# Growth and form of the mound in Gale Crater, Mars: Slope wind enhanced erosion and transport

Edwin S. Kite[1], Kevin W. Lewis[2], Michael P. Lamb[1], Claire E. Newman[3], and Mark I. Richardson[3]
[1]Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA
[2]Department of Geosciences, Princeton University, Princeton, New Jersey 08544, USA
[3]Ashima Research, Pasadena, California 91125, USA

## ABSTRACT

**Ancient sediments provide archives of climate and habitability on Mars. Gale Crater, the landing site for the Mars Science Laboratory (MSL), hosts a 5-km-high sedimentary mound (Mount Sharp/Aeolis Mons). Hypotheses for mound formation include evaporitic, lacustrine, fluviodeltaic, and aeolian processes, but the origin and original extent of Gale's mound is unknown. Here we show new measurements of sedimentary strata within the mound that indicate ~3° outward dips oriented radially away from the mound center, inconsistent with the first three hypotheses. Moreover, although mounds are widely considered to be erosional remnants of a once crater-filling unit, we find that the Gale mound's current form is close to its maximal extent. Instead we propose that the mound's structure, stratigraphy, and current shape can be explained by growth in place near the center of the crater mediated by wind-topography feedbacks. Our model shows how sediment can initially accrete near the crater center far from crater-wall katabatic winds, until the increasing relief of the resulting mound generates mound-flank slope winds strong enough to erode the mound. The slope wind enhanced erosion and transport (SWEET) hypothesis indicates mound formation dominantly by aeolian deposition with limited organic carbon preservation potential, and a relatively limited role for lacustrine and fluvial activity. Morphodynamic feedbacks between wind and topography are widely applicable to a range of sedimentary and ice mounds across the Martian surface, and possibly other planets.**

## INTRODUCTION

Most of Mars' known sedimentary rocks are in the form of intra-crater or canyon mounded deposits like the 5-km-high mound (Mount Sharp / Aeolis Mons) in Gale Crater (Hynek et al., 2003), but identifying the physical mechanism(s) that explain mound growth and form has proved challenging, in part because these deposits have no clear analog on Earth. The current prevailing view on the formation of intra-crater mounds is that sedimentary layers (i.e., beds) completely filled each crater at least to the summit of the present-day mound (Malin and Edgett, 2000). Subsequent aeolian erosion, decoupled from the deposition of the layers, is invoked to explain the present-day topography (e.g., Andrews-Hanna et al., 2010). Evaporitic, lacustrine, fluviodeltaic, and aeolian processes have each been invoked to explain formation of the layers (e.g., Anderson and Bell, 2010; Andrews-Hanna et al., 2010; Irwin et al., 2005; Niles and Michalski, 2009; Pelkey et al., 2004; Thomson et al., 2011). If layers formed subhorizontally in an evaporitic playa-like setting, then >>$10^6$ km$^3$ must have been removed to produce the modern moats and mounds (Zabrusky et al., 2012). These scenarios predict near-horizontal or slightly radially inward–dipping layers controlled by surface- or groundwater levels.

## GALE MOUND LAYER ORIENTATIONS

To test these scenarios at the Gale Crater mound, we obtained bed-orientation measurements from six 1-m-scale stereo elevation models using planar fits to extracted bedding profiles via the technique of Lewis and Aharonson (2006). Each elevation model is constructed from a High-Resolution Imaging Science Experiment (HiRISE) stereopair using the method of Kirk et al. (2008). Individual measurements were rejected where the angular regression error was >2°, and the 81 remaining measurements were averaged for each site to reduce uncertainty further, with the results shown in Figure 1. We find that layers have shallow but significant dips away from the mound center, implying 3–4 km of pre-erosional stratigraphic relief if these dips are extrapolated to the rim. Measurements of the marker bed of Milliken et al. (2010) show that its elevation varies by >1 km, confirming that beds are not planar. Postdepositional radially outward tilting is unlikely. Differential compaction of porous sediments, flexural response to the mound load, or flexural response to excavation of material from the moat would tilt layers inward, not outward. Layers targeted by the Mars Science Laboratory (MSL) near the base of Gale's mound show no evidence for halotectonics or karstic depressions at kilometer scale, and deformation by mantle rebound would require the Gale mound to accumulate extremely quickly (Fig. 2). Therefore, these measurements permit only a minor role

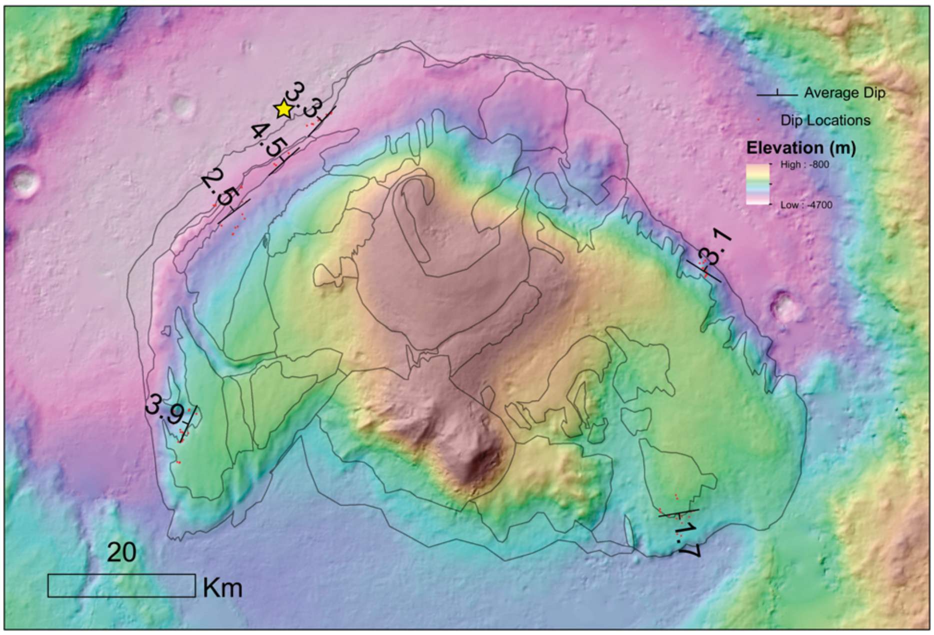


**Figure 1. Bedding orientation measurements from six locations around margin of Gale Crater mound (Mars). Individual measurements from HiRISE terrain models are marked in red, with average at each site indicated by dip symbol. Table DR1 (see footnote 1) provides a full listing of results. At each location, beds consistently dip away from center of mound, consistent with proposed model. Background elevation data is from the High-Resolution Stereo Camera (HRSC; http://europlanet.dlr.de/node/index.php?id=380), with geologic boundaries from Thomson et al. (2011). Star marks Mars Science Laboratory's landing site.**

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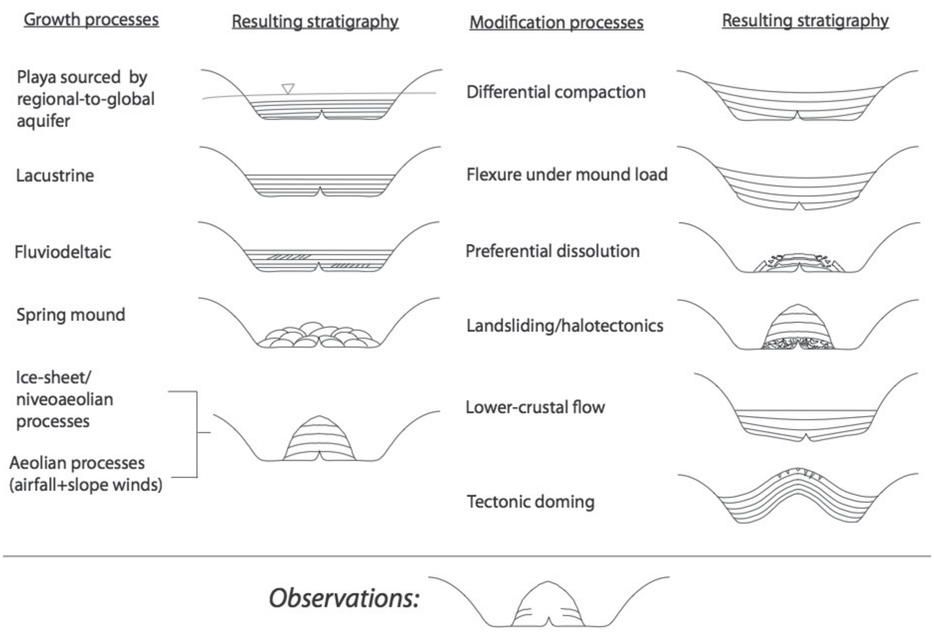



**Figure 2. Comparison of mound growth hypotheses to observations, for an idealized cross section of a mound-bearing crater. Inverted triangle marks past water table.**

for deposition mechanisms that preferentially fill topographic lows (e.g., playa, fluviodeltaic, or lacustrine sedimentation), but are consistent with aeolian processes (Fig. 2). This suggests the mound grew with its modern shape, and that the processes sculpting the modern mound may have molded the growing mound.

## SLOPE-WIND EROSION ON MARS

Mars is a windy place; active saltation occurs at rates that predict aeolian erosion of bedrock at 10–50 μm/yr (Bridges et al., 2012). Aeolian erosion of rock has occurred within the past ~1–10 k.y. (Golombek et al., 2010) and is probably ongoing. Because of Mars' thin atmosphere, slope winds are expected to dominate the atmospheric circulation in craters and canyons (Spiga and Forget, 2009). We have performed mesoscale (~4 km horizontal resolution) simulations of Gale Crater using the MarsWRF (http://planetwrf.com) general circulation model (Toigo et al., 2012, and references therein) with embedded high-resolution nests, and these provide further evidence that winds in Gale are expected to peak on the steep crater wall and mound slopes. Downslope-oriented yardangs, crater statistics, exposed layers, and lag deposits suggest that sedimentary mounds in Valles Marineris and Gale are being actively eroded by slope winds. Slope-enhanced winds appear to define both the large-scale and small-scale topography and stratigraphy of the polar layered deposits (e.g., Smith and Holt, 2010; Brothers et al., 2012), and radar sounding of intracrater ice mounds near the north polar ice sheet proves that these grew from a central core, suggesting a role for slope winds (Conway et al., 2012). Most of the ancient stratigraphy explored by the Opportunity rover is aeolian (Metz et al., 2009), and aeolian deposits likely represent a volumetrically significant component of the sedimentary rock record, including within the strata of the Gale mound (Anderson and Bell, 2010). Evidence for fluvial reworking within sedimentary mounds is comparatively limited and/or localized (e.g., Thomson et al., 2011). Quasi-periodic bedding at many locations, including the upper portion of Gale's mound, implies slow (~30 μm/yr) orbitally paced accumulation (Lewis et al., 2008). These rates are comparable to the modern gross atmospherically transported sediment deposition rate ($10^{1-2}$ μm/yr; Drube et al., 2010), suggesting that aeolian processes may be responsible for the layers. These data suggest that sedimentary deposits created by the accretion of atmospherically transported sediment (ash, dust, impact ejecta, ice nuclei, or rapidly saltating sand) formed readily on early Mars as well as in the more recent past (e.g., Cadieux, 2011).

Slope-wind erosion of indurated or lithified aeolian deposits cannot explain the outward dips observed at Gale unless the topographic depression surrounding the mound (i.e., the moat) seen in Figure 1 was present throughout mound growth. This implies a coupling between mound primary layer orientations, slope winds, and mound relief.

## MODEL

To explore this feedback, we aimed to develop the simplest possible model that can account for the structure and stratigraphy of Mars' equatorial sedimentary rock mounds. In one horizontal dimension ($x$), topographic change $dz/dt$ is given by

$$dz/dt = D - E, \tag{1}$$

where $D$ is an atmospheric source term and $E(x,t)$ is erosion or sediment entrainment rate. Initial model topography (Fig. 3) is a basalt (non-erodible) crater/canyon with a flat floor of width $2R$ and 20° slopes. Although dipping beds in the mound suggest a dominant role for aeolian processes in mound growth, our model does not preclude the possibility of intermittent fluvial/lacustrine deposits, perhaps later reworked by aeolian processes. To highlight the role of slope winds in building mounds through erosion and deposition, we initially assume $D$ is constant and uniform (e.g., Niles and Michalski, 2009; Fergason and Christensen, 2008) and focus on $E$ as the driver of wind entrainment and erosion. $E$ typically has a power law dependence on maximum shear-velocity magnitude at the air-sediment interface,

$$E = kU^{\alpha}, \tag{2}$$

where $k$ is an erodibility factor that depends on substrate grain size and induration/cementation, and $\alpha$ is ~3–4 for sand transport, soil erosion, and rock abrasion (Kok et al., 2012). We assume that sediments have some cohesive strength, most likely due to processes requiring liquid water (e.g., wetting, lithification, crust formation). Shallow diagenetic cementation (McLennan and Grotzinger, 2008), if it occurred, could have been driven by snowmelt, rainfall, or fog. Eroded material does not pile up in the moat but is instead removed from the crater, for example through breakdown to easily mobilized dust-sized particles. We model shear velocity magnitude as

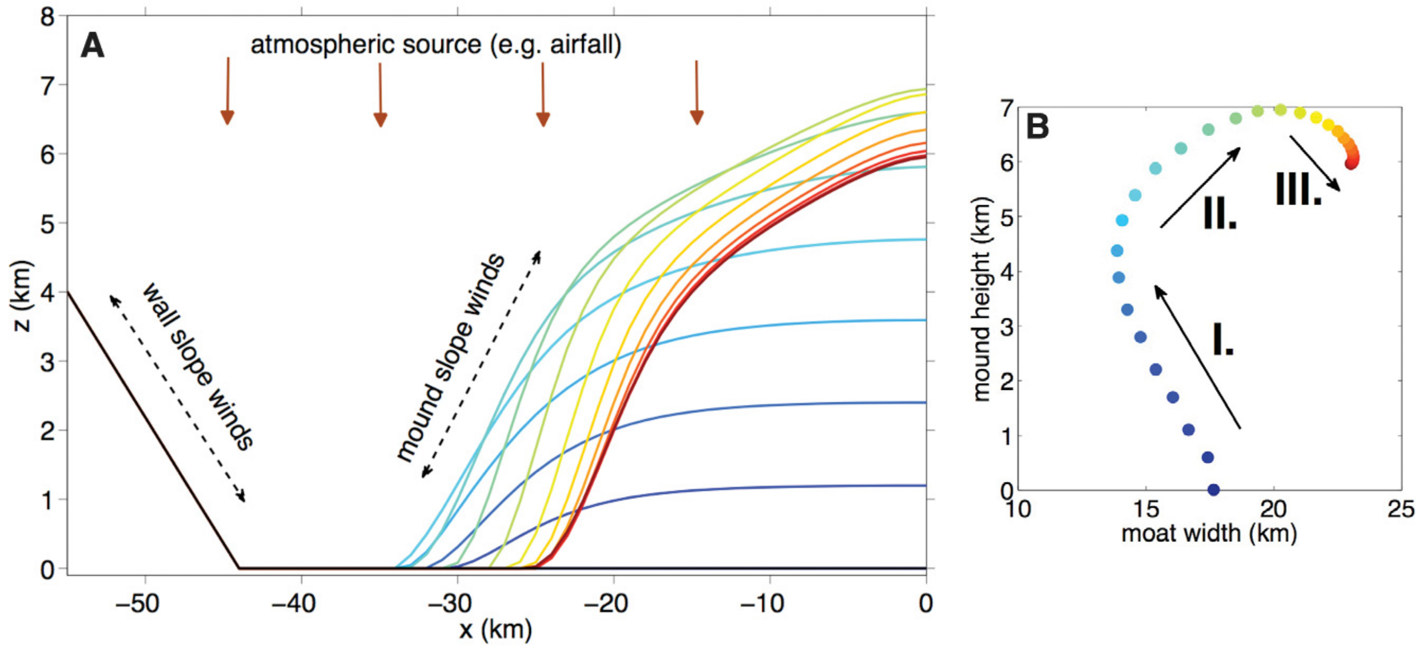
$$U(x) = U_0 + \max\left[\int_x^{\pm\infty} \frac{\partial z'}{\partial x'} exp\left(\frac{-|x-x'|}{L}\right)\partial x'\right], \tag{3}$$

which is the sum of a background bed shear velocity $U_0$ and the component of shear velocity due to slope winds. The "max |± ( )|" operator returns the maximum of downslope (nighttime) or upslope (daytime) winds, $z'$ is local topography, $x$ and $x'$ are distances from the crater center, and $L$ is a slope-wind correlation length scale that represents the effects of inertia. The slope winds are affected by topography throughout the model domain, but are most sensitive to slopes within $L$ of $x$.

## RESULTS

Model output characteristically produces Gale-like mound structure and stratigraphy. Figure 3 shows output for $\alpha = 3$, $D' = 0.4$, $L = 19$ km for a Gale-sized crater (the GSA Data Repository[1] shows the results from sensitivity tests; $D'$ is defined as deposition rate divided by mean erosion rate on crater/canyon floor at simulation start). Katabatic winds flowing down

[1]GSA Data Repository item 2013150, supplementary text, figures, and table, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



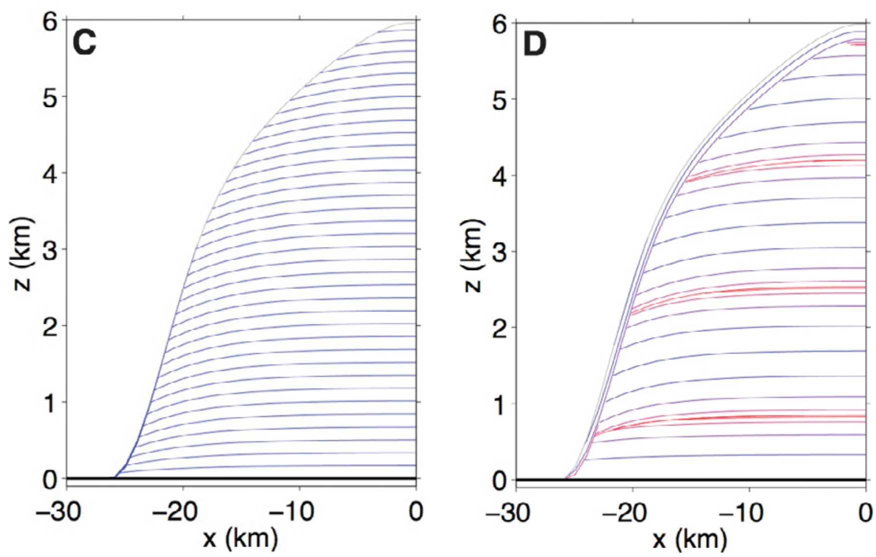




**Figure 3. Simulated sedimentary mound growth and form. A: Colored lines correspond to snapshots of mound surface equally spaced in time (blue is early, red is late), for a radial cut from crater wall to crater center. Black line corresponds to initial topography. B: Mound geometry, where time step between dots is half as long as time step between lines in A. I, II, and III highlight stages in evolution of the mound. The maximum model mound radius exceeds its current radius, consistent with observations of a possible mound outlier (Anderson and Bell, 2010, their figure 24). C: Stratigraphy formed for steady uniform deposition. D: Stratigraphy resulting from sinusoidally time-varying deposition. Color of strata corresponds to deposition rate: blue is high *D* (deposition rate), which might correspond to wet climates, and red is low *D*, which might correspond to dry climates (e.g., Kite et al., 2013). Note low-angle unconformities. A late-stage drape crosscuts layers within mound core at a high angle, and is itself broken up by further erosion (Fig. 2). Thin mesa units mapped at Gale and elsewhere have these characteristics (Malin and Edgett, 2000; Anderson and Bell, 2010).**

the crater walls inhibit sediment-layer accumulation both on the crater walls and for an inertial run-out length on the floor that scales with *L*. Layer accumulation in the quiet crater interior is not inhibited, so layers can be deposited there. Greater wind speeds close to the walls increase sediment erosion and entrainment. The gradient in slope-wind shear velocity causes a corresponding gradient in sediment accumulation, which over time defines a moat and a growing mound. Mound aggradation rate does not change significantly upsection, consistent with observations that show no systematic decrease in layer thickness with height (e.g., Cadieux, 2011). Growth does not continue indefinitely; when the relief of the mound becomes comparable to that of the crater walls, slope winds induced by the mound itself become strong enough to erode earlier deposits at the toe of the mound. This erosional front steepens the topography and further strengthens winds, so erosion propagates inward from the edge of the mound, leading to a late-stage net erosional state. This evolution does not require any change in external forcing with time; however, simulating discrete, alternating erosional and depositional events with a constant, short characteristic timescale produces the same model output. Exposure of layering at all elevations on the Gale mound show it has entered the late, erosional stage. Exhumed layers are buried to kilometer depths, but relatively briefly, consistent with evidence that clay diagenesis at Gale was minimal (Milliken, 2010). During early mound growth, $dz/dt$ is not much slower than *D*. If *D* corresponds to vertical dust settling at rates similar to today, then the lower Gale mound accumulated in a small fraction of Mars' history ($10^{7-8}$ yr), consistent with the orbital forcing interpretation of cyclic bedding (Lewis et al., 2008). Values of *L* and *D* on early Mars are not known, but Gale-like shapes and stratigraphy arise for a wide range of reasonable parameters (Fig. DR2 in the Data Repository). Consistent with observations across Mars, moats are infilled for small *R*/*L*, and for the largest *R*/*L* multiple mounds can develop within a single crater.

*D* could vary on time scales much shorter than the mound growth time scale—for example, if orbital cycles pace the availability of liquid water for cementation. To illustrate this, we set $D(t) = D(t = 0) + D(t = 0)\cos(nt)$ where the oscillation time scale, $n^{-1}$, is much less than the mound growth time scale, and find low-angle unconformities can be preserved. Deposition at a constant long-term-average rate is unrealistic for the entire mound history because the rate of sedimentary rock formation on Mars is close to zero in the modern epoch (Knoll et al., 2008), most likely because atmospheric loss has restricted surface liquid-water availability. To explore this, we decreased $D'$ over time; this allows winds flowing down the crater rim to expose layers and form a moat even when layers are originally horizontal.

## IMPLICATIONS FOR MSL

SWEET is incompatible with a deep-groundwater source for early diagenetic cementation of sedimentary rocks at Gale (e.g., Milliken et al., 2010), because deep-groundwater limited evaporite deposition would infill moats and produce near-horizontal strata. A water source at or near the mound surface (ice weathering, snowmelt, or rainfall) is predicted instead to explain those observations (e.g., Niles and Michalski, 2009; Kite et al., 2013). Because perennial surface liquid water prevents aeolian erosion, we predict long dry windy periods interspersed by brief wet periods at Gale, similar to observations at Meridiani (Metz et al., 2009). Upon arriving at the mound, MSL can immediately begin to collect observations that will test our model. MSL can confirm a dominantly aeolian origin using sedimentology measurements, and constrain present-day winds using its meteorology package, past winds by imaging fossilized bedforms, post-depositional tilting by measuring stream-paleoflow directions, and subsurface dissolution using geochemical measurements. Unconformities, if any, should be oriented away from the center of the present mound. Gale Crater's diverse geology records many environments. We argue that non-aeolian deposits are likely reworked by aeolian processes or interbedded with aeolian deposits, necessary conditions for our model to explain the mound's shape and stratigraphy. If the bulk of the mound did form by slow, perhaps orbitally paced, aeolian sedimentation, then the preservation potential of organic carbon would be low (e.g., Summons et al., 2011).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