

## Wind and Climate on Mars

Several apparently conflicting inferences in Matthew P. Golombek's Perspective on martian climate (1) can be reconciled by recognizing that surface sediment features associated with rocks at the Pathfinder landing site indicate the direction of the strongest winds only in the present climate regime and that this direction varies over martian orbital cycles. These winds are now from the northeast at both the Pathfinder site and the nearby Viking Lander 1 site (2). This is the direction indicated by surface sediment features at both sites, and is also the direction of light markings observed from orbit (3). Observed dust deposition on both landers is consistent with ongoing active wind modification of the surface, rather than with stability of sediment features over geological time. The hypothesis that the strongest winds of the current climate regime are modifying the surface at both sites is also consistent with the observed abundance of sand-sized particles at the Pathfinder site and with the discrepancy between wind direction inferred from surface sediment patterns and from ventifacts (1). Most ventifact features may have formed during a different, earlier wind regime.

If this interpretation is correct, it has important implications for the evolution of the martian surface. Because the strongest winds now correspond with the strengthening of the Hadley circulation when perihelion and solstice are near coincidence (2), wind direction probably reverses over the precessional period (51,000 years). Golombek's estimate of erosion rate, based on the assumption of constancy of the wind regime over several billion years, should be scaled upward by a factor of at least  $10^5$ . Moreover, because the threshold for moving particles by saltation varies with the square root of the surface pressure (3), and because saltation events (although widely evident in observed dust storms and dust devils) currently occur only on the extreme high wind tail of the wind speed distribution, even a modest increase in surface pressure would correspond to a very large increase in the frequency and intensity of saltation events and in the efficacy of wind erosion. Because of atmospheric loss by impact erosion, pressure was probably much higher during heavy bombardment prior to 3.9-Gyr age, so wind erosion and sedimentation would also have been much higher. This could account for the marked change in erosional style observed at that age. It would also be consistent with evidence from Mars Global Surveyor that

there has been substantial modification of craters by dust infilling in ancient cratered terrain (4). Overall, wind modification of the surface has probably been much more important, and modification by flowing water may have been correspondingly less important, than Golombek infers.

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*Response:* Leovy underscores some of the uncertainties in deriving quantitative erosion rates from landed surface views of a planet. Nevertheless, the issues he raises do not change any of the conclusions I derived in the Perspective (1). In fact, the simplicity of the argument is its strength. The surface appears to have changed minimally since deposition by catastrophic floods some 1.8 to 3.5 Ga. Even if the erosion of the landing site occurred in the past 51,000 years, as postulated by Leovy, the lack of change at the site argues that there were no net changes to the site for the previous 1.749 to 3.749 Ga, which results in the same long-term erosion rates derived in the Perspective. Regardless of what short-term rates may have operated, the geologic evidence does not allow (i) erosion rates as high as 1 to 10  $\mu\text{m year}^{-1}$  (as suggested by Leovy) to have operated at the site for an extended period of time, or (ii) crater rims on relatively young surfaces, which would have been planed off and erased (1 to 10 m of material would be removed) in a comparatively short 1 Ma. The freshness of crater rims observed from the Pathfinder lander and the general freshness of crater populations on similar aged surfaces on Mars suggests that such high erosion has not occurred. The agreement between the present wind direction and the wind tails at the site suggests that they formed in a wind regime similar to today's. The wind tails actually may represent only about half (3 cm) of the total deflation observed at the site (5 to 7 cm).

Nevertheless, the winds that formed them could have also occurred incrementally during multiple 100,000-year oscillations, when the strongest wind direction was similar to today's, and not just in the past 51,000 years, as suggested by Leovy.

There is no disagreement that fairly high redistribution of aeolian material has occurred in the past on Mars and may be occurring today. This activity could deposit and remove wind-borne material (sand size and smaller) fairly rapidly, but it does not appear to have eroded new material. This conclusion appears consistent with new high-resolution images of the surface returned by the Mars Orbiter Camera on the Mars Global Surveyor (2) in which deposition and exhumation of aeolian material may be common (that is, redistribution of wind-borne material), but erosion of new material may not be common. This process would lead to the deposition of wind-blown material into craters and other lows as observed (3). At the Pathfinder site, I detect no direct evidence for multiple burial and exhumation events (such as multiple soil horizons on rocks). The direct evidence outlined in my Perspective is that remarkably little has occurred at the site since it was deposited by catastrophic floods, and thus the long-term rate of change is remarkably slow (of order  $0.01 \text{ nm year}^{-1}$ ).

Finally, erosion in the heavily cratered terrain points directly to liquid water and is incompatible with aeolian erosion. Valley networks (some with central fluvial channels), ancient lake beds in craters and other depressions in the this terrain, and rimless craters with filled-in flat floors all point directly to erosion by water (4). Erosion rates derived from these terrains are comparable with slow continental denudation rates on the Earth produced by water. Although wind-related erosion on Mars in the past could have been more important than it is today, it is still basically incompatible with the observed suite of erosional forms and the estimated rate of erosion for these ancient terrains.

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