THE ORIGIN OF SAND ON MARS. M. P. Golombek[1], C. Charalambous[2], W. T. Pike[2], and R. Sullivan[3], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [2]Department of Electrical and Electronic Engineering, Imperial College, London, [3]CCAPS, Cornell University, Ithaca, New York.

Introduction: On Earth, the production of sand size grains (0.06-2 mm diameter) is dominated by chemical and physical weathering processes in which many minerals transform to clay-sized grains, leaving resistant sand-sized quartz grains [1]. Once formed, quartz sand grains become rounded during transport, but otherwise undergo little further size reduction.

On Mars, sand is dominated by basaltic particles and primary igneous minerals [2,3,4]. The presence of these primary igneous minerals, including olivine, which is particularly susceptible to aqueous alteration, indicates that the production of sand on Mars is primarily due to physical processes. Furthermore, global thermophysical data and surface exploration at seven landing sites show that sand is the dominant particle size of soils that make up the surface layer on Mars, which is of order one meter thick [5,6]. McGlynn et al. [7] argue from the size-frequency distribution and rounding of sand observed by Spirit at Gusev crater, that the sand is produced by impact and eolian activity. In this abstract, we further argue that the rock and sand size-frequency distributions at the landing sites, and the Sprit and InSight locations in particular where the production of the surficial layer has been dominated by impact and eolian processes, can be explained quantitatively by fragmentation theory due to meteorite impact and subsequent eolian saltation.

Sand in the Martian Surface Layer: Global thermal inertia and albedo data shows that ~80% of the surface of Mars has thermal inertia less than 300-350 J m^{-2} K^{-1} $s^{-1/2}$ and comparison to surface materials at the landing sites shows that they are dominated by sand size particles with or without minor cohesion and some rocks (generally <10%) [5,6]. Although a wide variety of atmospheric and surface processes have undoubtedly contributed, some process(es) have created a global surface layer of dominantly basaltic sand size particles on Mars.

Clues from the Spirit and InSight Landing Sites: These two landing sites appear to have produced relatively thick (~10 m) regolith layers composed mostly of sand on top of Hesperian basalt flows dominantly by impact and eolian processes.

At the Gusev cratered plains investigated by Spirit, rocks are dark, fine-grained basalts, and observations of the inner slope of Bonneville crater show jumbled blocks in the upper 10 m that are interpreted to be an impact-generated regolith developed over intact basalt flows with surface expressions of residual primary flow features [8]. Ubiquitous shallow, soil-filled, circular depressions, called hollows, are impact craters filled with sand. Rock abundance is generally <10%, and most of the soils are composed of sand size particles with varying amounts of cohesion [8]. Deflation of the surface 5–25 cm exposed two-toned rocks and elevated ventifacts by transportation of fines into craters [8,9]. The volume of material that deflated the surface is equal to that required to fill the hollows suggesting that the sand was produced by impact and filled the craters [9].

Geologic and remote sensing investigations of the InSight landing site show it also has an impact generated regolith developed on Hesperian basalts [10,11]. The surface is dominated by smooth terrain with homogeneous thermal inertia of ~200 J m^{-2} K^{-1} $s^{-1/2}$ consistent with a surface composed of dominantly cohesionless, fine sand (~0.17 mm). Rock abundance is very low (<6%) except near rocky ejecta craters where it can be as high as 35%. The onset diameter of rocky ejecta craters and observations of nearby Hephaestus Fossae show a relatively fine-grained regolith 3-17 m thick that grades into coarse breccia over jointed bedrock [10,11]. Nearby surfaces show lobate flows and inflation plateaus consistent with the bedrock being a stack of basalt flows ~300 m thick. Eolian bedforms are limited to the interior and continuous ejecta blankets of fresh rocky ejecta craters, suggesting the wind mobilizes the sand size fraction soon after impact, filling the craters.

Sand Characteristics: Microscopic images of sand on Mars generally show that the larger grains that can be resolved are rounded to sub-rounded and equant and have been rounded by eolian saltation [7]. Sullivan et al. [12] argues that as grain size falls below 0.8 mm, the probability of saltation increases, with kinetic energy during saltation collisions contributing to grain size attrition. Collisional attrition is likely to be less efficient once grain size reaches around 0.125 mm, because greatly reduced grain mass reduces kinetic energy available during collisions, and grains become increasingly susceptible to suspension during strong wind events. Sullivan et al. [13] argues that this process leads to poorly sorted deposits dominated by fine sand (<0.125 mm). This scenario suggests that eolian activity plays an important role in the size and shape of sand that makes up most of the surface layer of Mars.

Fragmentation: Recent work shows that under repeated fracture events (in this case, dominantly impacts), fragmentation results in a particle size distribution described as a negative binomial (NB) function [14]. The theoretical model has been applied to meteoritic impacts and eolian transportation, but not to thermal stresses cracking rocks that could be an additional contributing process on Mars [e.g., 15]. Two parameters govern the fragmentation processes modeled and the evolution of the particle size.

The first, the maturity index quantifies the number of fragmentation events experienced by the particle population, in this case set by the number of meteorite impacts at the landing site. For a maturity index of 1, the NB reduces to the well-known power-law relationship for the size distribution from a single fragmentation event expected from fractal analysis [16]. The average regolith gradation with depth and the particle size distribution can then be determined from the cratering production function and the age of the surface [17].

To derive a particle-size distribution of the martian regolith we use: orbital rock counts of the InSight landing site, which are similar to those of the Spirit landing site [10]; microscopic image measurements of sand at the Spirit and Curiosity landing sites [3,4,7]; and optical and atomic force microscope data from the Phoenix landing site down to 100 nm [18]. These data were converted to a cumulative fractional mass (CFM) versus diameter distribution [19]. An NB fragmentation prediction based on the Hesperian cratering record matches the size-frequency distribution for diameters of 10 m to 0.6 m (coarse sand) (Figure 1).

Below around 0.2–0.5 mm the particle-size distribution transitions from the NB statistics predicted by fragmentation theory to one controlled by Poissonian statistics (Figure 1). This would be expected for a mature population, saturated by undergoing randomly repeated, but substantially weak impacts [20]. The maturity index abruptly increases from <4 for the larger diameters to >100 for the smaller diameters, and the probability of fragmentation drops to ~0 for the smaller diameters. In other words, the grain population experiences multiple collisions with a very small probability of successful fragmentation. This provides a surge in the multiplicity effect inherent in the fragmentation theory, in contrast to highly energetic and efficient fragmentation events by meteorite impacts. An NB fragmentation model of this type fits the particle size distribution below 0.2-0.5 mm (Figure 1). The CFM distribution and model prediction was also converted to a particle size frequency distribution, which yields a unimodal peak in particles from 0.1-0.2 mm.

Summary: The transition in processes producing particles above and below 0.2–0.5 mm predicted from fragmentation theory is in general agreement with the observations and numerical modeling of Sullivan et al. [12,13] in which particles <0.8 mm have high kinetic energy during saltation that reduces particle size to around 0.125 mm where their reduced size decreases their susceptibility to further attrition by the wind. Fragmentation theory predicts that meteorite impact can efficiently produce sand size particles down to around 0.6 mm and that eolian activity is responsible for the subsequent reduction in particles down to around 0.125 mm. The end state is a size-frequency distribution with a unimodal peak in particle size from 0.1-0.2 mm in agreement with observations. These results suggest that the global surface layer of mostly sand size particles on Mars is produced by dominantly impact and eolian processes.

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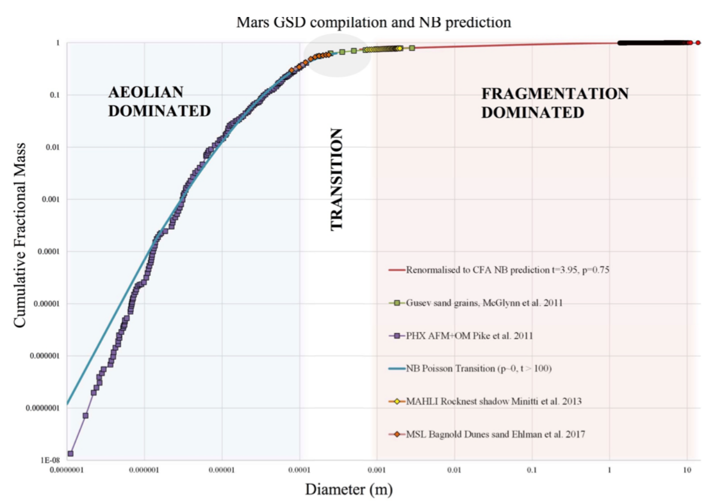

Figure 1: Cumulative fractional mass versus diameter distribution over 8 orders of magnitude and NB fragmentation models. Sand size particles are from Spirit and Gusev landing sites [3,4,7], particles 0.1 mm are from Phoenix [18], and rock distributions are from orbital images of the InSight landing site [10]. Note the transition in the fragmentation curves between impact dominated processes above 0.2-0.5 mm and eolian dominated processes below.