CONSTRAINTS ON THE TRANSPORT OF MATERIALS AT FIVE MARS LANDING SITES USING CLAST MORPHOLOGY. R.A. Yingst[1], L. Crumpler[2], J. Garvin[3], S. Gupta[4], L.C. Kah[5], and R.M.E. Williams[1]; [1]Planetary Science Institute (1700 E. Fort Lowell, Suite 106, Tucson, AZ 85719;yingst@psi.edu).

Introduction: Clasts (here defined as loose pebble- to cobble-sized rock fragments on the surface) can provide important clues to bedrock geology where bedrock outcrop is either poorly exposed or cannot be readily accessed. This is especially important on Mars, where access to primary sources of information (outcrop, laboratory sample analysis) is highly limited. Because they represent fragments dislocated from their parent outcrop, clasts also retain a primary record of transport processes, weathering history, and evolution of sediment [1-3]. Morphologic parameters such as size, shape (sphericity, form), roundness, sorting (range and proportion of clast sizes), and clast distribution (size-frequency and distances between clasts) all may be quantified and used to interpret clast history. We conducted an analysis of morphologic characteristics of surface particles at five different landing sites (Viking 1 and 2, Mars Pathfinder, Spirit at Columbia Hills, and Curiosity at Gale Crater), to identify types of clasts and potentially infer origin and transport history of discrete clast populations.

Prior studies: Clast characteristic assessment in this size range is a standard analysis technique for terrestrial sites [e.g., 4-8], especially at sites for which the particle transport mechanism is not clear. Previous efforts to assess characteristics of martian clasts have focused primarily on size or size-frequency distribution, and qualitative shape and roundness. For the Viking 1 and Viking 2 landing sites, quantitative characteristics such as size-frequency distribution and two-dimensional sphericity (also known as elongation [2,9]), and qualitative ones such as form, visually determined roundness, texture, cavity characteristics and the presence and distribution of surrounding sediments, all have been analyzed to determine general clast lithology [10-13]. For the Mars Pathfinder (MPF) landing site, studies of clast morphology included examination of general characteristics and setting (e.g., location, size, aspect ratio and size-frequency distribution [14]). Surface materials were also analyzed for shape, texture and other associated features that might indicate fluvial activity [15,16], impact [17], or eolian activity [18,19]. Studies of clasts at the MER and MSL sites include rock abundance and size-frequency distribution [20,21] qualitative shape and roundness [22] and the presence and morphology of associated features such as hollows (circular soil-filled depressions with rocky rims) [20,21].

Data and method: For the Viking and MPF missions, we used panoramic mosaics of each site in the highest resolution available. For rover missions, surface mobility allows lateral changes in clast characteristics to be assessed. The need for a systematic survey using a mobile platform led to the design of the first clast survey observation for the Mars Exploration Rovers (MER). This observation consists of a single image acquired from each camera eye from a standard viewing angle (where resolution is maximized by look as close to nadir as the camera mechanism allows without being occulted by rover hardware). The survey is acquired at the end of every drive nominally. The clast survey was also adapted for use by the Mars Science Laboratory (MSL) Mastcams [23]. Thus, for roving missions (Spirit and MSL) we utilized the clast surveys as our primary dataset.

A comparative study that covers multiple landing sites imaged from multiple platforms requires constraints to avoid bias potentially introduced from differences in instrumentation, resolution, and distance to the imager. We thus assessed only those clasts pebble- to cobble-sized, within 4 m of the imaging platform. Additionally, we were limited in our comparison to those clast characteristics that were measured for this clast size range for all studies.

Comparison of clast populations: Prior studies of clast morphology separated out surface clasts into a number of different classes or types based on characteristics that were specific to the locality of the mission in question. But clast morphology is a product of clast origin and environment. Since these parameters are different for each Mars landing site, and since they change laterally, direct comparison of clast types or classes among disparate sites is not always appropriate. Indeed, Garvin et al. [13] demonstrated that for Viking 1 and 2, different morphologic characteristics were important discriminators at different sites. Comparing one local clast type to another from site to site must be done with great caution. However, this also implies that any similarities in combinations of characteristics seen across locations may be instructive, because they may indicate commonalities in clast alteration process.

The single most common characteristic for clast types is angularity; nearly every clast type categorized in previous works [22-25] is sub-angular to very angular. This is in contrast to terrestrial clasts that often exhibit a range of roundnesses, even within a single population (e.g., [9]). **Figure 1** shows qualitative roundness estimates for clasts at each of five Mars sites. The two Viking and Mars Pathfinder (MPF) clasts have profiles with maximum values at angular clasts, while the Spirit and average MSL clasts display a profile that reflects a larger population of sub-rounded rocks. Note, however, that for nearly every population, there are almost no rounded clasts, and the percentage of well-rounded clasts is zero. The exception is the population of rocks near the Link outcrop in Gale crater, associated with a distinctive clast type described by [25]. The peak of this line is shifted towards the rounded end of the population. Additionally and uniquely, there are some well-rounded pebbles and cobbles in the population.

Discussion: While shape tends to be driven largly by lithology, roundness (or angularity) tends to be most influenced by transport process [8]. Thus, the differences in angularity/roundness at these sites indicate that some separation of populations is possible based on mode of transport. For terrestrial clasts, roundness is commonly used as a proxy for time in persistent transport. This implies that the results here indicate transported clasts at these sites have been primarily shaped by turbulent, intermittent processes such as mass wasting, ballistic impact, or sediment-gravity flows (including those involving limited water such as debris flows), rather than longer-acting forces such as sustained fluvial transport. By comparison, the class of rounded pebbles (a large subset of the Link clast population but existing elsewhere in Gale crater) is likely associated with persistent flow; the physical association of these pebbles in some locations with pebble-rich sandstone or conglomerate outcrops supports this hypothesis. This is an important point, because the prior presence of outcrop could then potentially be inferred by the existence of a clast population with unique characteristics that are shared by that particular outcrop. In the case of Gale crater, then, the presence of rounded to sub-rounded pebbles could be considered a proxy for the previous or nearby presence of pebble-rich sandstones or conglomerates. To test this, we are currently assessing the number, distribution and density of rounded pebbles in these outcrops to compare to clast fields where rounded pebbles are abundant. A similar density may indicate *in situ* wear of a pebble-rich outcrop, while a different distribution might mean transport of these pebbles to their present location.

References: [1] Krumbein, W. C., and L. L. Sloss (1963), Stratigraphy and Sedimentation, 660 pp. [2] Folk, R. L. (1974), Petrology of Sedimentary Rocks, Hemphill, Austin, Tex. [3] Pettijohn, F. J., et al. (1975), Sand and Sandstone, pp. 81–82. [4] Wadell, H. (1932), *J. Geol.*, 40, 443–451. [5] Zingg, T. (1935), *Schweiz. Mineral. Petrogr. Mitt.*, 15, 38–140. [6] Krumbein, W. C. (1941b), *J. Sediment. Petrol.*, *11*, 64–72. [7] Sneed, E. D., and R. L. Folk (1958), *J. Geol.*, 66, 114–150. [8] Barrett, P. J. (1980), *Sedimentol.*, 27, 291–303. [9] Dapples, E. C., and J. F. Rominger (1945), *J. Geol.*, 53, 246–261. [10] Moore, H. J., et al. (1977), *J. Geophys. Res.*, 82, 4497–4523. [11] Evans, D. L., and J. B. Adams (1979, *LPSC*, 10th, 1829–1848. [12] Strickland, E. L. (1979), *LPSC*, 10th, 3055–3077. [13] Garvin, J. B., et al. (1981), *Moon Planets*, 24, 355–387. [14] Golombek, M. P., et al. (2003*), J. Geophys. Res.*, 108(E12), 8086. [15] Basilevsky, A. T., et al. (1999), *Sol. Syst. Res.*, 33, 170–186. [16] Murchie, S., et al. (2001), *LPSC*, 32nd, 1825. [17] Hörz, F., et al. (1999), *Science*, 285, 2105–2107. [18] Bridges, N. T., et al. (1999), *J. Geophys. Res.*, 104, 8595–8615. [19] Greeley, R., et al. (1999), *J. Geophys. Res.*, 104, 8573. [20] Golombek, M. P., et al. (2006), *J. Geophys. Res.*, 111, E02S07. [21] Grant, J. A., et al. (2006), *Geophys. Res. Lett.*, 33, L16202. [22] Yingst, R. A., et al. (2007), *J. Geophys. Res.*, 112, E06002. [23] Yingst, R.A. et al. (2013), *J. Geophys. Res.*, 118, 2361–2380. [24] Yingst, R.A., et al. (2008), *J. Geophys. Res.*, 113, E12S41. [25] Yingst, R.A., et al. (2016), *Icarus*, 10.1016/j.icarus.2016.03.001.

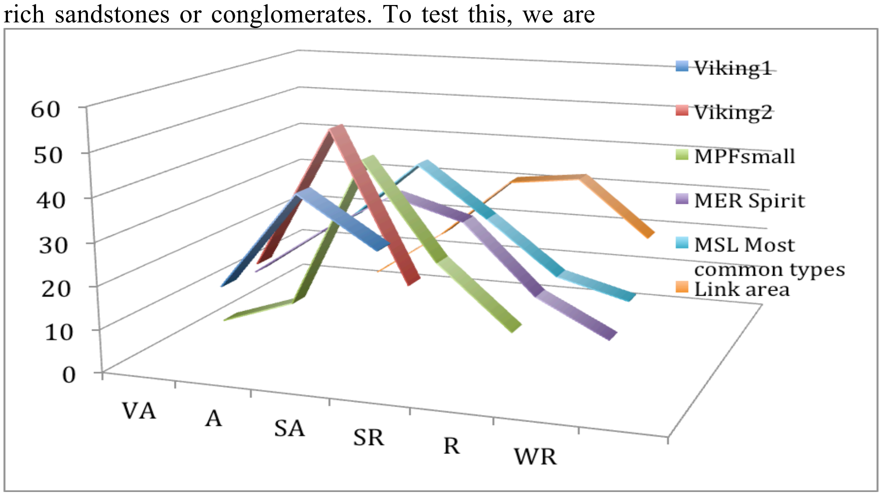

Figure 1. Angularity/roundess values for clasts at five martian landing sites as a percentage of clasts (y axis). Angularity (x-axis) ranges from very angular (VA) to well-rounded (WR).