DIVERSITY AND AREAL DENSITY OF IRON-NICKEL METEORITES ANALYZED BY CHEMCAM IN GALE CRATER. P.-Y. Meslin[1], D. Wellington[2], R.C. Wiens[3], J.R. Johnson[4], J. Van Beek[5], O. Gasnault[1], V. Sautter[6], I. Maroger[1], J. Lasue[1], P. Beck[7], J. C. Bridges[8], B. Cohen[9], J.W. Ashley[10], A.G. Fairén[11,12], H. Newsom[13], A. Cousin[1], O. Forni[1], F. Calef[10], W. Rapin[14], S. Maurice[1], B. Chide[1], S. Schröder[1,15], W.Goetz[16], N. Mangold[17], T. Gabriel[2], N. Lanza[3], P. Pinet[1]. [1]IRAP, UPS-CNRS, Toulouse (pmeslin at irap.omp.eu). [2]ASU, AZ. [3]LANL, Los Alamos, NM. [4]APL, Laurel, MD. [5]Malin Space Science Systems. [6]MNHN, Paris. [7]IPAG, Univ. Grenoble. [8]Univ. Leicester. [9]NASA Marshall, Huntsville, AL. [10]JPL, Pasadena, CA. [11]CAB, Spain. [12]Cornell Univ., N.Y. [13]Inst. of Meteoritics, Albuquerque, NM. [14]Caltech, Pasadena, CA. [15]DLR, Berlin. [16]MPS, Göttingen, Germany. [17]LPG, Nantes.

Introduction: On its ascent to Mount Sharp and before reaching the Vera Rubin Ridge, the *Curiosity* rover identified 12 iron meteorites or clusters of potential meteorite fragments [1-4], along a ~18 km traverse. They were identified by remote imaging, using MastCam and ChemCam Remote Micro-Imager (RMI), by multispectral imaging [3] and by chemical analysis using ChemCam's LIBS technique [2, 4]. This dataset extends the number of Martian finds that have been observed by the MER rovers (18 finds with pairs, incl. 10 iron meteorites) [5-7]. These analyses provide additional information that is of interest for 1) better understanding the fate of meteoroids through the Martian atmosphere and the associated craters size distribution and current resurfacing rate [8-10]; 2) reconstructing past variations of the atmospheric density [8]; 3) estimating the delivery of meteoritic material to the surface of Mars; 4) assessing the physical and chemical weathering conditions that prevailed since their fall [11,12].

Since sol ~1800, Curiosity has been exploring the Vera Rubin Ridge (VRR), a ~250 m wide ridge that runs along the northwest side of Aeolis Mons. The rover crossed it several times in search for suitable drill targets. The slow pace of the VRR exploration allowed us to implement a complementary approach between the MastCam and ChemCam identification and analytical capabilities: candidate iron meteorites were detected by multispectral imaging [13] and then analyzed by ChemCam if lying within its operational range (the meteorite Stoneyburn was successfully analyzed at ~8.5 m). Although multispectral coverage was more systematic on the VRR than across previous geological units, the rover did not intentionally deviate from its route to analyze meteorite candidates that were out of reach for ChemCam, limiting potential sampling biases.

New finds: Among MastCam candidates within ChemCam's reach [13], 9 targets were confirmed to be iron meteorites by ChemCam. This represents a 100% success rate, confirming the robustness of the multispectral identification. A systematic survey of high (Fe, Ni) points in the entire ChemCam dataset led to 4 detections of meteoritic debris dispersed in the regolith, only one of which could be resolved in RMI images (Crystal Spring #7).

Chemical composition: Rasters of 5 to 9 LIBS points each consisting of bursts of 30 to 150 laser shots were typically used to analyze these meteorites, at a scale of ~300 µm/point and over depths ≤ 25 µm. On a few samples, additional measurements (where the laser irradiance was intentionally varied) were acquired to test the sensitivity of our analyses to distance and focus quality ("Z-stacks"). Detailed chemical classification of these meteorites is limited by the fact that Ga, Ge, Ir and Au are below ChemCam's limit of detection. Cobalt, at typical levels of ~0.5 wt% in iron meteorites, was not detected either. However, ~70 emissions lines from nickel were detected, which allowed us to quantify this element (Table 1) and to determine whether nearby meteorites originated from the same fall or not. Nickel quantification was obtained in the lab by analyzing iron meteorites and (Fe, Ni) alloys with a ChemCam replica, using the 305.17 and 305.52 nm Ni lines, and using an adjacent iron line for normalization. Phosphorus was detected in Egg Rock #9 (schreibersite inclusion) [2] and a faint P signal was detected in a Black Cuillin Z-stack. Otherwise, each meteorite has a homogeneous composition. Sulfides, Cr-rich phases and silicate inclusions were not detected. Surface alteration can be assessed by the analysis of O, H and Cl peaks [2], although it can be obscured by the presence of a dust coating, whose thickness was found to vary significantly between samples. No evidence for strong chemical alteration was found.

Areal density: As of sol 2275, a total of 11 iron meteorites were analyzed by ChemCam (incl. Crystal Spring #7, but not smaller debris, which could also be metal nuggets relic from impact- or aqueously altered chondrites), among which 8 were found on VRR (Table 1). The land surface area scrutinized by the MSL team for daily ChemCam analyses was estimated in two ways: 1) by estimating the total areal coverage of the Navcam images of the near-field workspace (< 4.5 m); 2) by counting the number of stops where ChemCam did operate and by considering a typical region around the rover over which ChemCam targets are selected. The total surface area covered along the ~20 km rover traverse was between ~8700 m^2 and ~12000 m^2. This yields an average areal density of ~ 800 irons/km^2 (the Ni content was used to discriminate different falls, and Stoneyburn was excluded because it was identified outside the usual rover workspace radius). This estimate is a lower limit, as small or dust-covered iron meteorites were likely missed in the workspace (the largest surface area above was thus chosen in this estimation, for consistency).

Comparison to chondrites: Over that same area, based on pre-rover modeling estimations, the presence of ~5 to 5000 stony meteorites greater than 10 g in mass may be expected, depending on the rate of oxidative weathering and

Name	Sol	Geological Unit	Size	Analysis	Ni/Fe peak ratio ± raster std dev.	Ni (wt%) ± 2σ
Babrongan #10	605	Kimberley	Not resolvable - Mixed with regolith	1 point, 30 shots	-	-
CC_BT_0686a #7	686	Bradbury	Not resolvable - Mixed with regolith	1 point, 30 shots	-	-
Crystal Spring #7	727	Stimson	~2 mm	1 point, 30 shots	0.252	-
Tintic #1	910	Marias Pass	Not resolvable - Mixed with regolith	1 point, 10 shots	-	-
Aeolis Mons 001 (Egg Rock)	1505	Sutton Island	~4 cm	9 points, 30 shots	0.214 ± 0.026 (without pt #9)	4.8 ± 0.7 (without pt #9)
Aeolis Mons 002 (Ames Knob)	1577	Sutton Island	~8 cm	3 points, 30 shots	0.384 ± 0.017	11.7 ± 2.4
Mustards Island	1821	VRR	~4 cm	5 points, 150 shots	0.559 ± 0.024	19.5 ± 1.8
Black Cuillin (+ Z-stack)	1971 (+ 1980)	VRR	~4 cm	9 points (+1), 30 shots (+ Z-stack)	0.311 ± 0.020	8.6 ± 2.0
Ben Nevis	1981, 1985	VRR	~1 cm	9 points, 30 shots	0.198 ± 0.027	4.2 ± 0.4
Stoneyburn	2172	VRR	~7 cm	2 points, 30 shots	0.393 (uncertain)	Uncertain
Little Todday (+ 2 Z-stacks)	2232 (+ 2239, 2243)	VRR	~3 cm	5 points (+2), 30 shots (+ 2 Z-stacks)	0.269 ± 0.012	6.9 ± 1.6
Echt	2233	VRR	~4 cm	5 points, 30 shots	0.374 ± 0.014	11.2 ± 2.3
Kerrera	2244	VRR	~2 cm	3 points, 30 shots	0.321 ± 0.021	9.0 ± 2.1
Little Colonsay	2245	VRR	~2 cm	5 points, 30 shots	0.651 ± 0.019	23.7 ± 1.0

Table 1. Characteristics of iron meteorites analyzed by ChemCam (LIBS).

flux of meteorites to the surface [14]. So far, only 2 chondrite candidates have been identified in the ChemCam dataset (over ~20000 LIBS points) [15], which tend to support the "high weathering - low flux" scenario of [14]. Based on a comparison to terrestrial observations, where iron meteorites represent 4% of all falls, and assuming a similar alteration rate of stony and iron meteorites at the surface of Mars, at least ~150 ordinary chondrites and ~10 carbonaceous may have been present in the workspace. The presence of only 2 candidates suggests a much higher rate of weathering of chondrites relative to iron meteorites in the Martian environment, a different distribution of impactors, or could reflect their lower resistance to impact.

Accumulation of iron meteorites on the VRR: MastCam multispectral imaging has revealed a significant increase in the surface density of iron meteorites on the VRR [13]. To reconcile this observation with the lower deflation or abrasion rate of VRR sediments relative to previous Murray lacustrine sediments, either 1) the weathering of iron meteorites was also faster in the lower Murray formation, and their weathering timescale was significantly shorter than the timescale necessary to erode the differential ~200 m thickness of sediments of the lower Murray formation, 2) the VRR finds are mostly fragments of a few large impactors, or 3) a transport process led to their accumulation on VRR. For instance, if the VRR represented at some point in the deflation history of Gale crater a local depression with steep walls, iron meteorites may have accumulated there by gravity. Alternatively, glacial transport may have been involved in a relatively recent past [13,18] (i.e., younger than the weathering timescale of these objects). Of particular interest is the location explored twice by the rover over sols 1962-1985 and 2222-2250, where more than 14 pieces of meteoritic fragments have been identified in the direct vicinity of the rover [13]. Surprisingly, their chemical analysis shows that the 6 samples targeted by ChemCam have distinct (and homogeneous) Ni/Fe ratios. Therefore, they most likely represent different falls. The chemical analysis thus provides strong support to the third scenario above. It should be noted that another lag deposit of float rocks [16] was observed ~300 meters away on the ridge.

Residence time estimate: The meteorites detected by *Curiosity*, much smaller than the MER finds, are the first cm-sized iron meteorites found at the surface of Mars. They correspond to the smallest iron meteoroids (~ 1 cm) predicted to hit the surface of Mars at crater forming speeds under current atmospheric pressure [9]. With a size > ~1 cm, such meteoroids may form craters with a diameter > ~0.3 m [9]. The lack of such craters around the meteorites detected by *Curiosity* could be explained by the fact that the falls were unable to create an impact crater (e.g., they had a low impact energy), that they are post-impact fragments dispersed upon impact, or that their lifetime is longer than the time needed to erode these craters away. The systematic lack of associated craters could indicate that at least a few of them fall in the third category, in which case their minimal residence time would be ~6 Myr [2]. Alternatively, they may have fallen into an ice sheet, as proposed for Meridiani meteorites [11]. If the concentration process responsible for their high abundance on VRR is a glacial process [18], as proposed by [13], then their residence time was at least 5.5 Myr, the last time the planet's obliquity was ~45°, a regime where the accumulation of ice at equatorial latitudes is predicted by climate models [17], although not specifically in Gale crater.

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