IRON METEORITE FINDS ACROSS LOWER MT. SHARP, GALE CRATER, MARS: CLUSTERING AND IMPLICATIONS.
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Introduction: Meteorite finds on the martian surface have been reported from the MER-A, MER-B, and MSL rover missions [1,2,3]. Recognized on the basis of distinctive morphological, chemical, and/or spectral properties, confirmed and candidate finds are overwhelmingly iron meteorites (or suspected iron meteorites), likely due to a combination of greater resistance to impact and erosional processes, and ease of detection. Visible and near-infrared imaging, in particular, is highly capable of distinguishing metallic iron-nickel compositions from most common unoxidized and oxidized native martian materials. On NASA's MSL/Curiosity rover, this capability is provided by the Mastcam instruments, a pair of mast-mounted multi-filter stereo CCD imaging cameras [4,5]. Here, we make use of the Mastcam multispectral dataset to add to previous inventories of likely iron meteorites, and speculate on the implication the presence of these finds may have on recent martian climate history.

Methodology: Mastcam images are calibrated to radiance factor (*I*/*F*) by means of pre-flight measurements of the cameras' radiometric response, as well as in-flight measurements of the on-board calibration target to characterize the incident illumination [c.f. 5,6]. Each camera has a filter wheel with broadband and narrowband filters; for "multispectral" imaging (sequences acquired at one pointing through multiple filters), this allows imaging over up to twelve unique wavelength bands that span 400-1100 nm. Due to operational constraints, imaging using subsets of the full filter complement is common; on the Vera Rubin Ridge (VRR), L0356 (left camera broadband RGB (filter 0), narrowband 751, 867, and 1012 nm) is a common survey sequence because it captures both the visible color as well as the near-infrared ferric feature centered near the 867 nm filter, using the wide-angle left Mastcam instrument.

To identify candidate iron meteorites, we search through the multispectral dataset in two ways: 1) by displaying each pointing as a decorrelation stretch of narrowband, near-infrared filters L356 (751, 867, 1012 nm); and 2) by searching for image regions that match explicitly defined spectral characteristics consistent with Fe-Ni meteorites. Decorrelation stretching can be used to produce a false color image that enhances underlying spectral differences, within which anomalous material can usually be identified easily upon inspection. For the latter method, we define "iron meteorite-like" materials as those displaying a grayish visible spectrum and positive near-IR slope, consistent with published meteorite reflectance data from terrestrial samples [7].

False positives can exist as either unusual but native martian materials (some phases such as manganese oxides can exhibit similar spectra [8], but have not been found to be either common or widely distributed along Curiosity's traverse), or coincident combinations of phase, illumination, and spectral characteristics. On the VRR, locally derived float with a weak near-IR band (near zero 751-867 nm slope) but a longer-wavelength positive slope may be expected to be the most common potential mimics, especially when viewed at high phase angles [9]. Most unaltered iron meteorites will have a decidedly positive slope over these wavelengths; however, dust or alteration coatings may result in ambiguous spectra, or cause some to go unnoticed.

Results: Promising candidate iron meteorites identified in multispectral data across the VRR are shown in Table 1. Some of these were also targeted by the ChemCam LIBS instrument [10], whose chemical data is definitive for Fe and Ni identification, and whose dark observations also provide passive reflectance point spectra [11]. In addition to the rocks listed in the table, the total inventory of meteorites found by the rover includes the Aeolis Palus fragments identified by morphology and Mastcam spectra [3], previous candidates from multispectral data [12], and other rocks identified by ChemCam with or without accompanying Mastcam multi-filter observations [13,14,15]. Most commonly, iron meteorites found by Curiosity are cm-sized, appear minimally or only weakly altered, and occur in clusters. Several of the site-drive locations in the table occur fairly close to others; the Lake Orcadie drill area, where the meteorites imaged on sol 1964 were found, was revisited for the Highfield sample and additional meteorites (sols 2222-2235 in Table 1) were identified.

Meteorites and potential meteorites are not the only out-of-place float rocks that can be identified on the ridge in the spectral data; in fact, other float clearly not derived from the adjacent bedrock can be seen contrasting against the reddish-toned, in-place ferric units. Spectral variability among cm-sized grayish-toned rocks is consistent with varying abundances of primary ferrous phases and suggests diverse source regions. It is certainly the case that many of the meteorite clusters co-occur with some of these other float, although less clear how unique that association is, given sampling biases and the small sizes of many of these rocks that makes characterizing their distribution challenging.

Discussion: Perhaps the most salient feature of the collection of MSL meteorite finds is how numerous they are, relative to the MER finds. Within Gusev Crater, meteorite finds from Spirit rover observations were reported only from the Winter Haven location [1]. Opportunity, aided perhaps by the low abundance of native rocks in Meridiani Planum, has found between one and two dozen meteorites [1,2,16,17]. It is difficult to put a precise number on rover finds, for which variable supporting evidence is obtained for each stone (and some are small or unresolved in images), but Curiosity has likely observed several dozen iron meteorites to-date, and many of these in clusters. Some caveats must be placed on comparing finds between missions: operational differences, differences between the camera instruments (Mastcam is similar but not identical to Pancam), ease of detection between sites, and differences in preservation (by burial/exhumation, e.g.).

Despite with these limitations, perhaps the simplest explanation for the number of finds is that Curiosity has happened upon one or more strewn fields, with pre- and/or post-impact fragmentation and erosion inflating the count. It seems reasonable to expect some significant pairing among the Curiosity finds, given the obvious clustering, although this is not something that can be determined from the spectral data. At the Lake Orcadie/Highfield locality, observations by ChemCam LIBS showed chemical variability between individual stones [10], suggesting that at least some of these meteorites may not be paired to some of the others at this site. If they are not paired, then their close proximity is remarkable, and suggests that they were most likely transported to and concentrated at this location. On Earth, meteorite concentration occurs by glacial processes [18], similarly, these finds could be glacial erratics, although under necessarily different climate conditions than exist today.

Conclusions: Long-lived rover missions, including Curiosity, have encountered dozens of meteorites, to which count we add additional likely iron meteorites identified by a careful examination of the MSL/Mastcam multispectral data from the rover's most recent investigations on the Vera Rubin Ridge. Martian surface processes may play a role in meteorite abundances, and documenting the occurrences of these finds may provide insight on the environmental conditions encountered by these meteorites post-fall.

References: [1] Schröder et al. (2008) *JGR, 113,* E06S22. [2] Fairén et al. (2011) *Meteoritics & Planet. Sci., 46,* 1832-1841. [3] Johnson et al. (2014) *AGU Fall Mtg.,* P51E-3989. [4] Malin et al. (2017) *E&SS, 4,* 506-539. [5] Bell et al. (2017) *E&SS, 4,* 396-452. [6] Wellington et al. (2017) *Am. Min, 102,* 1202-1217. [7] Gaffey (1976) *JGR, 81,* 905-920. [8] Arvidson et al. (2016) *Am. Min, 101,* 1389-1405. [9] Johnson et al., this conf. [10] Meslin et al., this conf. [11] Johnson et al. (2015) *Icarus, 249,* 74-92. [12] Wellington et al. (2018) *49th LPSC,* 1832. [13] Meslin et al. (2017) *48th LPSC,* 2258. [14] Wiens et al. (2017) *80th Met. Soc. Mtg.,* 6168. [15] Lasue et al., this conf. [16] Fleischer et al. (2010) *JGR, 115,* E00F05. [17] Ashley et al. (2011) *JGR, 116,* E00F20. [18] Cassidy et al. (1992) *Meteoritics, 27,* 490-525.

Table 1: Candidate iron meteorites from Mastcam multispectral observations, sols 1800-2255.

Sol	#[1]	Site, Drive	Size(s)[2]	Mastcam Obs.	Filter Coverage[3]	Informal Names[4]
1814 1819	many	66, 0 66, 84	< 15 cm	mcam09364 mcam09396	L0356 R0-6	(unnamed)
1821	1	66, 246	~ 5 cm	mcam09401	L0-6, R0-6	"Mustards Island"
1964	1	68, 580	~ 2 cm	mcam10267	L0-6	"Ben Nevis"
1964	1	68, 580	~ 4 cm	mcam10269	L0-6, R0-6	"Black Cuillin"
2013 2016	1	69, 1384 69, 1552	~ 10 cm	mcam10610 mcam10633	L0-6 R0	"North Uist"
2161 2163 2169 2173	2	72, 2272 72, 2272 72, 2464 72, 2464	~ 7 cm each	mcam11638 mcam11652 mcam11681 mcam11719	L0356 L0356 L0-6, R0-6 R0-6	"Stoneyburn" and "Rockend"
2222	1	73, 448	~ 2 cm	mcam11774	L0356	(unnamed)
2229 2229 2231 2231 2235	14+	73, 550	< 5 cm each	mcam11824 mcam11825 mcam11838 mcam11839 mcam11884	L0356 L0356 L0-6, R0-6 L0-6, R0-6 L0356	"Little Todday", "Echt", "Little Colonsay", "Kerrera", and other unnamed rocks
2250 2255	1	73, 722 73, 800	~ 4 cm	mcam12040 mcam12069	L0 L0-6, R0-6	"Newburgh"

[1]Unresolved or inconclusive image data complicates exact counting. [2]Estimate is based on the longest axis and is approximate. [3]Band center wavelengths are 527-445-751-676-867-1012 nm (L1-6, left camera) and 527-445-805-908-937-1013 nm (R1-6, right camera); 0 is broadband RGB in each [4,5]. [4]Most informally named rocks were LIBS targets [10] as well; exceptions are North Uist, Rockend, and Newburgh.