SEDIMENTOLOGY OF MARTIAN GRAVELS FROM MARDI TWILIGHT IMAGING: TECHNIQUES

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Introduction: Quantitative sedimentologic analysis of gravel surfaces dominated by pebble-sized clasts has been employed in an effort to untangle aspects of the provenance of surface sediments on Mars using *Curiosity*'s MARDI nadir-viewing camera operated at twilight [1]. Images have been systematically acquired since sol 310 providing a representative sample of gravel-covered surfaces since the rover departed the *Shaler* region. The MARDI Twilight imaging dataset offers ~ 1 mm spatial resolution (slightly out of focus) for patches beneath the rover that cover just under 1 m^2 in area, under illumination that makes clast size and inter-clast spacing analysis relatively straightforward using semi-automated codes developed for use with nadir images. Twilight images are utilized for these analyses in order to reduce light scattering off dust deposited on the front MARDI lens element during the terminal stages of *Curiosity*'s entry, descent and landing. Such scattering is worse when imaging bright, directly-illuminated surfaces; twilight imaging times yield diffusely-illuminated surfaces that improve the clarity of the resulting MARDI product. Twilight images are obtained between 10-30 minutes after local sunset, governed by the timing of the end of the no-heat window for the camera. Techniques applied to terrestrial gravel surfaces representative of depositional and modification processes were also investigated, including sites from the Kau Desert in Hawaii and near Askja Caldera in Iceland from controlled field experiments by MCM. Methods employed include hyperbolic size distribution (LHD) analysis [2,3,4] and Delauney Triangulation (DT) inter-clast spacing analysis [5,6]. This work extends the initial results reported in Yingst et al. [7], that covered the initial landing zone, to the Rapid-Transit Route (RTR) towards Mount Sharp.

Observational Approach: Clast sizes were measured from the MARDI Twilight images in a 2-pass approach that initially identified all candidate clasts larger than 2mm in mean diameter and later supplemented by filtering out questionable clasts using a set of "filters" developed on the basis of experience and validation by the MMM team. A dataset consisting of mean clast diameters and other size parameters was then binned and fed into a hyperbolic distribution fitting algorithm for objective particle size distribution analysis, following the approach first suggested by Bagnold in the 1940s [2,4,7]. The resulting probability density functions for each distribution are compared on the basis of specific goodness of fit and related parameters, including mean, variance, skewness, kurtosis, sorting index (Mean/Variance), and *Cramer von Mises* goodness of fit. In cases where the single distribution of clasts did not meet a reasonable criterial for goodness of fit (CvM <0.1), an iterative process was employed to separate the finer fraction ($d< 0.48$cm) from the coarser ($d\geq 0.48$ cm). The hyperbolic distributions were then compared using simple computational methods related to the shapes of the hyperbolic distribution functions in log-log space and correlated with several terrestrial examples (i.e., Kau tephra, Icelandic sub-glacial debris; **Fig. 2**). This approach is illustrated for disparate martian gravel surfaces in **Figure 1**. Extremely diverse gravel surfaces such as that at Sol 359 contrast with the well sorted surface in Sol 371, which closely resembles the rocket plume-modified surface experienced at Sol 0 (Bradbury). Comparisons of martian gravel surfaces as observed by MARDI twilight images and terrestrial process analogue sites are illustrated in **Figure 2**, where examples from the Kau Desert (Hawaii) and a region near Askja in Iceland are featured (from field study sites by co-author M. C. Malin).

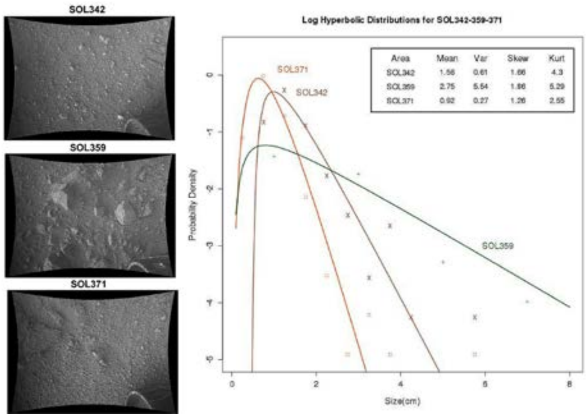

Figure 1: ***Examples of hyperbolic clast size distributions for three disparate populations observed from MARDI Twilight images (Sols 342, 359, and 371). A "sorting index" computed on the basis of the Mean/Variance of clast size demonstrates that the Sol 359 surface is one of the most poorly sorted observed in Gale crater, in contrast with the relatively well-sorted sol 371 surface.***

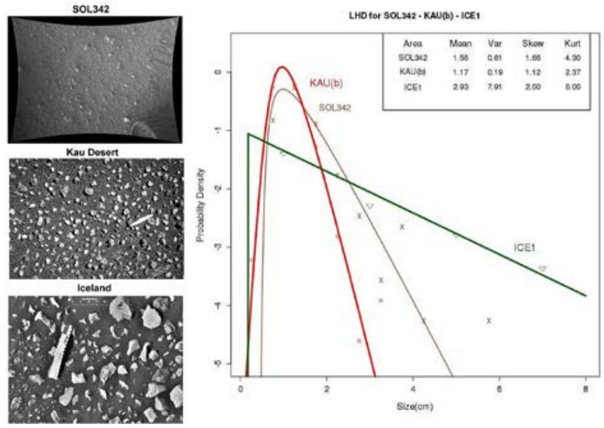

Figure 2: ***Comparison of hyperbolic clast size distributions for Sol 342 (Gale Crater) and those from two terrestrial reference sites: Kau desert (Hawaii) tephra and Icelandic sub-glacial debris near Askja caldera. Note the similarity between the distributions at Kau and Sol 342 and the contrast with the more poorly sorted Icelandic site. Development of a simple model to explain the evolution of such distributions is underway for the gravel sites on Mars.***

Additional Techniques: While the Hyperbolic clast size frequency analysis reveals the character of the gravel size distribution (see Figs. 1, 2), it does not capture the geometric aspects of the spacing of clastic particles and any associated patterns. In combinatorial geometry, the Delauney Triangulation (DT) approach is a well-trusted methodology for measuring inter-particle spacing statistics and allows for the computation of a "*Spacing Index*" on the basis of the Mean/Variance ratio of the resulting vector distances [5, 6]. **Figure 3** illustrates a DT spatial analysis of the Sol 310 surface observed by MARDI (in twilight) near *Shaler*. This was the first MARDI Twilight image acquired during the MSL mission and illustrates a *Spacing Index* (*Mean/Var* of inter-clast spacing distances) of 1.54, which is intermediate between the maximum values observed of ~ 2.0 (Sol 342) and the lowest values recorded at Gale thus far (Sol 371 value of ~ 1.30). Relative to the extremely regular spacing of tephra clasts at the Kau Desert (Hawaii: see **Fig. 2**), where the *Spacing index* approaches 1.10, the sol 371 value is very low for the 35 surfaces measured thus far in Gale Crater. We are currently comparing the martian results from our analysis of more than 35 gravel sites imaged by MARDI (at Twilight) with terrestrial process "reference sites" in Hawaii, Iceland, and in the Antarctic Dry Valleys.

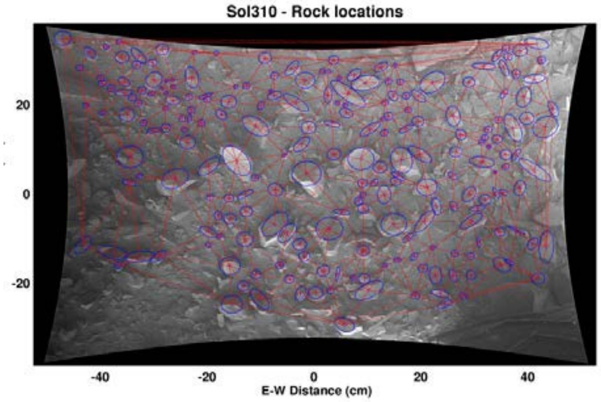

Figure 3: ***Delauney Triangulation (DT) analysis of the 217 clasts measured in the size frequency analysis of the MARDI twilight image acquired on Sol 310. The mean spacing between clasts (from DT analysis) is 5.1 cm, with a Mean/Std. Deviation ("Spacing Index") of 1.54, which is a relatively common value for the 35 sites in Gale crater for which this type of analysis has been conducted.***

DISCUSSION: We have applied the methods discussed here to more than 35 locations imaged by MARDI under twilight conditions. Various trends have been identified on the basis of our ongoing analysis, including variations in clastic particle sorting along the RTR that appear to correlate with localized geologic units. Spatial analysis of the measurements from the MARDI images together with those from other sensors is underway at the time this report was submitted (early 2014).

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REFERENCES: [1] The front element of the MARDI lens is covered with dust that scatters bright light and reduces the image contrast and quality. Twilight illumination reduces the effects of scattered light and produces substantially better images; [2] Garvin J. B et al. (2013)., *44th LPSC*, # 2493; [3] R. L. Folk (1970) *Petrology of the Sedimentary Rocks*, Hemphill, TX, 170 pp.; [4] Bagnold R. and O. Barndorff-Nielson (1980) *Sedimentology 27*, 199-207; [5] Guibas L and A. Stolfi (1985) *ACM Trans. Graphcs Vol 4*, 74-123; [6] Ruppert J. (1995) *Journal of Algorithms. Vol. 18 (no. 3)*, pp 548-585; [7] Yingst A. et al. (2013) *JGR Planets, Vol. 118*, pp 1-20.