Classification of Igneous Rocks Analyzed by ChemCam at Gale Crater, Mars. A. Cousin[1], V. Sautter[2], V. Payré[3], O. Forni[1], N. Mangold[4]., O. Gasnault[1], L. Le Deit[4], J. Johnson[5], S. Maurice[1], M. Salvatore[6], R. C. Wiens[7], P.Y. Meslin[1], P. Gasda[7], W. Rapin[1]. [1]IRAP, Toulouse, France; [2]MNHN, Paris, France; [3]Université de Nancy, Nancy, France; [4]LPGN, Nantes, France; [5]Johns Hopkins University Applied Physics Laboratory, MD; [6]University of Michigan-Dearborn, Mi; [7]LANL, Los Alamos, NM

Introduction: The Mars Science Laboratory (MSL) rover Curiosity, which landed in Gale crater in 2012 at the northern edge of the heavily cratered Noachian highlands, discovered evidence of magmatic diversity [1-5], as suggested from recent orbital observations [6,7] as well as from new Martian meteorites such as the regolith breccia NWA 7034 and it paired samples [8-12]. These observations of igneous targets are of great interest as they provide a unique window into the planetary interior (mantle partial melt, magma fractionation or crystal accumulation).

Curiosity's drive began at Bradbury Landing, on a plain at a distal portion of the Peace Vallis alluvial fan [13]. The Curiosity rover has the ability to characterize rock textures and compositions at a variety of distances with its sophisticated payload. Two remote instruments are located on the top of the rover mast. The MastCam instrument [14,15] is a set of 2 cameras mounted on the rover mast that provides critical contextual images. ChemCam is a Laser Induced Breakdown Spectrometer (LIBS) combined with a high-resolution imager (Remote Micro Imager; "RMI" – [16,17]).

For this study, we have used these remote instruments for extensive characterization of igneous rocks. The objective is to classify and review the wide range of igneous rocks observed during the traverse to Mt Sharp from sol 20 to sol 800. The ChemCam instrument gives access to the chemistry of rocks and soils at the sub-millimeter scale and is widely used on Mars due to its tactical ease, as targets can be analyzed up to 7 m away from the rover.

In the present study, we first describe the textures of the igneous targets using the large number of images acquired by the rover, as a means of differentiating intrusive from extrusive rocks. Then the chemistry of the igneous rocks is presented, and their mineralogy is inferred. In tandem, these textural and chemical analyses are used for a petrological assessment of the selected rocks. Finally, distribution of these rocks along the traverse is discussed, as well as their comparison with previous igneous rocks observed in situ by the MER, and with the mars meteorites.

Methodology: The first objective is to differenciate sedimentary rocks to igneous ones. In that purposed we have used images such as those from the MastCam and ChemCam instruments. Rocks showing sedimentary textures such as stratifications were easily to characterize as sedimentary. On the other hand, differentiating extrusive igneous rocks from fine-grained sandstones or pyroclastic flows is more difficult and other morphological criteria were used such as scoriaceous or vesicular surface features and conchoidal fracturing. The present study focuses solely on effusive and intrusive igneous rocks, excluding any putative volcanoclastic rocks. Therefore, samples with any kind of sedimentary features were discarded, with exception of individual pebble analyses. Also, rocks with undefined textures [13] such as Jake_M [1] have been eliminated for this study. More details on rock classification can be found in [13]. Chemical analyses used in this study are obtained from the ChemCam instrument. The quantification of the ChemCam data is described in [18].

Textural analyses: From the analyses of the images, 59 igneous rocks have been detected. We were able to differenciate intrusive from extrusive igneous rocks [19]. Three groups of extrusive rocks have been defined. Group 1 (20 rocks) contains dark and aphanitic rocks, with some conchoidal fractures; Group 2 (10 rocks) consists of porphyritic rocks with elongated whitish elongated phenocrysts (several mm) set in a dark grey mesostasis; Group 3 (6 rocks) represents aphanitic light-toned rocks with sometime vesiculated or pumiceous appearance. Rocks with intrusive textures are organized in 2 groups. Group 4 (10 rocks) contains fine-grained rocks with the same proportion of light-toned and dark-toned crystals, and Group 5 (13 rocks) corresponds to coarse-grained light-toned rocks.

Chemistry and Mineralogy: Assessing the chemistry and mineralogy of the sampled targets is possible by combining the visual observations and some chemical and mineralogical diagrams. For the chemistry, diagrams such as FeO vs SiO_2 and alkali vs Al_2O_3 have been used to differenciate between mafic phases (Fe-rich, alkali and Si-poor) and felsic ones (Si, alkali-rich and Fe-poor). From these diagrams Group 1 shows a cluster with no obvious trends betweens the elements. Group 2 shows points that are enriched in alkali and Si - corresponding to felsic phases, whereas others are more mafic, and correspond to the mesostasis. Group 3 points are all clustered and are alkali-rich, with few points corresponding to Fe-oxides. Group 4 shows a negative mixing trend between Fe and Si, and positive trend between alkali and Al. Finally, Group 5 is low in Fe, enriched in Si, alkali, Al and Ca.

Ternary diagrams were then used to asses the mineralogy, using relatively clean points only (from the visual point of view and from the chemistry). The main feldspar phases observed correspond to andesine (in groups 2, 4, 5), and anorthoclase and few sanidine (Group 3). Zoning between plagioclase and K-rich feldspars was observed in few rocks such as Harrison [2]. Pyroxenes observed in Gale igneous rocks are Fe-rich and Ca-poor, corresponding mainly to Fe-rich pigeonites and Fe-rich augites, which is consistent with the passive observations [20], but different from the sediments analyzed by CheMin [21], showing more Mg-rich pyroxenes. A few apatites were also observed in rocks from groups 1, 2 and 4.

Petrology: When plotting these rocks in a TAS diagram (Figure 1), Group 1 corresponds mainly to basalts with few trachybasalts and tephrites, Group 3 expands the trachyte group described in [2], and Group 4 corresponds to gabbro-norite from its textural analysis and its normative composition (~ 48% plagioclase, ~ 2-10% orthoclase, ~ 30-35 % pyroxene, ~ 5-19 % olivine and ~ 1-3 % ilmenite). In this present study no new rocks from Group 2 (trachyandesites) and Group 5 (quartz-diorite) have been observed since [2], and therefore these two groups are not discussed later.

Discussion: *Igneous rocks along the traverse.* The felsic targets (Group 2 trachyandesites, Group 3 trachytes and Group 5 quartz-diorites) have been observed near the landing site, close to the Peace Vallis alluvial fan. They have been transported by fluvial activity and therefore represent a sampling from the crater northern rim, while the mafic targets such as the basalts and the gabbros are mainly observed later on the traverse. Basalts represent the main type of igneous rocks sampled by ChemCam along the traverse. Nevertheless, the second most common igneous rocks correspond to the quartz-diorites. Moreover, the felsic igneous rocks all together represent up to 49 % of the observed igneous rocks, meaning that feldspars are widespread at Gale crater.

Comparisons with MER and Mars meteorites. Group 1 and Group 4 rock types plot in the TAS diagram close to the field of Columbia Hills and basaltic rocks form Gusev crater (Figure 1). However, looking at the mineralogy, rocks from groups 1 and 4 (as any other igneous rocks at Gale) do not show any olivine phenocrysts contrary to the MER basaltic rocks. Also, most of the Gale basaltic rocks are enriched in Fe (Mg# < 0.5) compared to MER basaltic rocks [22, 23, 24], and therefore the pyroxenes observed at Gale are more enriched in iron. This suggests that the basaltic rocks observed at Gale are more evolved than those observed by the MER. Feldspars observed in the Gale igneous rocks are similar to those of the MER basaltic rocks as well as the Mars meteorites. Fe-rich pyroxenes observed at Gale crater are not uncommon in some Mars meteorites, such as both in a few basaltic shergottites (Los Angeles with pyroxenes Fs_{45-95}, NWA 480, QUE 94201 – [25,26]) and in nakhlites [27,28].

The iron-rich basaltic composition of some of the Group 1 rocks such as Watterson is similar to the Nakhlite parental magma (NPM) [29, 30], which seems to have fractionated to a significant extent from its composition as well as from experimental data [31]. This suggests that the iron-rich type of basalt could be the mafic end-member of the calculated liquid line of descent passing through the rocks of Group 4 which parallels the liquid line of descent calculated by [31].

Group 4 micro-gabbros look like gabbroic shergottites such as Los Angeles, QUE 94201 [32,33] and NWA 7320 [34]. Los Angeles is the most geochemically evolved martian sample with the lowest Mg# (0.14) than any other martian meteorites, and has been interpreted as a part of shallow intrusion proceeded by an episode of fractional crystallization and/or assimilation of older crustal matter [32]. Rocks from Group 4 observed at Gale could result from the same processes.

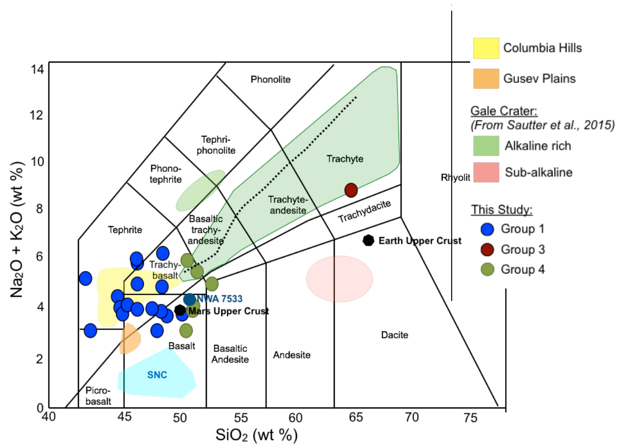

Figure 1: TAS diagram modified from [3].

References: [1]Stolper et al., 2013; [2]Sautter et al., 2014, [3]Sautter et al., 2015; [4]Sautter et al., 2016; [5]Schmidt et al., 2014; [6]Carter and Poulet, 2013; [7]Wray et al., 2013; [8]Agee et al., 2013; [9]Humayun et al., 2014; [10]Nyquist et al., 2016; [11]Santos et al., 2015; [12]Udry et al., 2015; [13]Palucis et al., 2014; [14]Malin et al., 2010; [15]Bell et al., 2012; [16]Wiens et al., 2012; [17]Maurice et al., 2012; [18]Clegg et al., accepted; [19]Cousin LPSC 2015; [20]Johnson et al 2015; [21]CheMin; [22]McSween et al., 2006a; [23]McSween et al., 2006b; [24]Squyres et al., 2006; [25]Mikouchi et al., 2001; [26]Warren et al., 2003; [27]Mikouchi et al., 2003; [28]Treiman et al., 2004; [29]Stockstill et al. 2005; [30]Sautter et al. 2012; [31]Udry et al. (2014a); [32]Rubin et al. 2000; [33]McSween et al. 1999; [34]Udry et al., 2016.