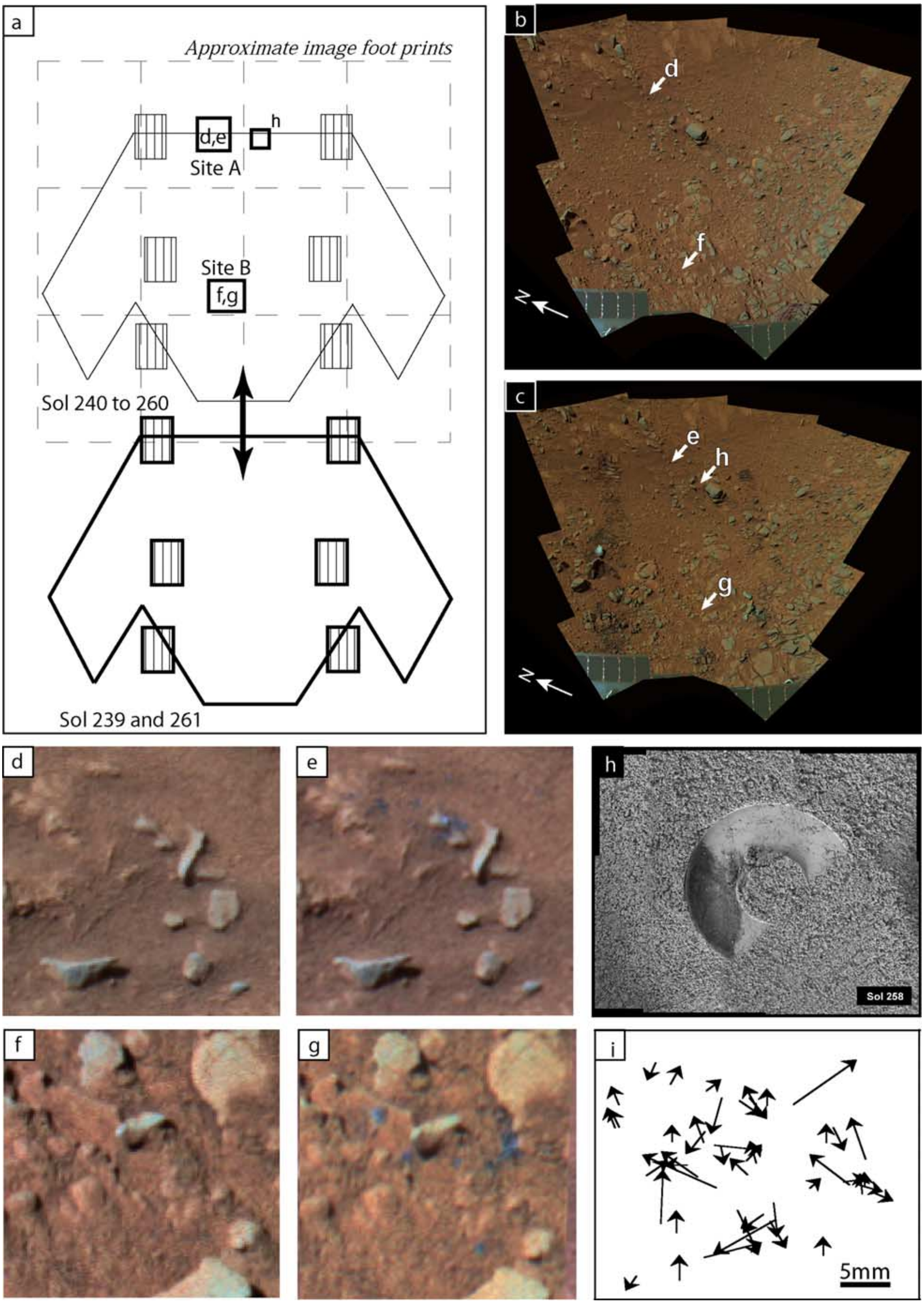
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Figure 3

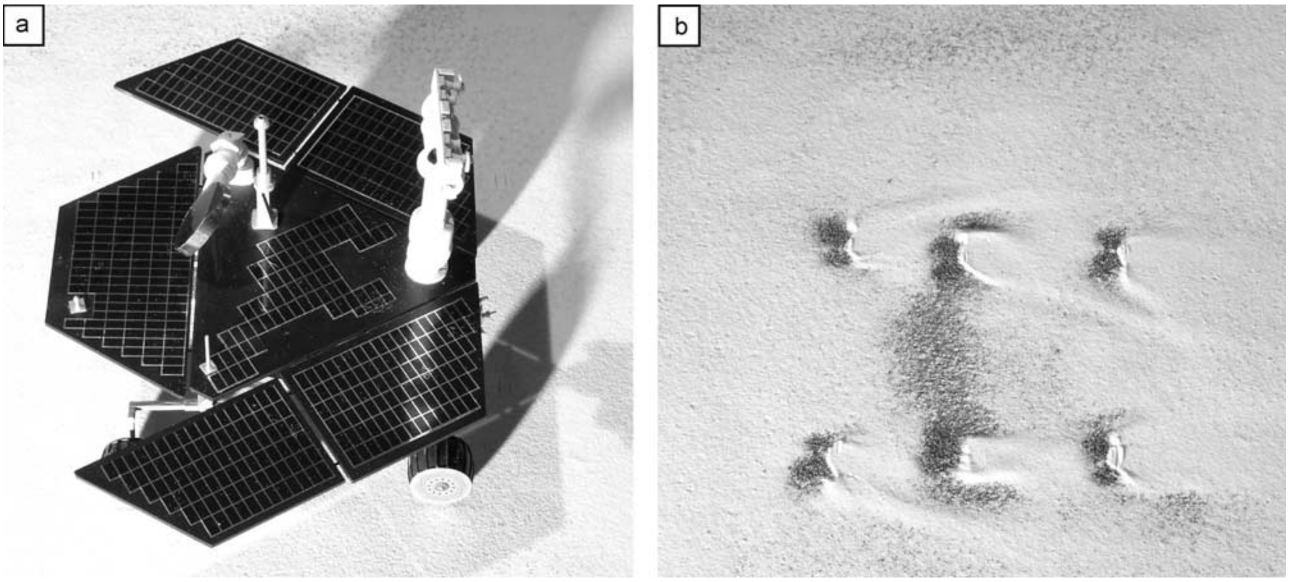

Figure 4. Wind tunnel experiments to simulate erosion and deposition of windblown particles around MER: (a) Model was placed on a test bed of fine, loose sand (white) with wind blowing from left to right. (b) Pattern in the white sands after the run and with the removal of the rover model; dark areas show where the rover wheels were located and where the loose sand was removed; note the dark patch corresponding to the zone beneath the body of the rover where winds were accelerated (arrow), generating a high wind surface shear stress.

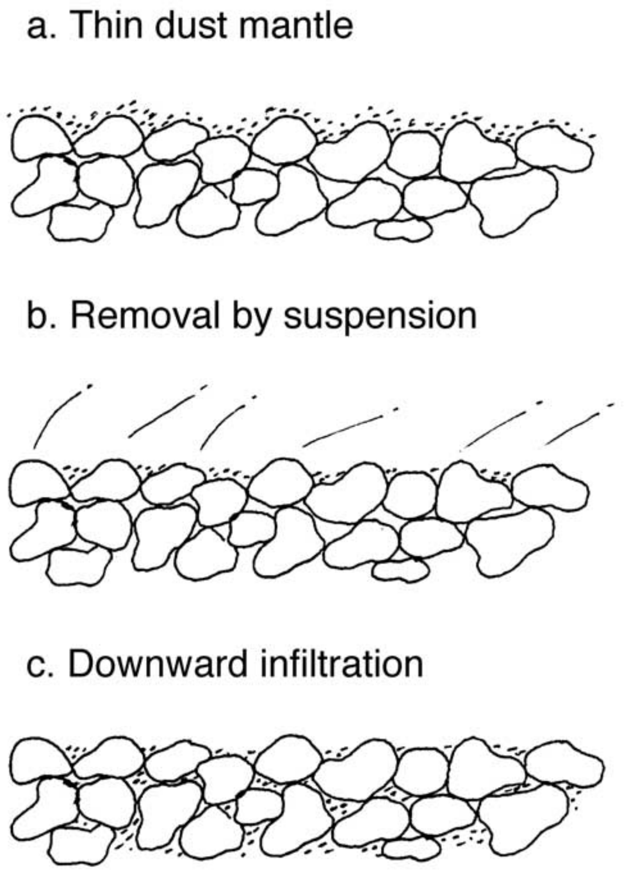

Figure 5. Diagrams of suggested movement of wind-blown particles to account for the formation of dark streaks: (a) thin mantle of fine dust settled from the atmosphere on a bed of sand; (b) dust "perched" on the tops of large sand grains is removed into suspension by the wind; (c) dust infiltrates between the sand grains by the movement of the sand; in both cases, there is a greater exposure of coarse grains that would result in a lower-albedo surface.

dustier than dark areas, the surface of which appears to be relatively free of dust. Observations of the sandy surface beneath the rover during an interval of 20 sols show that sand grains were repositioned without being removed, leading to the formation of relatively dark areas where winds are expected to be accelerated beneath the body of rover, generating high surface shear stresses. We suggest that local wind gusts and dust devils (rather than prolonged winds) can be responsible for the removal or infiltration of dust on a sandy surface to form some dark wind streaks.

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