ELSEVIER

Geomorphology 17 (1996) 167–185

GEOMORPHOLOGY

Wind streaks: geological and botanical effects on surface albedo contrast

James R. Zimbelman [a,*], Steven H. Williams [b]

[a] *Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, USA*
[b] *Department of Space Studies, Center for Aerospace Sciences, University of North Dakota, Grand Forks, ND 58202, USA*

Received 20 September 1994; revised 28 January 1995; accepted 23 February 1995

Abstract

Two wind streaks in the eastern Mojave Desert of California were examined to gain insight into the origin of the surface brightness contrast that makes them visible, both on the ground and in remote sensing data. The two localities are: a 4-km-long dark streak oriented S43E from the Amboy cinder cone (34°32′N, 115°46′W), located on a Quaternary basalt flow covered with aeolian sand, and a 2-km-long dark streak oriented S22E from a low hill near the southwestern base of Sleeping Beauty Mountain (34°48′N, 116°20′W), located on a sand-covered alluvial surface. In both cases, the dark streaks have enhanced rock abundances on the streak surface, relative to the surroundings. At the Amboy streak, slope wash likely contributed to the rock concentration on the streak surface, shielded from burial under aeolian sand by the cinder cone. At the Sleeping Beauty streak, the relative albedo contrast is strongly emphasized by the presence of Big Galleta grass only outside of the streak. The albedo contrast of the Sleeping Beauty streak can be effectively eliminated by the seasonal presence of annual grass preferentially within the streak. Some plants may have reflectances that are strongly dependent upon viewing and illumination geometry, raising the possibility that certain terrestrial aeolian features may appear variable on a diurnal basis. Alluvial processes appear to have been important at both localities for redistributing surface materials, even given the infrequent rain conditions present in the Mojave Desert.

1. Introduction

Many topographic features in arid environments have associated with them a narrow, elongated zone which has a distinctly different surface albedo than the surrounding area. Field and laboratory studies during the past fifty years have demonstrated that the zones of albedo contrast downwind of obstacles are the result of aeolian erosion and deposition (e.g., Bagnold, 1941; Greeley and Iversen, 1985). Such features, called wind streaks, reflect their origin and appearance and are important for at least two reasons. First, they indicate that the surface has active aeolian processes: loose, sand-sized material on the surface and winds of sufficient strength to move it. The rate of aeolian redistribution of surficial material must exceed the obliterating effects of gradational and other processes. Second, the orientation reveals the direction of the prevailing winds, or, in some cases, the direction of the most recent strong wind.

On Earth, wind streaks can be overwhelmed by the obscuring effect of running water and vegetation. Where they do occur, they often owe visibility to

* Corresponding author.

SSDI 0169-555X(95)00098-4

variations in rates of desert pavement formation and the effect on those rates of local sand throughput (Greeley and Iversen, 1985; Greeley et al., 1989). We have even found an interesting example where vegetation enhanced, not hindered, the detectability of wind streaks in arid regions. This paper investigates two wind streaks, as viewed both from the air and from the ground, in order to better understand the origins of the albedo contrast associated with wind streaks in arid environments.

A variety of types of wind streaks have been observed on Mars and Venus (Fig. 1); they have been used to assess regional and global wind circulation patterns on both planets (Arvidson, 1974; Thomas and Veverka, 1979; Thomas et al., 1981; Veverka et al., 1981; Ward et al., 1985; Wells and Zimbelman, 1989; Saunders et al., 1990; Greeley et al., 1992). Some martian wind streaks were observed to have changed between Viking observations (Sagan et al., 1973; Thomas and Veverka, 1979), proving that some sort of surface process was presently operating, with the wind being the only reasonable candidate. Most recently, Magellan radar observations of the venusian surface have revealed albedo features that are almost certainly a result of aeolian activity (Saunders et al., 1990; Greeley and Arvidson, 1990; Greeley et al., 1992). The general conditions necessary to generate the albedo contrast that makes the wind streak visible are the focus of this paper. Some mechanisms of desert pavement formation may not operate in various planetary environments, or they may operate at a substantially different rate. Therefore, it is important to understand how terrestrial streaks form and evolve in order to better understand both terrestrial and extraterrestrial aeolian environments.

The objective of this study was to better understand wind streak formation and modification processes through field examination of two distinctly

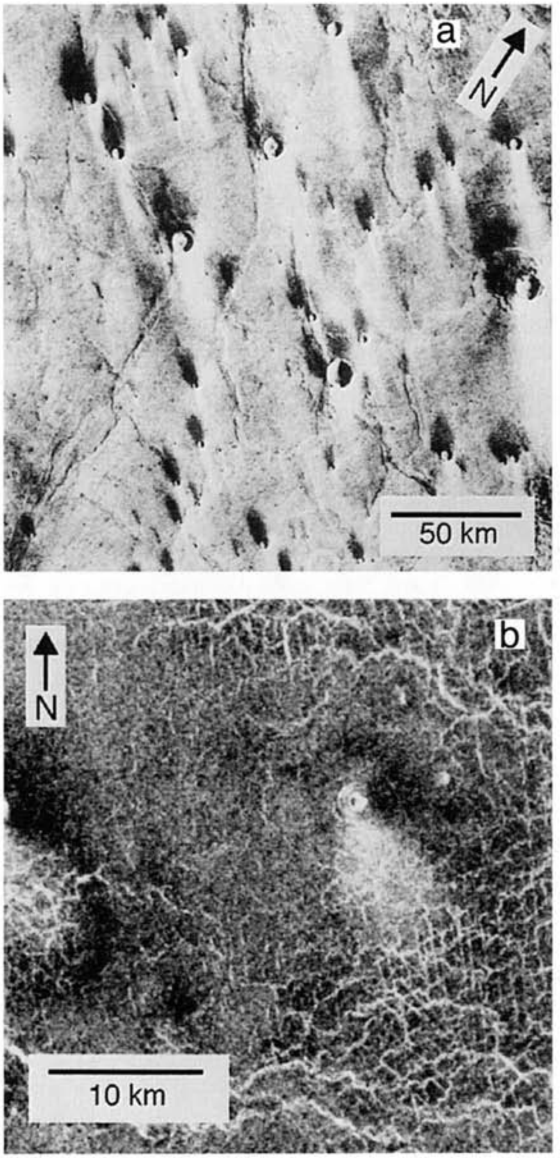


Fig. 1. Wind streaks on Mars and Venus. a. Bright and dark wind streaks are associated with craters in the Hesperia Planum region of Mars (28°S, 245°W). The entire surface presumably received a coating of high-albedo dust fallout during the last dust storm, with bright streaks forming in the lee of obstacles where dust deposition is enhanced. Later, when the air was not laden with dust, winds from the opposite direction caused erosion in the lee of obstacles where turbulence is enhanced. (Viking Orbiter image 553A54, NGF orthographic projection.) b. Differences in surface smoothness because of differential sedimentation are thought to be the cause of the variations in surface reflectance seen in this Magellan radar image of Venus. Many different types of venusian streaks have been observed; this one is a radar-bright fan-shaped streak surrounded by a radar-dark halo (see Fig. 13 of Greeley et al., 1992). The Amboy streak also shows up as radar-dark in Seasat images (see Fig. 2a,b of Greeley et al., 1992). Most venusian streaks are related to some sort of topographic obstacle; in this case, a small hill located at 22.3° N. lat., 332.1° long. (Portion of Magellan Press Release photograph P-36698; from a portion of Magellan F-MIDR 20N334.)

different wind streaks in the eastern Mojave Desert. We examined the Amboy and Sleeping Beauty wind streaks (described below) in order to assess the effect on surface albedo of rock populations and vegetative cover both inside and outside the streak. Rock abundances, both at the surface and at depth, were documented, a particle size analysis was made of subsurface rocks, and the plant population was characterized inside and outside of the Sleeping Beauty streak.

2. Background

2.1. The aeolian nature of wind streaks

Atmospheric stability is a very important factor for controlling the type of wind streak created downwind of an obstacle. At one extreme, if the atmosphere contains a sufficient quantity of suspended dust (as occurs regularly at Mars), the heat provided to the atmosphere by the dust particles can lead to a stable temperature profile and the suppression of turbulence. Flow of dust-laden wind past a topographic obstacle such as a hill or a crater produces a dead zone in its lee in which dust deposition is increased. Because the albedo of dust-sized particles is generally much higher than the material from which the dust is derived, the resulting depositional streak is brighter than its surroundings (Sagan and Pollack, 1969; Pollack and Sagan, 1969; Sagan et al., 1973). An entirely different situation arises when the atmosphere is not laden with dust. Turbulence in the atmosphere is increased, not decreased, in the wake of an obstacle because of a lowering of atmospheric stability brought on by increased surface heating. This creates a zone of enhanced erosion (or non-deposition of dust) that is usually darker than its surroundings because it lacks higher-albedo fine material (Greeley and Iversen, 1978, Greeley and Iversen, 1985, Greeley and Iversen, 1987). An example of both bright and dark streaks on Mars, formed under very different aeolian conditions, is shown in Fig. 1a.

Wind streaks on Earth are less common than those on Mars and Venus because of the gradational effects of wind, water, and soil formation. Further, terrestrial meteorologic conditions are such that simply moving around thin layers of dust, as in the mechanisms proposed for the formation of martian-like bright and dark streaks (Veverka et al., 1981), does not occur. Terrestrial topography can be responsible for the funneling of sand-sized material into streaks or stringers of material with a higher albedo than its surroundings (for example, see Breed and Grow, 1979), but they are not analogous to the martian streaks. Some good examples of erosional streaks exist on Earth, too, although they are typically smaller than those on Mars (Greeley and Iversen, 1985). Examples are the streaks of this study and the patterns of aeolian erosion and deposition at the Wolf Creek impact crater, Australia, and Aouelloul impact crater, Mauritania, that resemble crater-associated wind streaks on Mars (Greeley and Iversen, 1985). Terrestrial sand streaks and related sand accumulations are important in studies of Holocene paleoclimatology (for example, see Tchakerian, 1991; Zimbelman et al., 1996; Rendell, 1996).

Development of desert pavements or aeolian lag deposits can affect surface albedo profoundly (Greeley and Iversen, 1985; Williams and Zimbelman, 1994). Desert pavements typically consist of a layer of cm-sized rock fragments lying atop a soil layer that is free of fragments. Both internal processes, such as heaving by frost or by the wetting and drying of subsurface clays, and external processes (such as aeolian deposition, deflation and sheet wash) contribute to the formation and evolution of pavements (Cooke et al., 1993; Williams and Zimbelman, 1994). Without sheet wash or some other mechanism for causing lateral migration of rock fragments, however, deflation will increase fragment concentration until the surface becomes armored, leaving much of the high-albedo substrate visible from above (Chepil, 1950; Cooke et al., 1993; Williams and Zimbelman, 1994).

The traditional view of the evolution of desert pavement relied heavily on deflation without possible contributions from processes like sheet wash. A more plausible view of the development of desert pavement (and soil) on basalt flows has been described as the formation of an accretionary mantle (Wells et al., 1985; McFadden et al., 1987) rather than the modification of an initially heterogeneous soil layer. In their model, dust and salts from air fallout, local weathering, and rainfall gradually collect beneath fragments of pahoehoe ropes and the weathering rind lying atop a fresh basalt flow. Over time, dust and salts accumulate, causing more rock disintegration and the stones to 'float' atop the thickening layer. Sheet wash can keep the surface concentration of rock fragments high, often armoring the fines on the surface against aeolian deflation and sometimes causing compete interlocking of the edges of the fragments. In the initial stage of mantle formation, sheet wash can concentrate fragments without any soil being present, and the concentration of stones will be more or less maintained throughout soil development, representing a balance between deposition, which tends to spread the fragments, and sheet wash, which tends to concentrate them (Williams and Zimbelman, 1994).

2.2. Mojave study sites

The study sites discussed below are located in the Mojave Desert of the southwestern United States (Fig. 2; see Sharp, 1976, for general description of the Mojave Desert). Locally, sand is readily available for aeolian transport and its mobility is little impaired by the average rainfall of only a few inches

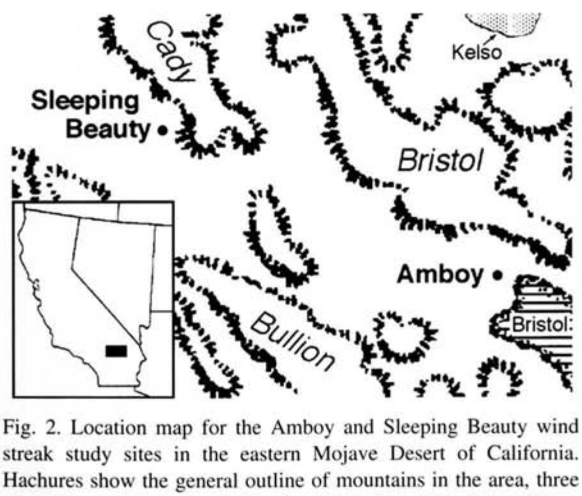


Fig. 2. Location map for the Amboy and Sleeping Beauty wind streak study sites in the eastern Mojave Desert of California. Hachures show the general outline of mountains in the area, three of which are labeled in italics (modified from Fig. 2-8 of Sharp 1976). Sleeping Beauty Mountain is at the southern end of the Cady Mountains. Lined pattern represents the Bristol Playa; dotted pattern at upper right corresponds to the Kelso dune field. Inset diagram shows the position of the map within the California state boundary.

annually. Rainfall, surface roughness, and vegetation limit aeolian transport to some degree, but the primary limiting factor is sand supply (Williams and Lee, 1995). Small wind streaks and sand stringers are common in the region, but here we will concentrate on the 4-km-long wind streak associated with the Amboy cinder cone (Greeley and Iversen, 1978, 1985) and a slightly shorter streak associated with a small hill immediately north of the Pisgah basalt flow (Zimbelman et al., 1987).

The Amboy streak (34°32′N, 115°46′W) is located in the Bristol Valley near the small town of Amboy, California, on the National Old Trails Highway (old Route 66) about halfway between Barstow and Needles (Fig. 2). The Amboy basalt field covers ~ 70 km^2, is Quaternary in age, and is mostly composed of hummocky, undifferentiated pahoehoe units with both platform and vent type lavas also present (Greeley and Iversen, 1978). The cinder cone at the apex of the S34E-oriented wind streak (Fig. 3a) is ~ 75 m high and is composed of at least four nearly coaxial nested conelets that represent different eruptive events (Greeley and Iversen, 1978). The basalt flow itself is partially covered by aeolian sand which has locally sand-blasted the basalt into ventifacts (Greeley and Iversen, 1978, Greeley and Iversen, 1985; Williams and Greeley, 1983). Desert pavement surfaces are prevalent, particularly in the wind streak itself, and the Amboy flow and pavements have been used in the development and confirmation of the accretionary mantle model of desert pavement development (Wells et al., 1985; McFadden et al., 1987; Williams and Zimbelman, 1994). Cinders from the cone do not significantly contribute to the pavement in the streak (Greeley and Iversen, 1978, Greeley and Iversen, 1987) as they do around one Egyptian wind streak described by El-Baz et al. (1979). The Amboy streak owes much of its albedo contrast to the higher degree of desert pavement development in the streak caused by the cone blocking sand from traversing through the streak area, possibly enhanced sand transport via saltation over the abundant surface rocks, and by the creation of lateral winds in the lee of the cone that inhibits sand from entering the streak (Greeley and Iversen, 1985).

The second wind streak study site is located in Broadwell Valley, immediately north of Interstate Highway 40 at the Pisgah lava flow, with a small knob at its apex (34°48′N, 116°20′W), colloquially referred to as 'Tortoise Hill' after the desert tortoises found there (Fig. 2). We will refer to this S22E-oriented dark streak as the 'Sleeping Beauty' streak (Fig. 3b), after the adjacent mountain, to avoid confusion with another nearby Mojave knob also referred to as 'Tortoise Hill' (Laity, 1992). The regional geologic setting is similar to that of the Amboy site; however, the streak is sited on sandy alluvium rather than sand-covered basalt. Vegetation is responsible for much of the albedo contrast that makes the Sleeping Beauty streak visible because only a limited albedo contrast exists between the sandy alluvium outside the streak and the rocky alluvium inside the streak. Both the illumination and viewing geometries may have a significant effect on the appearance of the streak.

3. Field results

3.1. Amboy

The Amboy cinder cone provides an obstacle to sand transport caused by the west-to-east storm winds of winter and spring, resulting in a streak with a low albedo relative to its surroundings (Fig. 3a). The streak is approximately as wide as the base of the cinder cone (~ 500 m) and can be traced for more than 4 km across the Amboy lava flow. The dimensions and albedo contrast of the streak are sufficient to be readily visible in Landsat images obtained from both the Multispectral Scanner (MSS) and the Thematic Mapper (TM) on the Landsat series of Earth-observing satellites. The streak appearance from orbit and its setting on a basaltic lava flow resulted in

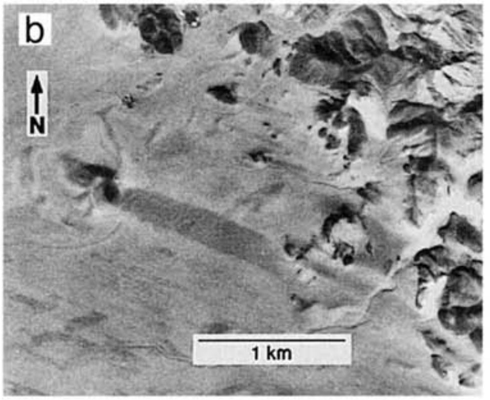


Fig. 3. (a) Vertical aerial photograph of the Amboy cinder cone and wind streak. The streak occurs on a basaltic lava flow, containing abundant tumuli and pressure ridges, that is overridden by aeolian sand. Line shows the location of the traverse for Fig. 5. Letters show the locations of surface photographs: A, Fig. 4a, and location of pit within streak; B, Fig.4b; C, location of pit outside of streak; D, Fig. 6. (Portion of U.S. Department of Agriculture photograph AXL-26K-36, taken on 1/10/52.) (b) Vertical aerial photograph of the Sleeping Beaty wind streak. (Portion of U.S. Department of the Interior photograph GS-VDQM-1-70, taken on 5/24/75.)

its use as a terrestrial analog for dark wind streaks on Mars (Greeley and Iversen, 1978, Greeley and Iversen, 1985). Our field studies were carried out in order to assess the surface characteristics that are responsible for the albedo contrast associated with the Amboy wind streak.

3.1.1. Surface characteristics

Initial reconnaissance studies of the streak surface quickly indicated that the albedo contrast visible from orbit resulted from a non-random distribution of dark basaltic rock intermixed with aeolian sand and dust deposits. The most striking aspect of the streak surface is the presence of a closely packed monolayer of basaltic pebbles within local depressions on the lava flow (Fig. 4a). The dark pebbles are mostly smaller than about 1 cm in diameter, but they are so closely situated that little of the bright underlying silt surface is visible unless the pebble layer is disturbed. The basaltic pebbles contain some vesicles but they are much more similar to fractured basalt than to highly vesiculated cinders. The bright material beneath the pebble layer is weakly indurated and highly vesicular near the surface, consistent with the descriptions of accretionary mantles developed elsewhere in the Mojave Desert (Wells et al., 1985; McFadden et al., 1987).

The monolayer concentration is highest in the streak near the cinder cone, attaining an areal coverage of 90% of the surface (Fig. 4a). The pebble concentration on the streak surface is in marked contrast to the appearance of the lava flow surface away from the streak, where basalt fragment size is much more variable and only about 25% of the surface consists of rocks, with aeolian sand comprising the remainder of the surface (Fig. 4b). Surface rocks outside of the streak are separated by several diameters from neighboring fragments, in sharp contrast to the close spacing attained within the streak, but consistent with the distribution of non-erodible elements in an armored surface that protects the surface from erosion by saltating sand (Chepil, 1950).

A traverse perpendicular to the streak axis was carried out 1.2 km downwind from the cinder cone in order to document the areal abundance of rock fragments across the streak (line in Fig. 3a). The surface was photographed vertically from a distance of 1.5 m at 30-m intervals along the 1.2-km traverse. Standard counting areas of 25 by 25 cm within each photograph were evaluated for the areal rock coverage in 16 bins, producing results repeatable to $\pm 5\%$ for the areal rock abundance at a given station (Fig. 5). The streak is clearly evident by a rock abundance of 70–80%, whereas the lava surface outside of the streak is quite variable but primarily confined to the range of 20–50%. Localized enhancements occur downwind of selected large pressure ridges (e.g. stop N420), and the traverse crossed two large pressure ridges within the streak where essentially 100% outcrop occurred. Outside of the streak the traverse crossed three separate patches of sand where the rock cover was effectively 0% (circles in Fig. 5); the sand accumulated in shallow depressions or downwind of features large enough to make local obstacles to wind flow. The traverse plot documents the general impression one gains by walking across the lava flow, with abundant active sand outside of the streak and increased rock fragment concentrations within the streak.

Bedrock outcrops are distributed randomly across the lava flow, both within and outside of the dark streak. The outcrops primarily consist of tumuli and pressure ridges in the basaltic flow that protrude 2 to 4 m above the adjacent surface. Between the outcrop ridges aeolian sand dominates the upper 3 to 5 cm, under which the bright silt of the accretionary mantles fills in the topographic lows. Creosote bushes are the dominant vegetation, roughly 1 to 1.5 m in height, randomly distributed at 5- to 10-m intervals across the flow surface both inside and outside of the streak.

Laboratory measurements of the normal reflectance at visual wavelengths were obtained for rock and soil samples from within and outside the streak. Reflectances for rocks collected both within and outside of the streak were measured by a laser goniometer at the University of California at Los Angeles; calculated normal albedoes ranged from 0.036 to 0.059, averaging 0.045 for typical basalt fragments. Surface soil (primarily silt-sized) from within the streak has an average normal albedo of 0.159, whereas soil from outside the streak (primarily sand-sized) has an albedo of 0.145; samples from both locations showed very little deviation in reflectance from repeated measurements across the powered samples. These results suggest that the areal concentration of rock fragments at the surface is the primary physical mechanism for changing the overall surface albedo, because the rocks are three to four times darker than the fines either within or outside of the streak.

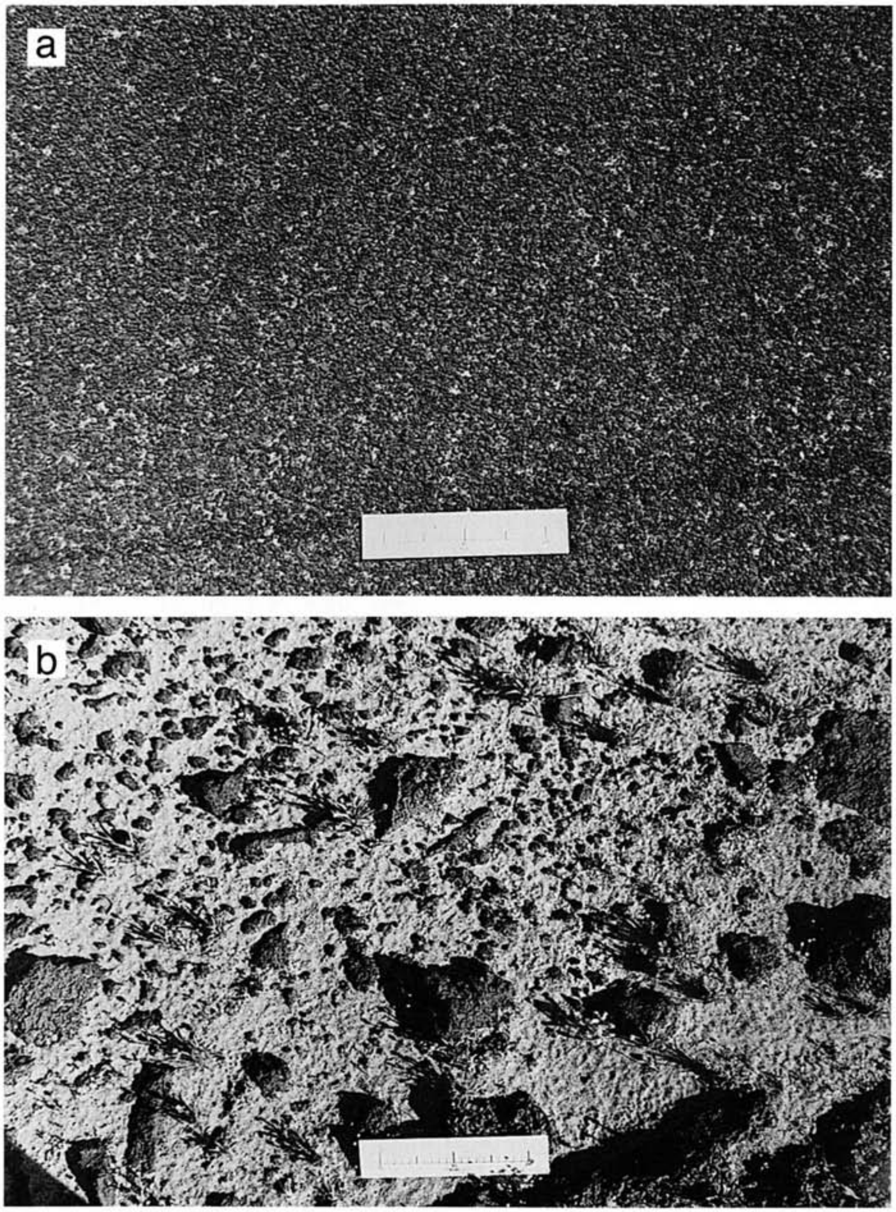


Fig. 4. Vertical photographs of the Amboy lava flow surface. White scale card is 25 cm in length. a. Closely packed monolayer of basalt fragments overlying a silt-clay substrate within the Amboy streak. Photograph taken within a depression between pressure ridges exposing basalt bedrock within the streak (see A in Fig. 3a). Pit was dug within a few meters of this location. (Photograph by JRZ on 4/7/79.) b. Widely spaced rock fragments on sandy substrate outside of the Amboy streak (see B in Fig. 3a). This surface is typical of an armored surface rather than a desert pavement. (Photograph by JRZ on 4/7/79; taken at traverse location 360N of Fig. 5.)

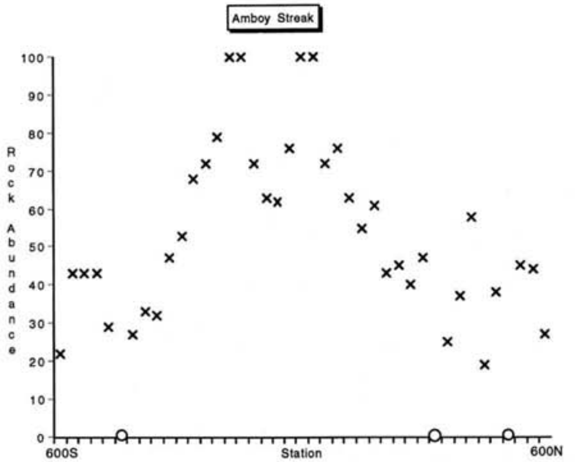


Fig. 5. Rock abundance on a traverse across the Amboy streak, located about 1 km downwind from the Amboy cinder cone (see line in Fig. 3a). The areal coverage of rocks was determined from vertical photographs taken at 30 meter intervals from south (left; station 600S) to north (right; station 600N). The streak has rock abundance of 60-80% whereas outside of the streak the rock abundance is generally 20-50%. Traverse stops on pressure ridges are shown as 100% rock abundance. Traverse stops on localized accumulations of sand are shown as 0% rock abundance.

3.1.2. Subsurface rock distribution

Samples were collected from two pits dug into the rock-fragment-covered lows, both within and outside of the streak. This investigation assessed whether the basalt fragments concentrated at the surface could have been raised through the fine silt via cyclical processing such as freeze–thaw or swell–shrink of wetted clay-rich soils (Springer, 1958). Rock fragments larger than 1 mm were sieved from soil collected in 10-cm increments from pits of 25 by 25 cm (locations A and C in Fig. 3a). Zones of induration within the soil manifested themselves as coherent soil fragments that withstood the 15-min Rotap shaking applied to each sieve set.

Surface rocks from within the streak have a well-sorted distribution around a mean size of 6 mm. The soil up to 10 cm below the surface monolayer of rocks is deficient in rocks larger than 4 mm and is moderately indurated. The only large rocks found within the pits were encountered between 10 and 30 cm depth within the streak, and no depth showed any significant enhancement in rocks in the 4–8 mm fraction that could have contributed to the distribution observed at the surface. Moderate induration was again encountered below 40 cm depth. In contrast to the results from within the streak, the surface rocks outside of the streak appear to represent the fining wing of a distribution with a much larger mean size—perhaps simply the distribution obtained from break-up of massive rock outcrops. Beneath the surface layer of rocks the soil is again deficient in large rocks but from 10 to 30 cm depth several rocks larger than 8 mm were encountered, with strong soil induration below 30 cm depth. It is very unlikely that significant vertical migration of rocks has taken place through the presently observed distribution of rock and soil at Amboy.

We also established several test sites, both within and outside of the streak, to monitor any possible vertical movement by marked rock fragments. Over a 13-year period we were unable to detect any observable vertical motion by rocks, even within only the topmost few centimeters of soil. We conclude that vertical migration mechanisms are not active at Amboy, at least at a macroscopic scale over decadal time intervals. Our results are consistent with the accretionary mantle hypothesis of Wells et al. (1985) and McFadden et al. (1987), where aeolian fines filter between and beneath rocks to gradually fill in low areas with tens of centimeters of silt. The greater thickness of non-indurated fines at depth within the streak, as compared to the thickness outside of the streak, raises the possibility that the accretionary mantle growth rate could be enhanced within the streak, where active aeolian sand does not scour away the growing silt layers.

3.1.3. Monitored surface rock movement

Test sites were also established to monitor the possible horizontal movement of rock fragments. Postulated agents for horizontal movement include gravitationally induced movement down slope, sheet wash, and the wind. Wind sufficient to roll mm- to cm-sized rocks is uncommon, but major storms that annually pass through the Mojave Desert region might cause some rock movement. Evidence of sheet wash mobilizing rock fragments over bedrock was recently described at the Pisgah lava flow, a Holocene basalt flow only 30 km west of Amboy (Williams and Zimbelman, 1994). Test sites at Amboy failed to provide any support for the wind as a major factor in

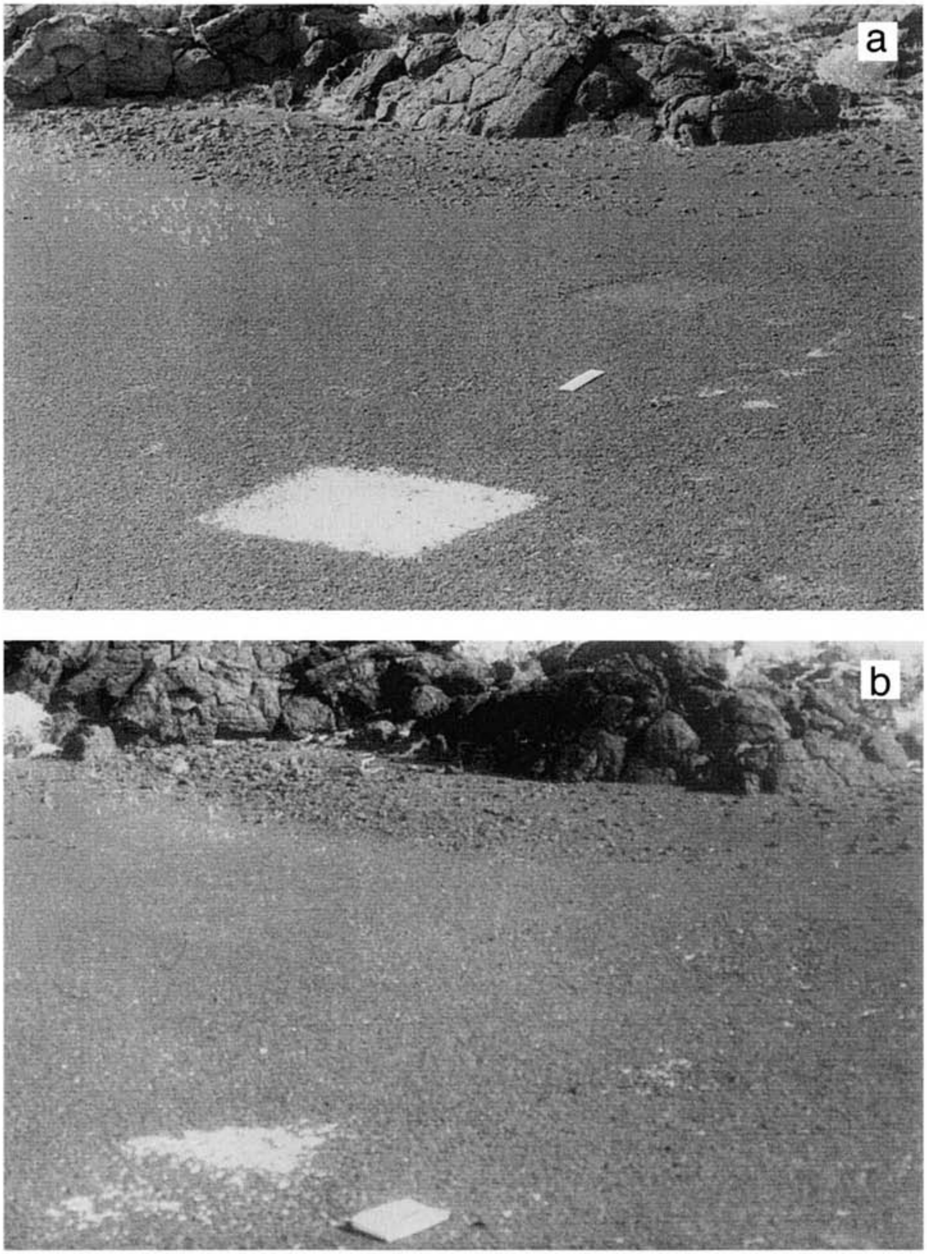


Fig. 6. Oblique views of a test patch within the Amboy streak where surface rocks were cleared away on 11/10/79. Both views are looking south-southeast, with basalt bedrock in the background. a. Cleared patch after one year. Relatively little change is seen in the rocks surrounding the square cleared area. White card is 15 cm in length. (Photograph taken by JRZ on 10/23/80.) b. Rocks have migrated down a gentle 1° slope away from the bedrock (toward the camera) in 10.5 years, covering about one-half of the original cleared area. The downslope direction is directly into the prevailing wind direction; the observed changes are not a result of aeolian activity. Notebook is 20 cm in length. (Photograph taken by JRZ on 5/7/90.)

the redistribution of rock fragments at the surface; nearly without exception the horizontal movement at Amboy documented over 13 years was down the local topographic slope. Over a 10-year interval rock fragments at one site moved down a 1° slope to partially fill a cleared area, in a direction opposite to the orientation of the wind represented by the streak (Fig. 6). In some locations, scars from rain impact were clearly preserved in the soil surrounding the rock fragments. Whereas simple mass movement cannot be eliminated, we conclude that sheet wash is more likely to play a significant, if not the dominant role in redistributing rock fragments along the shallow slopes present within isolated lows on the Amboy flow.

Sheet wash generated by the infrequent but locally intense thunderstorms common to the southwestern United States likely plays a significant role in forcing rock fragments into a minimum-spacing configuration (Wells and Dohrenwend, 1985), as is typical of the monolayer rock covers present within the Amboy dark streak. Sheet wash has the additional advantage of being capable of moving rocks irrespective of the limiting four-to-five-diameter spacing for non-erodible elements within a soil undergoing aeolian erosion (Chepil, 1950; Sharon, 1962). Sheet wash is potentially more effective within the streak than outside of the streak because of the enhanced silt/clay-sized materials collected between the pavement stones, typically forming a relatively impervious carapace that enhances overland flow, whereas the sand outside of the streak promotes infiltration.

3.2. Sleeping Beauty

Westerly winds that carry sand onto and around the Pisgah lava flow also have produced a group of dark streaks behind several low hills near the southwestern base of the Sleeping Beauty Mountain (Fig. 3b and Fig. 7). The largest of these dark streaks is over 2 km in length and about 300 m in width, extending east from a rock-covered ridge on an isolated knob ('Tortoise Hill'); here we refer to the 2-km-long dark streak as the Sleeping Beauty streak. The Sleeping Beauty streak occurs on sandy alluvium rather than bedrock, in contrast to the Amboy streak discussed above. The Sleeping Beauty streak also is roughly perpendicular to the 2°–3° topographic slope that is oriented toward the south. Field

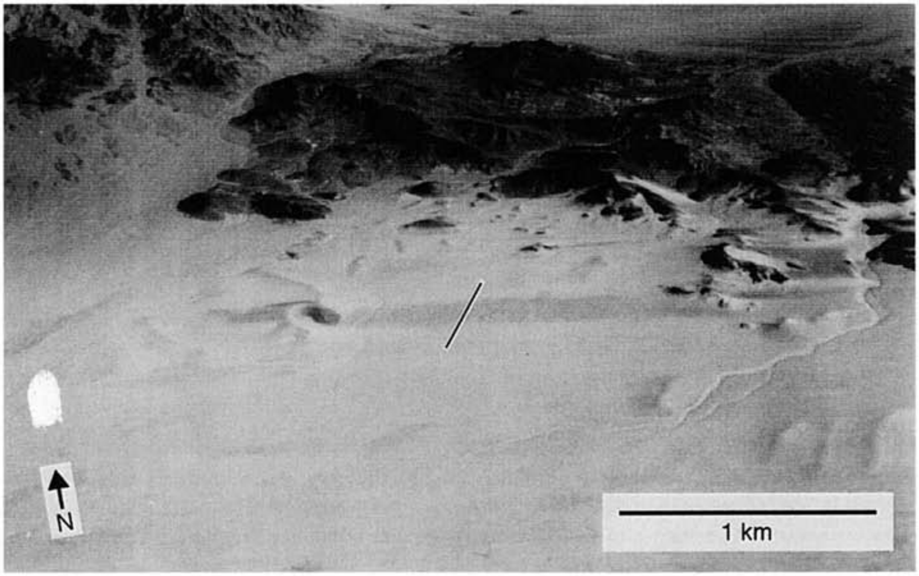


Fig. 7. Oblique aerial photograph of the Sleeping Beauty streak, looking north. The dark streak extends east-southeast from Tortoise Hill. A portion of the Cady Mountains are in the background; Sleeping Beauty Mountain is out of the frame to the right. Line shows the location of the traverse results in Fig. 9. (Photograph taken by Hugh Kieffer, Fall, 1978.)

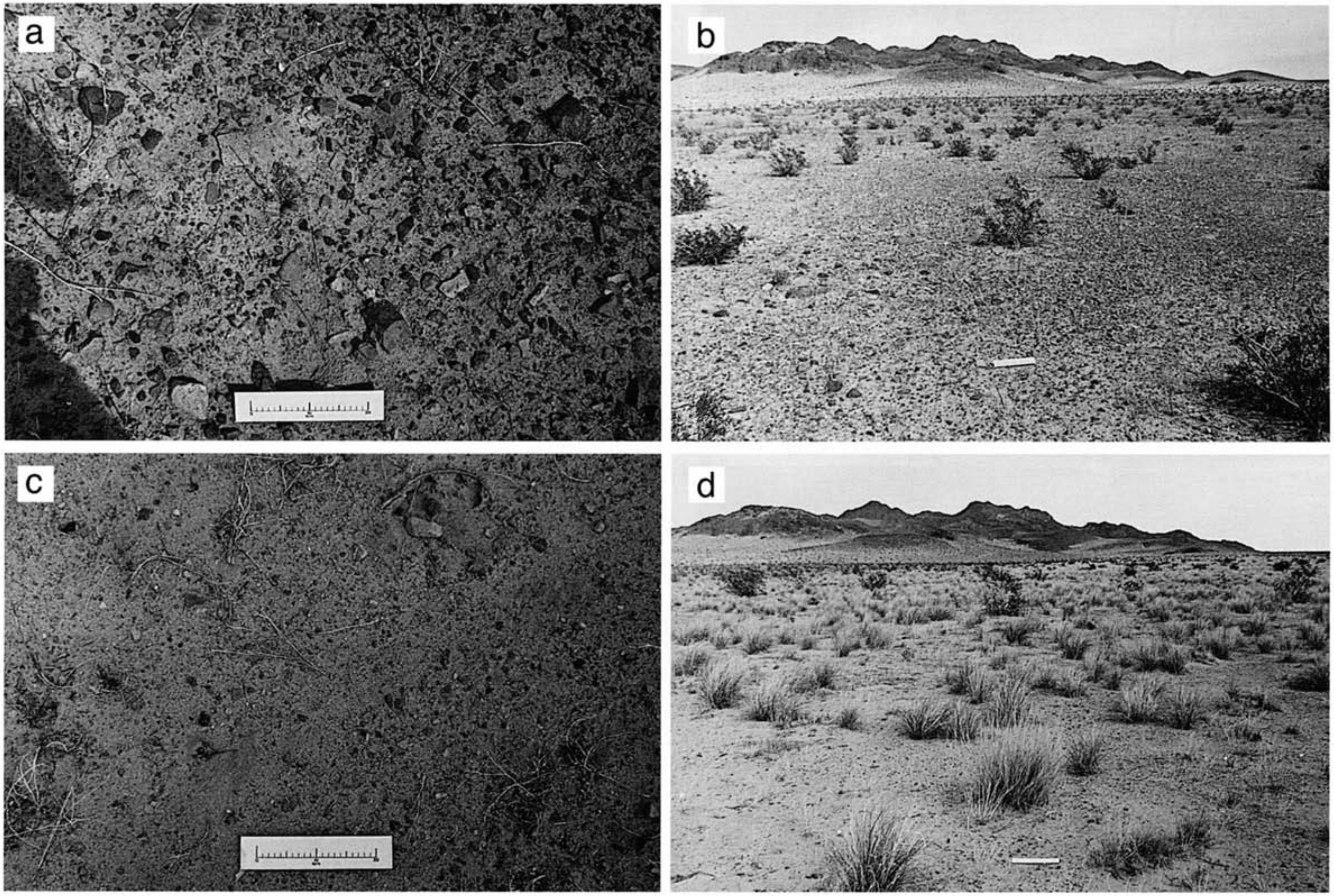


Fig. 8. Vertical and downwind photographs taken during the traverse at the Sleeping Beauty streak. In all views, white scale card is 25 cm in length. a. Vertical view of armored surface within the streak, with 45% rock abundance. (Photograph taken by JRZ on 4/8/79 at traverse location 30S.) b. Oblique view within streak, looking east toward Sleeping Beauty Mountian (named, no doubt, by a lonely prospector with an active imagination), with creosote bushes scattered across the surface. (Photograph taken by JRZ on 4/8/79 at traverse location 30S.) c. Vertical view of sandy surface outside of the streak, with 3% rock abundance. (Photograph taken by JRZ on 4/8/79 at traverse location 150S.) d. Oblique view outside the streak, with Big Galetta grass present among the creosote bushes. (Photograph taken by JRZ on 4/8/79 at traverse location 150S.)

examination of this streak revealed that vegetation is likely more important than rock population in contributing to the albedo contrast between the streak and its surroundings.

3.2.1. *Surface characteristics*

The streak surface contains a wide assortment of rock fragments that account for up to 45% of the surface area (Fig. 8a). The rocks vary greatly in size, shape, and composition, in marked contrast to the uniform basaltic fragments present in the Amboy streak. The dominant rock type in the Sleeping Beauty streak is andesite, occurring both as competent crystalline rocks and crystal-rich ignimbrite fragments. These chemically evolved rocks impart a distinct lavender hue to the dark streak, as viewed either from the upwind hill or on the streak surface. Less abundant rock types present in the streak include isolated basalts, both as dense rock and vesiculated scoria, and gneiss. The rock distribution on the streak surface is consistent with emplacement as alluvium derived from the surrounding low hills and mountains.

Plants are non-randomly distributed between the streak and its surroundings. The streak itself is dominated by ~ 1-meter-high Creosote bushes (*Larrea tridentata*) randomly spaced 5 to 10 m apart throughout the area (Fig. 8b). Outside of the streak the surface becomes very sandy, with only a minor component of rock fragments (Fig. 8c), and abundant meter-sized clumps of the perennial Big Galleta grass (*Hilaria rigida*) are mixed with the Creosote bushes (Fig. 8d). The tan hue of the dried Big Galleta grass dominates the albedo of the surface outside of the streak, but Big Galleta grass is completely lacking inside of the streak.

A traverse perpendicular to the streak, and, hence, roughly parallel to the local topographic slope, was carried out about 500 m downwind of Tortoise Hill (Fig. 7). The surface conditions at 30 m intervals were documented with both vertical and downwind photographs (e.g., Fig. 8). The surface rock abundance determined from the vertical photographs shows an even more dramatic contrast between the Sleeping Beauty streak and its surroundings (Fig. 9) than was observed at the Amboy streak (Fig. 5). Within the streak, the rock abundance generally ranges between 40 and 50% of the surface, although local minimums occur where ephemeral streams transport fines across the streak. The sand between the rocks is not conducive to overland flow, similar to the situation outside of the Amboy streak. The streak margin corresponds to a sharp drop in rock abundance to 15%, followed by a gradual decrease to 2–5% typical of the sandy off-streak surface. The presence of Big Galleta grass appears to be a very sensitive indicator of the thick sand off the streak, with the transition from grass to no-grass areas occurring within a distance of only 3 to 5 m.

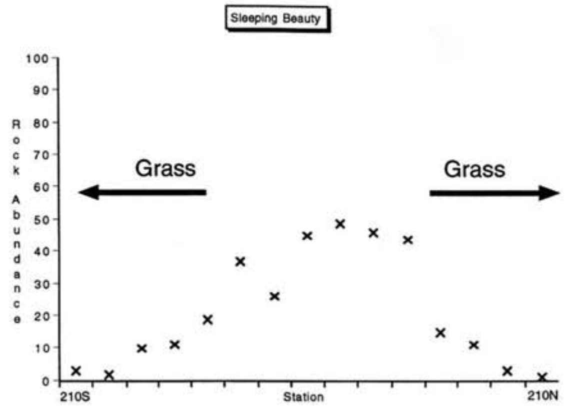
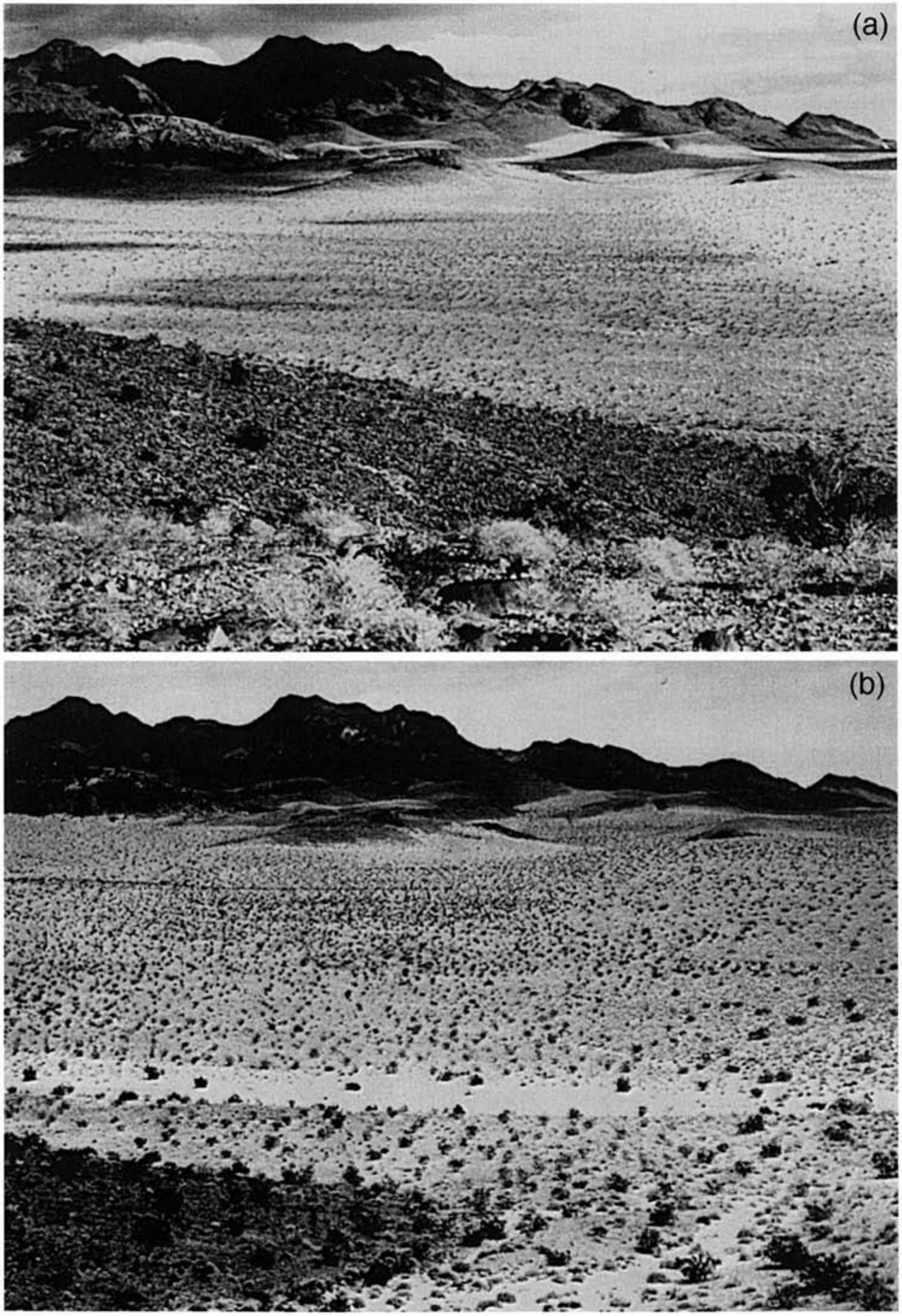


Fig. 9. Rock abundance on a traverse across the Sleeping Beauty streak, located about 1 km downwind from Tortoise Hill (see line in Fig. 7). Within the streak, rocks form an armored surface with 40-50% rock abundance (see Fig. 8a), whereas outside of the streak the rock abundance falls to < 5% (see Fig. 8c). Big Galetta grass is present outside of the streak (see Fig. 8d) where sand thickness attains 10 cm, but the grass is absent within the streak where sand thickness is generally 1-2 cm (see Fig. 8b).

Samples of the rocks and surface soil were col-

Fig. 10. Oblique view looking east-southeast from Tortoise Hill along the Sleeping Beauty streak. Both views were taken at about 2 pm local time; dark areas on the plain are surface albedo contrasts and not cloud shadows. a. The streak is clearly highlighted by the bright Big Galetta grass that is present only outside of the streak. (Photograph taken by JRZ on 1/11/82.) b. The streak appears to have completely disappeared because of the presence of annual grasses, both inside and outside of the streak, during late spring. (Photograph taken by SHW on 5/2/87.)

lected both on and off the streak and normal albedo measured with the U.C.L.A. goniometer. Rock albedos from both locations ranged from 0.069 to 0.141 and averaged 0.106, indicative of the lighter-hued andesite rocks from the Cady Mountains and Sleeping Beauty Mountain, as compared to the Amboy



basalts. Multiple spot reflectances of the fine materials averaged 0.165 inside the streak and 0.161 outside of the streak, the slight increase within the streak possibly caused by an increased amount of silt trapped around the surface rocks. The surface fines at both locations are dominated by aeolian sand.

3.2.2. Subsurface characteristics

Pits were dug inside and outside of the streak (at traverse stations 0 and 210S in Fig. 9) to examine the subsurface characteristics. The pit within the streak revealed a vesicular, indurated, silty soil underlying 1–2 cm of sand. The vesicular nature of the soil ceased at about 10 cm depth, below which the silty soil was strongly indurated. Very few rocks were encountered within the indurated soil, with the notable exception of some rocks 10–20 cm across. The indurated soil became impenetrable below about 50 cm. In marked contrast, the pit outside of the streak revealed only aeolian sand to a depth exceeding 1 m, with neither rocks nor silty soil evident at any intermediate depth. No macroscopic layering was evident

Fig. 11. Annual grass (bottom) and the fibrous-coated Desert Fiddleneck (center) outside the southern margin of the Sleeping Beauty streak. U.S. 1-cent coin is 1.9 cm across. (Photograph taken by JRZ on 5/2/87.)

in the sand, and the sand near the bottom of the pit was slightly moist. We also examined the roots of a Big Galleta grass patch outside of the streak; the roots were very dense to a depth greater than 50 cm, with individual root stems extending well below that depth.

3.2.3. Vegetation

The plant population at the Sleeping Beauty streak locality plays a significant role in the contrast and visibility of the dark streak. This condition was emphasized to us when a colleague visited the hill at the head of the streak in April 1987, and reported that the streak was no longer visible. Because the streak has been located on aerial photographs dating back to the 1950s, we were quite perplexed by this report. On May 2, 1987, we visited the site to investigate the disappearance of the streak, which indeed could no longer be seen from Tortoise Hill (Fig. 10). Examination of the streak surface, however, revealed that the characteristic surface rock and soil conditions were still present. The important change was the presence of an annual grass on the streak surface that caused it to have an albedo similar to that of the Big Galleta grasses outside of the streak.

The remarkable distribution of the annual grass around the streak prompted us to investigate the local plants more closely. Identification of the principal plants was provided by Prof. Frank Vasek of the Department of Botany at U.C. Riverside. Creosote (*Larrea tridentata*) is distributed uniformly both on and off the streak. Closely allied with the Creosote is the Desert Sand Bur (*Ambrosia dumosa*); this plant also was distributed uniformly both on and off the streak. As discussed above, Big Galleta grass (*Hilaria rigida*) occurs exclusively outside of the streak, becoming abundant wherever the sand thickness exceeds about 10 cm. The annual grass present in May of 1987 (*Schismus barbatus*) has short stalks of from 2 to 5 cm height (Fig. 11); it is present in the Mojave Desert during several weeks of spring. The grass was present wherever more than 1.5 cm of sand was found, but it was most abundant where sand was 3 to 10 cm thick. Finally, the Desert Fiddleneck (*Amsinckia tesselata*), also present outside of the streak (Fig. 11), is covered with very fine fibers that strongly forward-scattered sunlight, producing 'glory' brightening when viewed directly toward the sun.

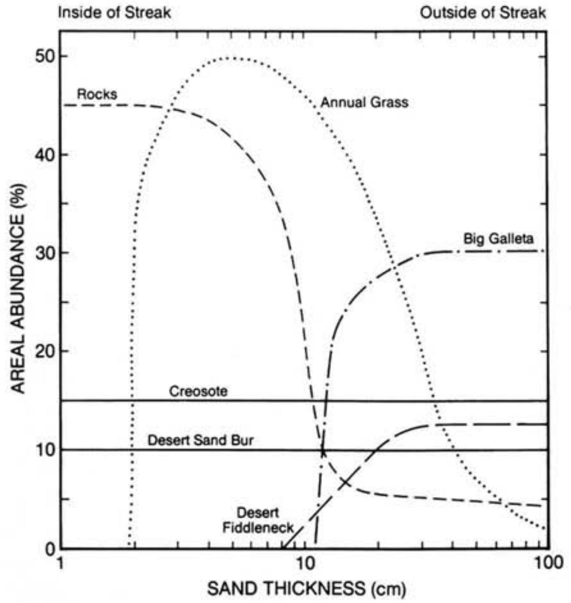


Fig. 12. Summary of observations of plants at the Sleeping Beauty streak seen during May, 1987, shown as a function of sand thickness. Rock abundance falls off where Big Galetta grass becomes common, when sand exceeds 10 cm depth. Creosote and Desert Sand Burr are randomly distributed, irrespective of the streak location. In late spring, annual grasses (bottom of Fig. 11) are abundant wherever sand exceeds 1 cm depth, becoming less common where sand exceeds 30 cm depth. Desert Fiddleneck mimicks the occurance of Big Galleta grass outside of the streak; the fibrous coating on this plant (Fig. 11) is strongly forward-scattering, creating a "glory" brightening around the plant when viewed directly up-sun.

The relative abundance of these five plants as a function of sand thickness are shown in Fig. 12, which is summarized from May 1987 observations across the streak boundary. The variation in rock abundance across the boundary appears to be secondary in importance to the abrupt appearance of the highly reflective Big Galleta grass when sand thickness attains at least 10 cm. The ubiquitous presence of sand between the rocks, however, allows the annual grass to grow well both inside and outside the streak. The similar reflectance of both the annual and Big Galleta grasses (when dried out, which occurs very rapidly in the desert) causes the streak to seem to disappear for several weeks during the spring. The Desert Fiddleneck mimics the Big Galleta grass in distribution and it likely contributes very little to the general reflectance brightness outside of the streak. The curious 'glory' brightening displayed by this plant when viewed directly up-sun, however, might add significantly to the overall streak contrast.

The desert plants observed at the Sleeping Beauty streak appear to be very sensitive to the soil drainage represented by the sand cover. The Big Galleta grass clearly requires a minimum of 10 cm of sand to trap enough of the infrequent moisture present in the Mojave Desert in order to flourish. The much shorter annual grasses, with associated shorter root systems, can exploit the thinner sand cover on the streak surface to flourish for a few weeks out of each year. The friable stalks of the annual grass fell apart under very slight pressure, and could easily be entirely removed by saltating sand after their short growth period. To our knowledge, this is the first documented case of an aeolian feature whose albedo characteristics can be completely obscured by an ephemeral plant that then disappears without a trace.

4. Discussion

The two dark wind streaks in the eastern Mojave Desert have shown that two distinct processes are at work in the formation and modification of the albedo contrast that identifies the streak; one is strictly geologic in nature, whereas the other is primarily a botanical consequence of the characteristics of the aeolian surface. The geomorphic processes that work to concentrate rock fragments in an aeolian environment can clearly enhance the albedo contrast of surfaces affected by the wind; these processes may (or may not) be active on other planetary surfaces. These conclusions are consistent with many previous studies of terrestrial wind streaks as possible analogs to streaks observed on other planets (e.g. Greeley and Iversen, 1978, Greeley and Iversen, 1985; El-Baz et al., 1979). In contrast, the botanical effects observed at the Sleeping Beauty streak will be restricted to Earth. Botanical effects may be more significant in semi-arid aeolian environments than had been previously thought.

The first stage in the production of a dark wind streak appears to involve the emplacement of fine aeolian materials through the interaction of the wind with topographic obstacles. Fine materials, both sand and silt, typically have higher albedos than cm-scale blocks of the same composition. Fine materials carried by the wind preferentially are kept from deposition behind a topographic obstacle through vortical winds set up from the edges of the obstacle (Greeley and Iversen, 1978). As long as the underlying material has a lower albedo than the aeolian fines, a dark streak will develop downwind from the obstacle. At Amboy, saltating sand brightens the dark basaltic lava flow surface without completely burying the meter-scale relief of the flow. We have found that the formation of desert pavement within the wind shadow downwind from the obstacle, however, also increases the albedo contrast.

A key limit to the development of a pavement solely through the action of the wind is the critical spacing of non-erodible elements that protects a particulate substrate from further aeolian erosion (Chepil, 1950). The result is an 'armored surface' in which the spacing between the rocks is much greater than in a well-developed desert pavement (Greeley and Iversen, 1985). The surface of the Amboy lava flow outside of the dark streak appears to meet the criteria of an armored surface, whereas the rock fragments within the streak are more representative of a well-developed pavement. The Amboy pavements lack the subsurface soil and rock characteristics that are found in locations where vertical motion of rock fragments has been documented (Péwé, 1978), and instead are consistent with the accretionary mantle process identified on other Mojave lava flows (Wells et al., 1985; McFadden et al., 1987). The Sleeping Beauty streak also includes an armored surface rather than the concentrated monolayer pavements present in the Amboy streak, consistent with a lack of local sources for rock fragments within the Sleeping Beauty streak.

Whereas the accretion of a mantle of aeolian silt takes place beneath the surface rock fragments within the Amboy streak, downslope movement of surface debris through slope wash also is contributing to the close spacing of rocks, as was observed on the nearby Pisgah lava flow (Williams and Zimbelman, 1994). The numerous bedrock outcrops represented by the several-meter-scale pressure ridges present across the entire Amboy flow provide ample local sources for small rock fragments produced by weathering of the outcrops. At Amboy we documented rock movement down slopes as small as 1°, in some instances in directions opposite to the dominant wind direction. These subtle movements take place on at least a decadal time scale, most likely through infrequent but locally intense rainstorms. Thus, water contributes to the enhancement of the albedo contrast that was initially established by the wind.

The drainage properties of the aeolian materials involved in the above sequence appear to be the primary constraint on how botanical factors can interact with the wind streak. When sand is abundant, the non-streak surface is inundated by a layer of active sand which can efficiently preserve moisture at a relatively shallow depth. If sand is preferentially kept out of the streak area, the dominant aeolian material added to the surface will be silt- to clay-sized dust raised by the action of the moving sand and settled out of suspension. Once emplaced on a rocky surface, the wind can no longer remobilize the fines unless the protecting rocks are somehow removed. The silty material has very poor drainage properties, particularly in terms of preserving moisture in a fashion accessible to plant roots. Plants that have sufficient root systems to reach below the growing silt mantle (i.e. Creosote) are unaffected by the aeolian redistribution of surface materials. Grasses, however, seem to be particularly sensitive to sand thickness concerning where they can best grow. The shallow-rooted annual grasses provide a seasonal mechanism for altering surface albedos that can mask the physical conditions produced by the wind. The fibrous coating of plants, like the Desert Fiddleneck, might provide a means to detect the streak even when seasonal plants are present, under appropriate viewing and illumination conditions (e.g., oblique, up-sun photographs taken at either sunrise or sunset).

The varying time scales of the geologic and botanical factors indicate that the aeolian terrains may have an exceedingly complex recent history. This history will be difficult to interpret through remote sensing studies alone, which is at present the only source of data for extra-terrestrial wind streaks. One can argue that botanical concerns are of no consequence to wind streaks produced on Mars or Venus, nor is it likely that running water has been involved in altering the surface conditions in these streaks. Yet the goal of better understanding the physical processes that have shaped an extraterrestrial terrain is still advanced when we can better constrain the many processes active on wind streaks on Earth. The potential influence of plants and infrequent rains on the albedo contrast of wind streaks certainly must be considered when extrapolating analog field studies to other planets.

5. Conclusions

Two aeolian wind streaks in the eastern Mojave Desert of California, both with lower albedos than the surroundings, were examined to gain insight into the origin of the observed surface brightness contrast. The two localities consist of a 4-km-long dark streak downwind of the Amboy cinder cone, located on a Holocene basalt flow coated with aeolian sand, and a 2-km-long dark streak downwind of a low hill west of the Sleeping Beauty Mountain, present on a sandy alluvial surface downslope from the mountains. In both cases, the dark streaks are distinguished by enhanced rock abundances on the streak surface relative to the surroundings. At the Amboy streak, slope wash likely contributed to the rock concentration on the streak surface, shielded by the cinder cone from burial by aeolian sand. At the Sleeping Beauty streak, the relative albedo contrast is strongly enhanced year-round by the presence of Big Galleta grass outside of the streak. The albedo contrast of the Sleeping Beauty streak can be effectively eliminated by the seasonal presence of annual grass within the streak. Some plants may have reflectances that are strongly dependent upon viewing geometry, raising the possibility that certain aeolian features may appear variable because of illumination and reflectance conditions. Alluvial processes have been important at both localities for redistributing surface materials, even given the infrequent-rain conditions present in the Mojave Desert.

Acknowledgements

The review comments of two anonymous reviewers were very helpful in clarifying the initial manuscript. Dr. Hugh Kieffer, Branch of Astrogeology, U.S. Geological Survey, Flagstaff, first noted the Sleeping Beauty streak during an airplane flight over the eastern Mojave Desert in 1978, and we appreciate his help in our preliminary studies of the streak. The authors are very grateful to Dr. Kieffer (then at the University of California at Los Angeles) and Dr. Ronald Greeley, along with the Planetary Geology Group at Arizona State University, for much assistance during many of the field excursions. Dr. Larry Pleskot graciously carried out the goniometer reflectance measurements of rock and soil samples at the University of California at Los Angeles. Dr. Frank Vasek, Department of Botany, University of California at Riverside, was very helpful in identifying the plants encountered in the Sleeping Beauty streak area.

References

Arvidson, R.E., 1974. Wind blown streaks, splotches, and associated craters on Mars: statistical analysis of Mariner 9 photographs. Icarus, 21: 12–27.

Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Chapman and Hall, London, 265 pp.

Breed, C.S. and Grow, T., 1979. Morphology and distribution of dunes in sand seas observed by remote sensing. In: E.D. McKee (Editor), A Study of Global Sand Seas. U.S. Geol. Surv. Prof. Pap., 1052: 253–308.

Chepil, W.S., 1950. Properties of soil which influence wind erosion: the governing principle of surface roughness. Soil Sci., 69: 149–162.

Cooke, R.U., Goudie, A.S. and Warren, A., 1993. Desert Geomorphology. UCL Press, London, 526 pp.

El-Baz, F., Breed, C.S., Grolier, M.J. and McCauley, J.F., 1979. Eolian features in the western desert of Egypt and some application to Mars. J. Geophys. Res., 84: 8205–8221.

Greeley, R. and Arvidson, R.E., 1990. Aeolian processes on Venus. Earth, Moon, and Planets, 50/51: 127–157.

Greeley, R. and Iversen, J.D., 1978. Field guide to Amboy lava flow, San Bernardino County, California. In: R. Greeley, M.B. Womer, R.P. Papson and P.D. Spudis (Editors), Aeolian Features of Southern California: A Comparative Planetary Geology Guidebook. U.S. Govt. Printing Office, Washington, 033-000-00706-0, pp. 23-52.

Greeley, R. and Iversen, J.D., 1985. Wind as a Geological Process on Earth, Mars, Venus, and Titan. Cambridge University Press, Cambridge, 333 pp.

Greeley, R. and Iversen, J.D., 1987. Measurements of wind friction speeds over lava surfaces and assessment of sediment transport. Geophys. Res. Lett., 14: 925–928.

Greeley, R., Christensen, P.R. and Carrasco, R., 1989. Shuttle radar images of wind streaks in the Altiplano, Bolivia. Geology, 17: 665–668.

Greeley, R., Arvidson, R.E., Elachi, C., Geringer, M.A., Plaut, J.J., Saunders, R.S., Schubert, G., Stofan, E.R., Thouvenot, E.J.P., Wall, S.D. and Weitz, C.M., 1992. Aeolian features on Venus: preliminary Magellan results. J. Geophys. Res., 97: 13319–13345.

Laity, J., 1992. Ventifact evidence for Holocene wind patterns in the east-central Mojave Desert. Z. Geomorphol., Suppl., 84: 73–88.

McFadden, L.D., Wells, S.G. and Jercinovich, M.J., 1987. Influences of eolian and pedogenic processes on the origin and evolution of desert pavements. Geology, 15: 504–508.

Péwé, T.L., 1978. Terraces of the lower Salt River valley in relation to the Cenozoic history of the Phoenix basin, Arizona. In: D.M. Burt and T.L. Péwé (Editors), Guidebook to the Geology of Central Arizona. Geol. Soc. Am. 74th Cordilleran Sect. Meet., Spec. Publ., 2: 1–45.

Pollack, J.B. and Sagan C., 1969. An analysis of martian photometry and polarimetry. Space Sci. Rev., 9: 243–299.

Rendell, H.M., 1996. Luminescence dating of sand ramps in the eastern Mojave Desert, California. Geomorphology, 17: 187–197.

Sagan, C. and Pollack, J.B., 1969. Windblown dust on Mars. Nature, 223: 791–794.

Sagan, C., Veverka, J., Fox, P., Dubisch, R., French, R., Gierasch, P., Quam, L., Lederberg, J., Levinthal, E., Tucker, R., Eross, B. and Pollack, J.B., 1973. Variable features on Mars, II. Mariner 9 global results. J. Geophys. Res., 78: 4163–4196.

Saunders, R.S., Dobrovolskis, A.R., Greeley, R. and Wall, S.D., 1990. Large-scale patterns of eolian sediment transport on Venus: predictions for Magellan. Geophys. Res. Lett., 17(9): 1365–1368.

Sharon, D., 1962. On the nature of hamadas in Israel. Z. Geomorphol., 6(2): 129–147.

Sharp, R.P., 1976. Field Guide to the Geology of Southern California. Kendall/Hunt Pub. Co., Dubuque, Iowa, 208 pp.

Springer, M.E., 1958. Desert pavement and vesicular layers of some desert soils in the desert of the Lahontan basin, Nevada. Proc. Soil Soc. Am., 22: 63–66.

Tchakerian, V.T., 1991. Late Quaternary aeolian geomorphology of the Dale Lake sand sheet, southern Mojave Desert, California. Phys. Geogr., 12: 347–369.

Thomas, P. and Veverka, J., 1979. Seasonal and secular variation of wind streaks on Mars: an analysis of Mariner 9 and Viking data. J. Geophys. Res., 84: 8131–8146.

Thomas, P., Veverka, J., Lee, S. and Bloom, A., 1981. Classification of wind streaks on Mars. Icarus, 45: 124–153.

Veverka, J., Gierasch, P. and Thomas, P., 1981. Wind streaks on Mars: meteorological control of occurrence and mode of formation. Icarus, 45: 154–166.

Ward, A.W., Doyle, K.B., Helm, P.J., Weisman, M.K. and Witbeck, N.E., 1985. Global map of eolian features on Mars. J. Geophys. Res., 90: 2038–2056.

Wells, G.L. and Zimbelman, J.R., 1989. Extraterrestrial arid surface processes. In: D.S.G. Thomas (Editor), Arid-Zone Geomorphology. Halsted, New York, pp. 335–358.

Wells, S.G. and Dohrenwend, J.C., 1985. Relict sheetflood bedforms on late Quaternary alluvial fan surfaces in the southwestern United States. Geology, 13: 512–516.

Wells, S.G., Dohrenwend, L.D., McFadden, L.D., Turrin, B.D. and Mahrer, K.D., 1985. Late Cenozoic landscape evolution on lava flows of the Cima volcanic field, Mojave Desert, California. Bull. Geol. Soc. Am., 96: 1518–1529.

Williams, S.H. and Greeley, R., 1983. Desert pavement study at Amboy, California (abstract). NASA TM-86246, pp. 169–170.

Williams, S.H. and Lee, J.A., 1995. Aeolian saltation transport rate: an example of the effect of sediment supply. J. Arid Environ., 30: 153–160.

Williams, S.H. and Zimbelman, J.R., 1994. Desert pavement evolution: an example of the role of sheetflood. J. Geol., 102: 243–248.

Zimbelman, J.R., Williams, S.H. and Kieffer, H.H., 1987. Field observations of albedo contrasts associated with wind streaks: fluvial and botanical effects on aeolian features (abstract). Eos, Bull. Am. Geophys. Union, 68(44): 1341–1342.

Zimbelman, J.R., Williams, S.H. and Tchakerian, V.T., 1996. Sand transport paths in the Mojave desert, southwestern United States. In: V.T. Tchakerian (Editor), Advances in Aeolian Geomorphology. Chapman and Hall, London, in press.