EGG ROCK ENCOUNTER: ANALYSIS OF AN IRON-NICKEL METEORITE FOUND IN GALE CRATER BY CURIOSITY. P.-Y. Meslin[1], J.R. Johnson[2], O. Forni[1], P. Beck[3], A. Cousin[1], J. Bridges[4], W. Rapin[1], B. Cohen[5], H. Newsom[6], V. Sautter[7], E. Lewin[3], M. Nachon[8], R.C. Wiens[9], V. Payré[10], O. Gasnault[1], S. Maurice[1], A.G. Fairén[11,12], S. Schröder[1,13], N. Mangold[14], N. Thomas[15]. [1]IRAP, UPS-CNRS, Univ. Toulouse (pmeslin@irap.omp.eu). [2]APL, Laurel, MD. [3]IPAG, Univ. Grenoble. [4]Univ. Leicester, UK.[5]NASA Marshall, Huntsville, AL.[6]Inst. of Meteoritics, Albuquerque, NM. [7]MNHN, Paris. [8]UC Davis, Davis, CA. [9]LANL, Los Alamos, NM. [10]Univ. Lorraine, Nancy. [11]CAB, Spain. [12]Cornell Univ., USA. [13]DLR, Berlin. [14]LPG, Nantes.[15]Caltech, Pasadena, CA.

Introduction: On sol 1505, while crossing the Murray Formation on its ascent route to Mount Sharp, at a drive distance of ~14.7 km from the Bradbury Landing site, Curiosity encountered a small iron-nickel meteorite, informally named Egg Rock. This is the third meteorite identified by the rover. Previous finds were first observed on Sol 634 [1] at a distance of ~4.3 km from Egg Rock. They consisted of two large meter-sized boulders (Littleton and Lebanon) separated by ~20 m. Lebanon was accompanied by a smaller piece (~0.3 m) named Lebanon-B. Their distance to the rover (~12 m at closest approach) only allowed the team to observe them by remote imaging (MastCam and ChemCam RMI), including VNIR multispectral reflectance spectroscopy (MCAM) [1]. Egg Rock is therefore the first meteorite found in Gale crater whose chemical composition could be measured. It was done so by the ChemCam instrument, using the LIBS technique, and passive VNIR spectra were also collected with ChemCam and Mastcam images. This discovery extends the number of Martian finds that have been observed elsewhere on Mars by the MER rovers (22 finds with pairs, incl. 8 iron meteorites, 3 of which have been analyzed more extensively: Heat Shield Rock, Block Island and Shelter Island) [2-4]. Hence, it provides additional information that is of interest for 1) better understanding the fate of meteoroids through the Martian atmosphere and the associated craters size distribution [5-7]; 2) estimating the delivery of extraterrestrial material to the surface of Mars; 3) assessing the physical and chemical weathering conditions that prevailed since their fall [8,9].

Size and texture: Egg Rock is a ~4×5 cm meteorite, whose shape appears to be near-hemispherical or possibly bowl-shaped (although images were acquired from a single viewing angle, preventing us from obtaining a 3D model). With an assumed density of 7.9 $g.cm^{-3}$, its mass should be of the order of 200 g (± 50%). It is significantly less massive than the iron meteorites found by the MER rovers (50 to 240 kg) [7] and by MSL (~8000 kg), and thus represents a new category of iron meteorite sizes found at the surface of Mars, which could correspond to the smallest iron meteoroids (~ 1 cm) hitting the surface of Mars at crater forming speeds under current atmospheric pressure [6]. It has a lustrous blue-gray color. Its exposed surface is rounded and devoid of angular features that would suggest fracturing or fragmentation [7], although the meteorite seems to have a cavernous interior. It exhibits oval shaped depressions that are most likely regmaglypts resulting from ablation during atmospheric entry. This thus suggests that at least this side of the meteorite was exposed during the atmospheric entry stage and has had limited physical weathering since its fall. It is thus unlikely to be the remaining portion of a once larger meteorite that was weathered away. Nonetheless, it contains smooth and elongated finger-like protrusions, and cavernous and elongated hollows (lamellae-like, sometimes with sharp edges) that could result from ablation during entry or *in situ* differential alteration of less-resistant inclusions. MCAM color images reveal the presence of purple-hued surface patches for which MCAM reflectance spectra are consistent with ferric materials. Other regions' VNIR spectra are consistent with lab spectra of iron meteorites. The very shiny laser pits, the preserved regmaglypts, and the presence of some faint banding on its best exposed face, however, suggest very limited post-fall surface alteration.

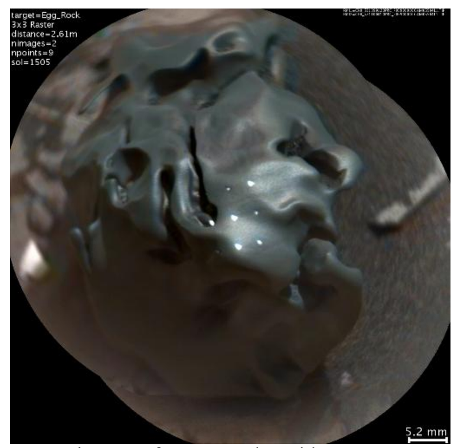

Figure 1: RMI image of Egg Rock, with Mastcam merge for colorization. Laser pits are indicated and numbered in red.

Chemistry: The chemical composition of Egg Rock was measured by LIBS spectroscopy at nine locations, at a scale of ~400 µm. Thirty shots (i.e., spectra) were recorded on each point, providing insight into possible chemical gradients with depth (the estimated analysis depth remains to be established for this type of material). Two groups of points can be distinguished. Points #1, 2, 3, 4, 5, 7, 8 show quasi-identical spectra, dominated, as expected, by iron peaks. The second element identified in these points is nickel. Comparison of Egg Rock spectra with spectra acquired in the laboratory with the instrument replica on unaltered and inclusion-free sections of the iron-nickel meteorites Mont Dieu and Muonionalusta [10,11] show very similar results, suggesting that Egg Rock contains a similar Ni abundance of ~8wt%. No other element has been identified in these points. Although a few emission lines remain to be identified in the spectra, we can rule out the presence of S, Cr, P, Co, C or silicate phases in significant amounts in these points. This together with the Ni content indicate that the face of Egg Rock analyzed by ChemCam is mostly made of kamacite (α-(Fe,Ni)). This result is similar to that obtained on Heat Shield Rock by Opportunity [2,4,12].

Point #9, located right on the edge of an elongated cavity, differs from the previous points by its larger Ni and P contents. This concomitant increase suggests the presence of schreibersite $(Fe,Ni)_3P$, an iron-nickel phosphide. The intensities of the Ni and P peaks are consistent with a mixture of schreibersite and kamacite. Point #6, located on an opposite edge of this cavity, also reveals the presence of phosphorus, albeit in lower concentration, which suggests the presence of a small proportion of schreibersite there too. The weaker P signal may also be due to a degraded focus quality, as point #6 is deeper in the cavity.

Surface coating/rind: Each depth profile shows the presence of a thin dust layer covering the surface of the meteorite, despite its lustrous aspect. This is evidenced by the presence of Mg, Si, Ca, etc. peaks that rapidly decay with depth. Residual peaks from this dust coating are visible through the 5 first shots in the first group of points, while the iron peaks reach their steady intensity after only 2 shots. In points #9 and #6, on the other hand, the dust signature, although rapidly decaying and superimposed over the strong Fe lines, persists over ~15 shots.

Typical alteration phases of metallic iron in meteorites in the presence of trace amounts of water are iron oxides or oxyhydroxides, including goethite, lepidocrocite, magnetite, maghemite and akaganéite, which sequesters its chlorine from the environment [3]. These phases could be detected by enrichments in O, H and Cl (for akaganéite). The oxygen signal measured by ChemCam, however, is dominated by the oxygen signal stemming from the dissociation of atmospheric CO_2, making this analysis tricky [13]. An unusual C/O ratio, however, could reflect a lower than usual oxygen content (e.g., a lack of oxidation). This approach, however, should be tested first in the lab by comparing the C/O ratio of an oxidized meteorite crust and of its unaltered interior. MCAM spectroscopy suggests Egg Rock is covered by patches of apparently oxidized material. Chlorine is detected in the first shots of the two categories of points, with a stronger and more persistent signal in points #9 and 6. However, it is difficult to decipher whether this signal results from the dust coating described above or from an alteration rind. The hydrogen signal, on the other hand, reveals a strong contrast between the two categories. It decays to a very low level in the first category, suggesting the absence or very limited abundance of oxyhydroxides, while it persists at a high level throughout the depth profiles of points #9, 6.

Discussion: The surface of Egg Rock, except for a few discontinuous patches of oxidized material, appears to be characterized by a low degree of physical and chemical weathering. On the other hand, it exhibits cavernous hollows with a lamellae shape, whose rims appear to be hydroxylated and enriched in schreibersite, which is commonly found in plates or tablets, or rods and needles, embedded in or along grain boundaries of kamacite [14], with sharp edges, as seen here. We therefore suggest that the cavities were filled with schreibersite, or that its presence marks the boundary between kamacite and another phase. Since troilite inclusions are often surrounded by this phosphide, they may also have filled these cavities, but no sulfur was detected on their rim. Since the surface of Egg Rock was only weakly chemically altered, we favor a physical process to weather out these cavities (ablation during atmospheric entry, wind abrasion, or possibly thermally-driven mechanical erosion). Note that schreibersite is very brittle [14]. This phosphide is relevant for the development of prebiotic chemistry and phosphorylated biomolecules, as its corrosion can produce water-soluble, chemically reactive components that constitute more biochemical useful forms of phosphate than apatite [15,16].

Iron meteoroids with a cut-off size of ~1 cm may form craters with diameter ~0.3 m in the current atmosphere [6]. Such a crater is absent, which suggests that the fall was either unable to create an impact crater (e.g., with a low angle entry), that it was displaced there by another impact, or that the time spent by the meteorite at the surface of Mars is greater than the time needed to erode this crater away. In the latter case, taking a diameter of ~0.3 m as a lower limit (because the size of Egg Rock is somewhat larger – and note that the smallest crater diameter found in Gale is ~0.6 m[17]), a crater depth-to-diameter ratio of 0.2 [17], and assuming an erosion rate of ~10 mm/Myr estimated for Gale crater [17], its minimal residence time would be ~6 Myr.

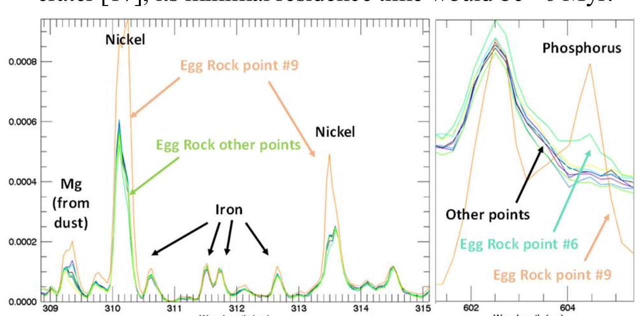

Figure 2: LIBS spectra of Egg_Rock (normalized to iron total intensity), showing the nickel enrichment in pt #9, and phosphorus enrichment in pts #9 and #6.

References: [1] Johnson et al. (2014), *AGU*, #P51E-3989. [2] Schröder et al. (2008), *JGR*, 113. [3] Ashley et al. (2011), *JGR*, 116. [4] Fleischer et al. (2011), *Meteorit. Planet. Sc*., 46. [5] Vasavada et al. (1993), *JGR*, 98. [6] Popova et al. (2003), *Meteorit. Planet. Sc.,* 38. [7] Chappelow and Golombek (2010), *JGR*, 115. [8] Fairén et al. (2001), *Meteorit. Planet. Sc*., 46. [9] Schröder et al. (2016), Nature Comm. [10] Desrousseaux et al. (1996), *Meteorit. Planet. Sc*., 31. [11] Wasson et al. (2001), *GCA*, 65. [12] Morris et al. (2006), *JGR*, 111. [13] Beck et al., this issue. [14] http://rruff.info/doclib/hom/schreibersite.pdf. [15] Pasek et al. (2007), *GCA*, 71. [16] Bryant et al. (2013), *GCA*, 109. [17] Newsom et al. (2015), Icarus, 249.