ROCKNEST SAND SHADOW AT THE *CURIOSITY* FIELD SITE: MORPHOLOGY, ORIGIN AND STABILIZATION.

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Introduction: The Rocknest sand shadow was the site of the first scooping activities by the MSL rover *Curiosity* in October/November 2012. The purposes of this study are to (1) describe the morphology of the bedform within the context of sand-shadow formation, and (2) determine the wind regime that gave rise to the sand shadow and that is required to remobilize it.

Description: The Rocknest sand shadow (terminology of 1) is a sharp-crested, nearly symmetrical, ~15 cm high, N-S-trending aeolian accumulation that extends ~5 m southward from a ~7 m wide cluster of dark cobbles (Fig. 1). Although wind ripples with a migration direction to the south occur on the western flank of the sand shadow near its northern terminus, the surface of the sand shadow is predominately characterized by subrounded, coarse (~ 1 mm) sand grains, which are coated by rims of dust (Fig. 2). The coarse surface grains contrast with the interior of the sand shadow, in which a substantial proportion of the grains are finer than 0.150 mm. Formation of millimeter-scale surface fissures, and breakage of the coarse-grained veneer into cohesive rafts by the scooping operations show that the upper surface forms a weakly indurated "crust" with a thickness of one or two grains (1-2 mm). Fractures formed within sediment pushed forward during scooping, well defined cleat marks from the rover wheels, and high-angle scoop-trench walls show cohesiveness to the sediment with probable high dust content.

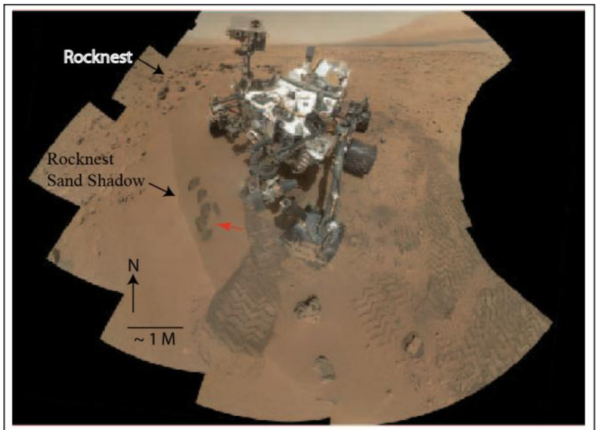

Figure 1: MAHLI Sol 84 mosaic showing Rocknest sand shadow extending south ~ 5 m from a cluster of cobbles. The sand shadow is ~ 15 cm in height. Note well defined kleat marks from rover wheels and scoop sites (red arrow).

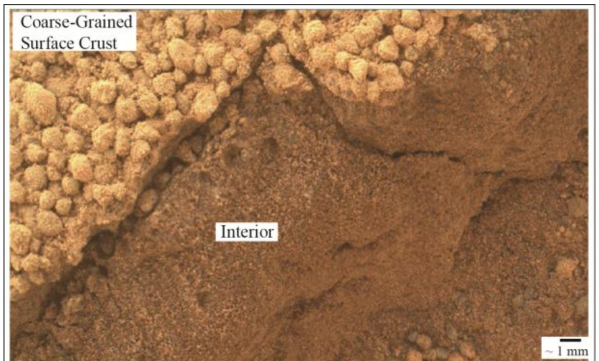

Figure 2: Sol 67 scoop of the Rocknest sand shadow showing surface coarse-grained, cohesive crust and finer-grained interior.

Formation: Sand shadows form in the lower-velocity wake of an obstacle in the path of the wind [1-3], and are most prominent in sand-starved areas where deposition occurs only locally in the lee of obstacles [4]. Field observations and wind-tunnel experiments show that the surface flow is deflected around the obstacle to give rise to a pair of counter-rotating vortices in the streamwise direction such that sand is obliquely swept toward the centerline where the vortices converge and define the crest of the sand shadow [3, 5]. In experiments with obstacles of similar heights, sand shadow height increased as a function of obstacle width and as limited by the angle of repose [3]. For a given obstacle width, shadow dune length decreased as wind speed increased because of greater wind speeds within the wake [3]. Where obstacle height differs, sand shadow height is limited by obstacle height, and sand shadow length may be limited by sediment availability [2].

Formative Wind Regime and Stabilization: Because sand shadows form in the lee of obstacles, they are indicators of their formative wind regime. The southward extension of the Rocknest sand shadow indicates a formative wind from the north. Dust rimming of the surface coarse grains and weak induration of the surface indicate a probable significant period of time since the sand shadow was active.

On Earth, sand-shadow stability is typically determined by the consistency of wind direction, wind speed, and obstacle size. For the Rocknest sand shadow, the indurated, coarse-grained crust provides an overriding stabilization feature that is rarely reported for shadow dunes on Earth [6], but that appears to be common for aeolian bedforms on Mars, especially for dusty coarse-grained ripples [7-9]. Coarse grains armoring the surface of aeolian bedforms on Mars could develop by: (1) winnowing of *in situ* sediment to form a residual lag, (2) lifting of coarse grains to the surface by pedogenic processes [e.g., 10], or (3) selective deposition of coarse grains at the terminal growth phase of the sand shadow. Given the paucity of coarse grains within the interior, especially the absence of coarse-grained laminae, winnowing to form a lag is unlikely. Pedogenic processes, especially those related to freeze/thaw, cannot be excluded as speculation, but physical processes of selective deposition of coarse grains can best explain the surface armoring. Rare, high-energy wind events that mobilize coarse grains as creep are likely to also deplete supplies of finer saltating grains, and leave armored bedforms then subject to dust deposition and induration [9]. Alternatively, where a sand shadow reaches its ultimate size as defined by the aerodynamic parameters of its parent obstacle, only deposition of coarse grains may be possible whereas the finer saltating population bypasses the bedform.

Regardless of the origin of the coarse surface crust, neglecting the effects of induration, winds sufficient to reactivate the Rocknest sand shadow can be estimated. The critical shear velocity to initiate motion, u_{*c}, after [11] using data from [12] is

$$u_{*c} = \sqrt{0.123\left(sgd + \frac{0.0003\, kg/s^2}{\rho_f d}\right)}$$

where $s = \rho_s/\rho_f$ and ρ_s is the density of the grains using basalt (3000 kg/m^3) and ρ_f is the density of Martian air (0.02 kg/m^3), g is the acceleration due to gravity (3.72 m/s^2), and d is grain diameter of the armoring coarse sand (0.001 m). The calculated u_{*c} 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_{*c}, or 1.9 m/s as applied to the Rocknest sand shadow. These shear velocities can be related to wind speeds near the surface using the law-of-the-wall

$$u_z = \frac{u_*}{k}\, ln\left(\frac{z}{z_o}\right)$$

where u_z is the wind speed at height z above the surface (taken here as 1 m), k is von Karman's constant (0.407), and z_o is the roughness height where zero velocity occurs. Although z_o is not known in detail, following [1] z_o = k/30 where k is ripple amplitude taken as 10 mm. Wind speeds to remobilize the surface coarse grains at 1 m are 51.2 m/s (114.5 mph) and 37.4 m/s (83.7 mph) without and with saltation, respectively. Because of the lower gravity and lesser atmospheric density on Mars, a greater hysteresis exists than on Earth between the fluid shear velocity to initiate motion and the shear velocity needed to maintain transport once saltation has begun [13, 14]. In addition, the impact of saltating grains upon grains in creep is more energetic than on Earth [15]. For these reasons, remobilization of the coarse grains armoring the Rocknest sand shadow by the impact of saltating grains can occur at a lower shear velocity than calculated above. Nevertheless, wind speeds at or approaching hurricane-force likely represent the formative winds of the sand shadow, and are required for remobilization. Given the apparent rarity of these wind speeds on Mars, the Rocknest sand shadow is thought to represent a relict feature from a past major wind event at Gale crater.

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