The Rocknest aeolian deposit is similar to aeolian features analyzed by the Mars Exploration Rovers (MERs) Spirit and Opportunity. The fraction of sand <150 micrometers in size contains ~55% crystalline material consistent with a basaltic heritage and ~45% x-ray amorphous material. The amorphous component of Rocknest is iron-rich and silicon-poor and is the host of the volatiles (water, oxygen, sulfur dioxide, carbon dioxide, and chlorine) detected by the Sample Analysis at Mars (SAM) quadrupole mass spectrometer/gas chromatograph/tunable laser spectrometer suite of instruments (SAM/SPaH-CHIMRA) instrument (3). Scoops 1 and 2 were processed by CHIMRA and discarded to reduce (by entrainment and dilution) any terrestrial organic contamination that may have remained after a thorough cleaning on Earth (4) and to coat and passivate the interior surfaces of the collection device with Mars dust. Portions remained after a thorough cleaning on Earth (4) but could not be analyzed by CheMin.

## Results

**Description and Interpretation of the Rocknest Sand Shadow**

The Rocknest sand shadow (7) is an accumulation of wind-blown sediment deposited in the lower-velocity lee of an obstacle in the path of the wind. The orientation of the sand shadow indicates that the constructive winds were from the left (Fig. 1A). Trenches created during the scooping show that these larger grains form an armored surface ~2 to 3 mm in thickness (Fig. 1B). Beneath the armored surface, the bedform interior consists of finer-grained material whose size distribution extends through the resolution limit of Mars Hand Lens Imager (MAHLI) images (~30 μm per pixel under the conditions of the observation) (8). Because of CHIMRA’s 150-μm sieve, the larger grains that armor the surface could not be analyzed by CheMin.

Coarse sand grains that fell from the crust into the scoop-troughs lost their dust coating and show diversity in color, luster, and shape. Among the grains are gray and red lithic fragments, clear/translucent crystal fragments, and spheroids with glassy luster (Fig. 1C). Some grains showed bright glints in the martian sunlight, suggesting specular reflections from mineral crystal faces or cleavage surfaces [similar features were observed by the optical microscope on board the Mars Phoenix Lander (9)]. MAHLI images of a sieved portion of material deposited on the observation tray (3) showed a variety of particle types from clear to colored to dark, angular to spherical, and dull to glassy-lustered (Fig. 1D).

During the scooping process, fragments of the armored surface were cohesive to the extent that “rafts” of surface crust were laterally compressed and displaced forward, and fragments of the crust fell into the scoop hole as cohesive units (Fig. 1B). The surface crust was also fractured and broken into rafts during sifting by rover wheels (a process by which an excavation is made into the subsurface of unconsolidated regolith by rotating a single rover wheel). Material beneath the crust also had some cohesion, as shown by the overstep walls of the scoop scars (much greater than the angle of repose and vertical in some cases).

The sand shadow has a discernible internal structure. On the headwall and flanks of each scoop trench, a lighter-tone layer is apparent ~1 cm beneath and parallel to the dune surface (Fig. 1B). The origin of the layering is not understood, and three hypotheses are viable. First,
the layering may represent changes in bulk composition or grain size that occurred during deposition. Second, the layering may be the result of changes in oxidation state or other chemical properties that occurred after deposition, in which case the conformable nature of the banding and the surface of the sand shadow reflect depth-dependent postdepositional chemical processes. Finally, the layering may represent zones richer or poorer in light-toned dust, reflecting times of lesser or greater sand accumulation relative to the air-fall dust.

The aeolian bedform at Rocknest is quite similar to coarse-grained ripples encountered at Gusev by the MER Spirit (10, 11) and at Meridiani Planum by the MER Opportunity (12, 13) in that a coarse-grained, indurated, dust-coated surface overlies an interior of markedly finer sediment. Coarse-grained ripples on Earth typically consist of a surface veneer of coarse grains and a finer-grained interior (7, 14), and the martian bedforms have been considered analogous features (13, 13). The spatial grain-size sorting within coarse-grained ripples is thought to arise because of the short grain excursion length of the coarse grains traveling in creep and the much longer excursion length of finer saltating grains (16). With ripple migration, coarse grains are recycled through the bedform and become concentrated on the ripple surface, where impacts from saltating grains tend to buoy the grains upward.

Although the dynamics of sand shadows differ from those of coarse-grained ripples, and sand shadows on Earth do not characteristically show a coarse-grained surface, similar dynamics may arise owing to the mix-load transport of grains in creep and saltation. Alternate interpretations are also possible. First, the coarse-grained surface could represent a lag formed as winds deflated finer grains. However, the paucity of coarse grains within the interior indicates that an unreasonable amount of deflation would have had to occur to produce the veneer. Second, the coarse-grained veneer could represent the terminal growth phase of the bedform. Because the size of a sand shadow is fixed by the upwind obstacle size (17), once the terminal size is approached, the lower wind speeds that characterize the wake and allow for deposition of finer sediment are replaced by wind speeds that approach the unmodified (primary) winds. At this point, there would be selective deposition of coarse grains traveling in creep, whereas finer saltating grains would bypass the bedform. Third, the sand shadow could have formed largely by the more readily transported fine saltation load, but as the area became depleted in finer grains, more of the residuum of...

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**Fig. 1. The Rocknest sand shadow, where Curiosity spent sols 57 to 100 conducting engineering tests and science observations of the material.** (A) Mosaic of 55 MAHLI images showing Curiosity parked on the east side of the Rocknest sand shadow during the sampling campaign on sol 84. The location of each of the five scoops is indicated. The inset is a portion of Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment image ESP_028678_1755 showing the Rocknest sand shadow as seen from about 282 km above the ground. (B) MAHLI image of third scoop trench, showing the dust-coated, indurated, armoring layer of coarse and very coarse sand and underlying darker finer sediment. (C) MAHLI image of Rocknest sand shadow surface disrupted by the rover’s front left wheel on sol 57. The larger grains came from the armoring layer of coarse sand on the sand shadow surface. (D) MAHLI image of a <150-μm sieved portion from the third scoop: grains similar to those delivered to the CheMIn and SAM instruments, delivered to Curiosity’s Ti observation tray.
coarser grains would be incorporated into transport, with the coarse-grained surface arising through subsequent deflation.

None of these interpretations explains the general absence of observed coarse grains in the interior; the contrast in grain size between the surface and the interior is more marked in the Rocknest sand shadow and in some of the coarse-grained ripples observed by MERs than in many Earth examples. This may reflect the greater impact energy of saltating grains on Mars compared with Earth and their ability to transport disproportionally larger grains in creeps (18). Regarding the apparent absence of interior coarse grains, the small scooped areas may not be representative of the entire bedform, and interior horizons of coarse grains could easily have been bypassed. In addition, as seen with coarse-grained ripples on Earth, the amount of coarse sediment occurring in the interior varies and decreases with the supply of coarse grains.

Regardless of the origin of the coarse-grained surface, this armored surface would stabilize the bedform during all but the strongest wind events. In turn, the armored surface would allow time for surface induration to develop, further stabilizing the sand shadow. The similarity of the armoring and induration of the sand shadow at Rocknest to coarse-grained ripples encountered by Spirit and Opportunity suggests that the processes of grain transport and stabilization are similar across equatorial Mars and that Mars’ winds (in recent eras) rarely were strong enough to transport sand grains of 1- to 3-mm diameter. To move the grains at the current atmospheric pressure of 0.02 kg/m$^3$, the wind velocities would need to be ~36 m/s (80 mph) and ~52 m/s (116 mph), with and without saltation, respectively. Under conditions of high obliquity, during which time the atmospheric pressure could increase to 0.04 kg/m$^2$, these values would decrease to 26 m/s (58 mph) and ~37 m/s (83 mph), respectively (see Materials and Methods).

The potential antiquity of the Rocknest sand shadow is highlighted by comparing it with granule ripples on Meridiani Planum, where cratering postdates a field of pristine granule ripples and the crater count suggests an age of 50,000 to 200,000 years (19).

### Mineralogy of the Rocknest Sand Shadow

Analysis and interpretation of the mineralogy of the Rocknest sand shadow is given in Bish et al. (20). Rocknest consists of both crystalline and x-ray amorphous components. The crystalline component is basaltic, composed of plagioclase feldspar, forsteritic olivine, and the pyroxenes augite and pigeonite (20). All of the minor phases are consistent with a basaltic heritage, with the exception of anhydrite and hematite. By constraining the compositions of the individual crystalline phases on the basis of their measured unit-cell parameters, the chemical compositions of the minerals of Rocknest were determined (21, 22).

The crystalline component of Rocknest is chemically and mineralogically similar to that inferred for martian basalts across the planet and many of the basalts found in martian meteorites (Table 1) and, apart from somewhat lower Fe and K, broadly similar to estimates of the average martian crust (23). These basalts all contain (or have chemical compositions consistent with) the minerals olivine, augite, pigeonite, and plagioclase feldspar. The mineral proportions of the crystalline component of Rocknest are virtually identical to those calculated for the unaltered Adirondack class basalts from Gusev Crater (CIPW normative mineralogy from their APXS analyses (Table 1) (24, 25). Chemically, the mafic minerals of the Rocknest sediment (olivine, augite, and pigeonite) are all consistent with high-temperature chemical equilibria among Ca, Fe, and Mg at 1050 ± 75°C (Fig. 2). This consistency with chemical equilibria suggests, but does not prove, that these minerals and the plagioclase feldspar all derived from a common basaltic source rock, which was broken down into individual grains or lithic fragments and transported to Rocknest from regional source areas.

### Bulk Chemistry of the Rocknest Sand Shadow

APXS provided an independent means of determining bulk chemistry of material in the Rocknest sand shadow. A measurement was made in a wheel scuff named Portage, which was largely devoid of surface crust (Fig. 1A). The chemical composition (taking into account analytical uncertainties) is within 2 SD of MER APXS analyses of basaltic soils (Table 2). The APXS chemical composition of basaltic soils analyzed by the MERs at Gusev Crater and Meridiani Planum landing sites (Table 2) are within 1 SD of each other except for MgO and Na$_2$O, which are the same within 2 SD (24-28). The MER compositional averages exclude soils that contain a substantial local component (high SO$_3$ and high SiO$_2$ for Gusev and high Fe$_2$O$_3$ for Meridiani). The near identity of compositions of the Rocknest, Gusev, and Meridiani basaltic soils implies either global-scale mixing of basaltic material or similar regional-scale basaltic source material or some combination thereof.

### Table 1. Mineralogy of Rocknest soil [CheMin x-ray diffraction (XRD)] and normative mineralogy of basaltic materials from Gusev Crater and of martian meteorites.

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample</th>
<th>Rocknest sand shadow</th>
<th>Adirondack</th>
<th>Backstay</th>
<th>Irvine</th>
<th>Shergotty NWA 6234</th>
<th>EETA 79001A</th>
<th>QUE 94210</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>1.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>40.8</td>
<td>39</td>
<td>49</td>
<td>32</td>
<td>23</td>
<td>19</td>
<td>19</td>
<td>32</td>
</tr>
<tr>
<td>K-spar</td>
<td>1.3</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Low-Ca Pyx</td>
<td>13.9</td>
<td>15</td>
<td>14</td>
<td>21</td>
<td>46</td>
<td>30</td>
<td>47</td>
<td>15</td>
</tr>
<tr>
<td>High-Ca Pyx</td>
<td>14.6</td>
<td>15</td>
<td>5</td>
<td>13</td>
<td>25</td>
<td>16</td>
<td>16</td>
<td>38</td>
</tr>
<tr>
<td>Olivine</td>
<td>22.4</td>
<td>20</td>
<td>15</td>
<td>16</td>
<td>0</td>
<td>27</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>Fe-Cr oxides</td>
<td>3.2</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>0.9</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Apatite</td>
<td>–</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg no.</td>
<td>61 ± 3</td>
<td>57</td>
<td>62</td>
<td>55</td>
<td>51</td>
<td>63</td>
<td>63</td>
<td>40</td>
</tr>
<tr>
<td>An</td>
<td>57 ± 3</td>
<td>42</td>
<td>29</td>
<td>19</td>
<td>51</td>
<td>50</td>
<td>60</td>
<td>62</td>
</tr>
</tbody>
</table>
In contrast to the APXS measurement at the Portage wheel scuff, both CheMin and SAM measurements were carried out on the sieved, <150-μm-size fraction of soil. To discriminate potential differences between the fines delivered to CheMin and SAM and the bulk material analyzed in the wheel scuff, APXS chemistry was obtained from portions of sieved material deposited on the observation tray. APXS spectra from the bulk and sieved material are nearly identical, with the exception of a prominent Ti peak and increased background from the observation tray (reflecting Ti metal of the tray). Additionally, Ca, Mn, and Fe signals in spectra from the observation tray are lowered proportionally as a function of their atomic number, which suggests that a fraction of these grains is smaller than the APXS sampling depth (29). Slightly elevated S and Cl, with a S/Cl ratio similar to that found in soils by MERs (30), suggest a potential enrichment of these two elements in the <150-μm fraction delivered to the observation tray.

To determine the amount and composition of the amorphous component, mass balance calculations were performed using the chemical composition of the bulk sample, the chemical compositions of the individual phases (e.g., plagioclase, sanidine, and olivine) and the relative proportions of those phases in the crystalline component. The empirical formulas of the major crystalline phases (Table 3) and their chemical compositions (table S2) were calculated from cell parameter data (20, 21) (table S1). The chemical formulas and compositions of the minor crystalline components were assigned by stoichiometry (e.g., ilmenite as TiFeO₃). The relative proportions of amorphous and crystalline components and their respective bulk compositions are summarized in Table 4, with Rocknest having ~45 weight percent (wt %) amorphous and ~55 wt % crystalline components (31). The chemical compositions and proportions of amorphous and crystalline components were calculated on a light-element–free basis. The relative proportion of the amorphous component will in reality be greater than 45 wt % because the volatile inventory is associated with that component (32).

Abundance estimates for the x-ray amorphous component of a sample may vary considerably, depending on the method used for their determination. Bish et al. (20), for example, used a full pattern-fitting method together with known amorphous standard materials analyzed in the laboratory to determine the amount of amorphous or poorly crystalline material contained in the CheMin x-ray diffraction pattern. Their reported value of ~27 wt % ± 50% (1 SD range of 13 to 40 wt %), as calculated from diffraction and scattering data alone, is somewhat lower than the ~45% calculated from mass balance considerations, but both values are within the combined analytical uncertainty of the two techniques.

The inferred chemical composition of the amorphous component (Table 4) contains ~23% FeO + Fe₂O₃, suggesting that ferric nanophase oxides [npOx (25, 26, 33)] is present in abundance. Similarly, S (principally contained within the amorphous component) is closely associated with the npOx in dunes at the MER sites (24, 27) as well. Abundances of SO₃ and Cl are correlated in soils from Gusev and Meridiani, which implies that both are associated with npOx in the amorphous component because these elements are not associated with Mg, Ca, or Fe in crystalline phases. The elements Cr, Mn, and P were associated with the amorphous component (Table 4), but

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Table 2. Basaltic soil compositions from APXS analyses for Rocknest Portage, Gusev Crater, and Meridiani Planum.

<table>
<thead>
<tr>
<th>Component</th>
<th>Rocknest</th>
<th>Gusev</th>
<th>Meridiani</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>1*</td>
<td>48†</td>
<td>29†</td>
</tr>
<tr>
<td>SiO₂ (wt %)</td>
<td>42.88 ± 0.47</td>
<td>46.1 ± 0.9</td>
<td>45.7 ± 1.3</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.19 ± 0.03</td>
<td>0.88 ± 0.19</td>
<td>1.03 ± 0.12</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>9.43 ± 0.14</td>
<td>10.19 ± 0.69</td>
<td>9.25 ± 0.50</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.49 ± 0.02</td>
<td>0.33 ± 0.07</td>
<td>0.41 ± 0.06</td>
</tr>
<tr>
<td>FeO2 + FeO</td>
<td>19.19 ± 0.12</td>
<td>16.3 ± 1.1</td>
<td>18.8 ± 1.2</td>
</tr>
<tr>
<td>MnO</td>
<td>0.41 ± 0.01</td>
<td>0.32 ± 0.03</td>
<td>0.37 ± 0.02</td>
</tr>
<tr>
<td>MgO</td>
<td>8.69 ± 0.14</td>
<td>8.67 ± 0.60</td>
<td>7.38 ± 0.29</td>
</tr>
<tr>
<td>CaO</td>
<td>7.28 ± 0.07</td>
<td>6.30 ± 0.29</td>
<td>6.93 ± 0.32</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.72 ± 0.10</td>
<td>3.01 ± 0.30</td>
<td>2.21 ± 0.18</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.49 ± 0.01</td>
<td>0.44 ± 0.07</td>
<td>0.48 ± 0.05</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.94 ± 0.03</td>
<td>0.91 ± 0.31</td>
<td>0.84 ± 0.06</td>
</tr>
<tr>
<td>SO₃</td>
<td>5.45 ± 0.10</td>
<td>5.78 ± 1.25</td>
<td>5.83 ± 1.04</td>
</tr>
<tr>
<td>Cl</td>
<td>0.69 ± 0.02</td>
<td>0.70 ± 0.16</td>
<td>0.65 ± 0.09</td>
</tr>
<tr>
<td>Br (μg/g)</td>
<td>26 ± 6</td>
<td>53 ± 46</td>
<td>100 ± 111</td>
</tr>
<tr>
<td>Ni</td>
<td>446 ± 29</td>
<td>476 ± 142</td>
<td>457 ± 97</td>
</tr>
<tr>
<td>Zn</td>
<td>337 ± 17</td>
<td>270 ± 90</td>
<td>309 ± 87</td>
</tr>
<tr>
<td>Sum (wt %)</td>
<td>99.85</td>
<td>99.88</td>
<td>99.88</td>
</tr>
<tr>
<td>CuSO₄</td>
<td>0.13 ± 0.02</td>
<td>0.12 ± 0.02</td>
<td>0.11 ± 0.01</td>
</tr>
</tbody>
</table>

*Gellert et al., 2013 (35); analytical uncertainty. †±1SD of average.

---

Table 3. Empirical chemical formulas of the four major phases identified in the Rocknest soil estimated by crystal-chemical techniques.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine</td>
<td>(Mg₀.₆₂₀Fₑ₀₃.₆₀₂Sio₄</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>(Ca₀.₅₁₇₃M₀.₄₂₉Al₁₅₇₃Si₂₄₉₀ O₈</td>
</tr>
<tr>
<td>Augite</td>
<td>(Ca₀.₇₅₄M₀.₈₈₁₉₀Fₑ₀.₃₇₂Si₂₀O₆</td>
</tr>
<tr>
<td>Pigeonite</td>
<td>(Mg₀.₁₃₁₀₂Fₑ₀.₆₈₁₉₀Ca₀.₁₉₂Si₂₀O₆</td>
</tr>
</tbody>
</table>
they could instead be present as crystalline phases
(e.g., Ca-phosphate and chromite) at abundances
below the ChemCam detection limit and/or as sub-
stitutional impurities in the major crystalline phases
(e.g., Mn and Cr in pyroxene).

The SAM instrument analyzed Rocknest for
volatile species and organic molecules (32), and
it detected, in order of decreasing abundance,
H2O, SO2, CO2, and O2. The crystalline phases,
aside from a minor anhydrite component, do not
include these species as a part of their structure,
so they must either be present in the amorphous
component or be present in the crystalline com-
ponent at levels below the XRD detection limit,
or both.

ChemCam spot observations in the scoop
walls of Rocknest are characterized by the strong
emissions from elemental hydrogen, although
ChemCam is not sensitive to its bonding state (34).
Comparison of this result with those of ChemMin
and SAM suggests that ChemCam detections
of hydrogen most likely correspond to the H2O
associated with the amorphous component de-
tected by ChemCam.

Discussion

Global, Regional, and Local Sources

The crystalline phases in the Rocknest fines are
consistent with a basaltic source and fit well
within the measured qualitative mineralogy of
basaltic martian meteorites and the normative
mineralogy of Adirondack class olivine basalts
at Gusev Crater (25) (Table 1). If the Rocknest
assemblage of basaltic crystalline and amorphous
components is locally derived, it is distinct from
mafic float rocks analyzed to date by APXS and
ChemCam in Gale Crater (34, 35). This observa-
tion suggests that the similarity in the chem-
ical compositions of aeolian bedforms (basaltic
soil) at Gale, Gusev, and Meridiani (Table 2)
might result from global-scale aeolian mixing of
local-to-regional basaltic material that may or
may not have variable chemical compositions.
This process would require sufficiently
strong winds occurring with sufficient frequency
over a long enough time to achieve global or
regional-scale transport of grains by saltation and
suspension.

An alternative explanation for the compara-
tible chemical compositions of aeolian bedforms
at Gale, Gusev, and Meridiani is that the chem-
cal compositions of martian basalts are similar
at regional scales everywhere on the planet. The
Rocknest sand shadow could reasonably have
locally sourced 1- to 2-mm particles, with finer-
grained regional basaltic material plus a contri-
bution from global dust. The similarity of soil
compositions (Table 2) suggests that the basaltic
fine-grained materials at Gusev, Meridiani, and
Gale Crater provide a reasonable approximation
to the bulk composition of the exposed martian
crust (36, 37).

It is tempting to suggest that the light-toned
martian dust is largely represented by the Rocknest
amorphous component. However, we have no
data to show that the <150-mm size fraction (clay
to fine-sand size fraction) of material analyzed
by ChemMin has its finest material preferen-
tially enriched in amorphous material. The evi-
dence from MER for basaltic soils suggests that
the chemical composition of the fine-grained,
light-toned soil is approximately the same as the
coarser-grained, dark-toned soils [e.g., table 10
in (38)].

The central mound of Gale Crater (Mt. Sharp
or Aeolis Mons) exhibits reflectance spectra sug-
gestng the presence of crystalline hydrated sulfate
minerals and phyllosilicates (39), but neither
was seen in Rocknest (above the 1 to 2% level).
The absence of material from Mt. Sharp could
arise from the wind pattern during formation of
the Rocknest sand shadow; it is oriented so
as to imply sediment transport from the north,
and Mt. Sharp is east and southeast of Rocknest.

Materials and Methods

Calculation of Wind Speeds Required
to Form the Rocknest Sand Shadow

The wind velocity required to move the coarse
grains of the sand shadow by creep can be cal-
culated. The critical shear velocity (u*) of the
wind needed to transport 1-mm-diameter (d) grains
is given by (42) as

\[ u_* = \sqrt{0.0123 \left( \frac{sgd}{\eta_f d} + \frac{0.0003 \text{ kg/s}^2}{\eta_f d} \right)} \]

where \( s \) is the density of the grains
using basalt (3000 kg/m³), \( \eta_f \) is the density of
amorphous material, and \( d \) is the diameter
of the grains.

Table 4. Chemical composition and proportion of XRD amorphous component in Rocknest Portage from APXS and ChemMin data.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Remove XRD crystalline component†</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>APXS†</td>
<td></td>
</tr>
<tr>
<td></td>
<td>APXS+ChemMin</td>
<td></td>
</tr>
<tr>
<td>Plagioclase</td>
<td>42.88</td>
<td>37.20</td>
</tr>
<tr>
<td>Sanidine</td>
<td>30.88</td>
<td>34.57</td>
</tr>
<tr>
<td>Olivine</td>
<td>25.95</td>
<td>23.14</td>
</tr>
<tr>
<td>Augite</td>
<td>21.63</td>
<td>16.03</td>
</tr>
<tr>
<td>Pigeonite</td>
<td>17.51</td>
<td>11.01</td>
</tr>
<tr>
<td>Limestone</td>
<td>17.51</td>
<td>10.91</td>
</tr>
<tr>
<td>Hemaite</td>
<td>17.51</td>
<td>10.91</td>
</tr>
<tr>
<td>Magnesite</td>
<td>17.51</td>
<td>10.91</td>
</tr>
<tr>
<td>Anhydrite</td>
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<tr>
<td>Quartz</td>
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<tr>
<td>MnO</td>
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<tr>
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<tr>
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<tr>
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<td>P2O5</td>
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<tr>
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<tr>
<td>CI</td>
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<td>11.01</td>
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<td>SO3-Cryst§</td>
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<tr>
<td>Fe2O3-Cryst¶</td>
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†Plagioclase, An57; Olivine, Fo62; Augite, En44Fs20Wo36 (Mg/Fe, 2.2 atomic); Pigeonite, En56Fs35Wo8 (Fe/Mg, 1.6 atomic).
‡APXS chemistry from Gellert et al. (35).
§Cr2O3 and MnO calculated with the amorphous component.
¶Total Fe as FeO+Fe2O3 because APXS does not distinguish oxidation states.
||FeO required for Fe2+ crystalline phases (olivine, augite, pigeonite, lillinite, and magnetite).
#SO3 required for crystalline SO3 crystalline phase (anhydrite).
Curiosity at Gale Crater

margian air (0.02 kg/m³), and $g$ is the acceleration due to gravity (3.71 m/s²). The calculated $u_{w,0}$ is 2.6 m/s, which represents the fluid shear velocity to initiate motion. Because grains in creep derive a portion of their momentum from collisions by saltating grains, on Earth once saltation begins, creep can occur down to 0.7 $u_{w,0}$ (1.8 m/s as applied to the Rocknest grains), which represents the impact threshold for motion. Given a boundary layer created by winds blowing over the surface, shear velocities can then be related to the wind speeds above the surface by the law of the wall

$$u_z = \frac{u_{w,0}}{k} \ln \left( \frac{z}{z_0} \right)$$

de where $u_z$ is the wind speed at height $z$ above the surface (taken here as 1 m), $k$ is a constant of 0.407, and $z_0$ is the roughness height where the idealized logarithmic wind profile is predicted to be zero. Roughness height varies by grain size and the height of surface features, such as wind ripples (7), and also by the height and intensity of the saltation cloud (47). Rocknest conditions are unknown, but $z_0$ is taken as 0.3 mm, which would be the roughness height with wind ripples 10 mm in height. Estimated wind speeds at 1 m above the surface are ~52 m/s (116 mph) and 36 m/s (80 mph), without and with saltation, respectively. As a result of the lower gravity and reduced atmospheric density on Mars, a greater hysteresis exists than on Earth between the fluid and impact thresholds, and saltation impacts upon grains are more energetic (18, 44, 45). The combined effects suggest that initial transport of the coarse surface grains probably occurred at lower wind speeds than those calculated. Conversely, reactivation of the sand shadow would require considerably higher wind speeds because of diminution of the surface.

Although observations from the Viking Lander 1 suggest that wind speeds of 30 m/s at a height of 1.6 m occurred during its 2-year lifetime (46), we do not know how often Mars winds can be capable of transporting 1- to 2-mm grains. The wind estimates above suggest that formation of the Rocknest sand shadow has involved rare strong winds and that reactivation of the sand shadow from its currently indurated state would require even stronger and rarer winds.

Given the possibility of considerable antiquity of the Rocknest sand shadow and similar coarse-grained bedform on Mars, could their activation correspond to the martian obliquity cycle? At low obliquities, the atmosphere collapses onto the polar caps, but at high obliquity, CO₂ is released to the atmosphere (47, 48). Taken as an end member, atmospheric density may double at high obliquity and thereby enhance aeolian activity (48). As a comparison with the above values calculated for the present martian atmosphere, using 0.04 kg/m³ for atmospheric density, the calculated fluid $u_{w,0}$ is 1.9 m/s and the impact $u_{w,0}$ is 1.3 m/s, which correspond to wind speeds at the 1-m height of ~37 m/s (83 mph) and 26 m/s (58 mph), respectively. Although considerably lower than values calculated for present conditions, rare strong wind events are still implied.

References and Notes

1. A Mars solar day has a mean period of 24 hours, 39 min, 35 s and is customized to a so-called “solar day” to distinguish it from the roughly 3% shorter day on Earth.

2. A sand shadow is an accumulation of wind-blown sediment deposited in the lower-velocity lee of an obstacle in the path of the wind.


9. W. Goetz et al., Socotra nanophase ferric oxide (npOx) is a generic name for amorphous, poorly crystalline, or short-range ordered Fe₃O₄ that occurs on Mars, one or more forms of npOx on the planet could be derived from a “soil” to distinguish it from the roughly 3% shorter day on Earth.


15. Because APXS does not discriminate among iron oxidation states, the total Fe concentration was proportioned in accordance with the oxidation state information carried by the crystalline phases (Table 3, column 3). FeO-Cryst and Fe₂O₃-Cryst are the concentrations of FeO and Fe₂O₃ required to accommodate olivine, augite, pigeonite, ilmenite, and magnetite and hematite, in accordance with their valence states. The remaining iron (FeO + Fe₂O₃) is then associated with the amorphous component without implications for oxidation state. Similarly, some SiO₂ is reported as SiO₂-Cryst to accommodate anhydrite as a crystalline component.


17. Nanophase ferric oxide (npOx) is a generic name for amorphous, poorly crystalline, or short-range ordered products of oxidative alteration/weathering that have octahedrally coordinated Fe⁷⁺ (Mössbauer doublet) and are predominantly amorphous/hydrous in nature. Depending on local conditions, npOx (as encountered on Earth) can be any combination of superparamagnetic hematite and goethite, lepidocrocite, ferrhydrite, schwertmannite, akaganite, hisingerite, and the octahedral Fe₃⁺-rich particles that pigment iron oxide and palagonite. npOx can also incorporate anions like (SO₄²⁻), Cl⁻, and (PO₄³⁻)₅ through specific chemical adsorption. Because of different local conditions on Mars, one or more forms of npOx on the planet may be uncommon or not present on Earth.

18. P.-Y. Meulst et al., Soil diversity and hydration as observed by ChemCam at Gale Crater. Science 341, 1238650 (2013); doi:1126/science.1238670


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Supplementary Materials
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Supplementary Text
Figs. S1 to S4
Tables S1 and S2
References
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