CHEMCAM: ZAPPING MARS FOR 10 YEARS (AND MORE). O. Gasnault[1], N. Lanza[2], R. Wiens[3], S. Maurice[1], N. Mangold[4], J. Johnson[5], E. Dehouck[6], P. Beck[7], A. Cousin[1], P. Pinet[1], J. Bridges[8], G. Dromart[6], T. McConnochie[9], S. Le Mouélic[4], and the ChemCam team[*], [1]IRAP (ogasnault@irap.omp.eu, Toulouse – France), [2]LANL (nlanza@lanl.gov, Los Alamos – USA), [3]EAPS (West Lafayette – USA), [4]LPG (Nantes – France), [5]APL (Laurel – USA), [6]LGL (Lyon – France), [7]IPAG (Grenoble – France), [8]SPA (Leicester – UK), [9]SSI (Boulder – USA).

Introduction and Context: On Mars since 2012, the *Curiosity* rover has been exploring Gale crater, which accumulated fluvio-lacustrine and eolian sediments during the early Hesperian. This mission has studied the geology and past habitability of the terrain traversed, and the modern environment [1].

Recognizable on the rover by its 110 mm diameter telescope, *ChemCam* is capable of laser-induced breakdown spectroscopy (LIBS, from UV to NIR), used for the first time on Mars, passive spectroscopy, and high-resolution imaging [2-3].

A catalog of the compositional diversity is built by repeating these fast measurements with high precision. In 3,700 sols, 930,000 LIBS spectra were acquired over 3,500 unique targets. *ChemCam* data are archived on the PDS and guidelines[§] are available [4].

Geochemistry: Analysis of at least 5 points, each with 30 or more laser shots, gives the bulk chemistry of rocks and soils met along the rover's traverse. The regularity of the measurements allows building a chemostratigraphy. Repeated laser shots on each point can reveal correlations between chemical elements, and depth variations as the laser ablates ~0.6-5 µm per shot [3]. The sub-millimeter size of the laser impacts can give access to the composition of individual phases (e.g., crystals) and small diagenetic features.

Chemostratigraphy. A large volume of river-transported material has filled the portion of Gale crater traversed by *Curiosity* and provides some compositional homogeneity to the fine-grained sedimentary rocks, consistent with limited alteration and an alkali basalt source. Analysis of non-diagenetic and less-altered targets led to the identification of five igneous end-members [5-6]. The most evolved igneous clasts indicate a previously unsuspected magmatic diversity, including unique feldspar-rich cumulates, possible relicts of a primary crust [7-8].

Tracing the stratigraphy from the Yellowknife Bay formation of the Bradbury group to the Mirador formation of the Mount Sharp group, the rover successively identified fluvial conglomerates with igneous clasts [9], fine-grained mudstones and sandstones possible sharing a common source [10]. Further on, fine- to coarse-sandstones from Kimberley formation likely contained alkali feldspars revealing a change in depositional system or sediment provenance [11]. As *Curiosity* entered the Mt. Sharp group at the base of Aeolis Mons, *ChemCam* measurements on fined-grained sediments indicated a gradual increase in the chemical index of alteration (CIA>50) in the Murray formation, interpreted as the transition to an open alteration system consistent with dissolution by liquid water [12] and the detection of smectite clays. Higher in this formation, on the erosion resistant Vera Rubin ridge (VRR), the composition was found to be broadly similar to those of the underlying layers with a decrease in lithium interpreted as dissolution of clay minerals in multiple fluid events [13-14]. After VRR, the rover crossed the Glen Torridon topographic depression, where the main exposure is found to be relatively enriched in K_2O and SiO_2, interpreted as the presence of an illite-smectite mixture [15]; the other exposure type was slightly enriched in MgO and may include small amounts of Mg-sulfates, which are present in the upper stratigraphic layers. More frequent S-rich detections were made in the Mirador formation bedrock [16], with significant Mg sulfate at Canaima.

Diagenetic diversity. The spatial resolution of *ChemCam* permits analyses of small diagenetic features with a remarkable diversity of shape and composition [17]. Nodules, veins, aggregates, ridges, and halos were discovered, with a range of compositions including Ca or Mg sulfates, Fe and Mn oxides, Si-rich materials, and even fluorite [14, 17-20].

These diagenetic phases testify to the evolution of the fluids that interacted with the sediments (composition, acidity, temperature, and depth of burial) in a post-depositional, complex, long-term surface and groundwater system. There were at least two episodes of deposition/burial/exhumation to build the Murray and Stimson formations, with evidence of upwelling groundwater along fractures through the different strata that remobilized and locally precipitated the chemical elements observed in diagenetic features [13, 21]. The presence of high levels of oxides (Fe, Mn) in some areas indicates that redox conditions have varied across locations and/or time [14, 22], requiring oxidants, whose origin remains debated.

The almost ubiquitous presence of hydrated Ca sulfates along the rover traverse attests to a late regional episode of fracturing and filling in the form of light-toned veins composed mainly of bassanite, probably resulting from dehydration of gypsum [23].

The multiplicity of fluid events complicates the modeling of the genesis of diagenetic phases [24].

Soils. In addition to rocks, *ChemCam* has analyzed unconsolidated materials (dust, soil, sand dunes). *ChemCam* is sensitive to the composition, size, coating, and mixing of grains, but in practice the compositional diversity in Gale's soils is only noticeable for coarse grains (>0.5-1 mm) [25]. The fine-grained soil component chemistry was found rather homogeneous, similar to other Mars landing sites and the martian crust, but different from the analyzed rocks, thus possibly resulting from the mixture of several components [26]. Notably, it contains a hydrated fraction in its amorphous component, which seems to be a mixture of Mg, Fe and Ca sulfates [27], and explaining the broad-scale hydration observed from orbit. On the other hand, larger grains showed compositional differences that may result from physical alteration of local rocks, transport, or mixtures as in fine-grained soil [26].

Geologic results from passive spectroscopy. In its passive mode, *ChemCam* determines the relative reflectance of targets (400-840 nm), providing additional information mainly on Fe-bearing minerals. Beyond the overall dusty nature of the landing site, targets with fresh exposures (brushed, broken, drilled, partly cleaned by LIBS) revealed variations in spectral features consistent with presence of Fe oxides (e.g., hematite), rare ferric sulfates (e.g., jarosite), and opaque oxides (e.g., magnetite or ilmenite) [28-29]. Bagnold Dune sands revealed spectra consistent with dominantly mafic grains in the coarse fraction (olivine, high-Ca pyroxene) and ferric materials in the finer grains (e.g., hematite, nanophase Fe-oxides) [30], which is also supported by LIBS analyses [31].

Geological imaging: In addition to the images for spectroscopy, and as the focusing capability was improved, numerous mosaics were taken with *ChemCam* to help establish stratigraphic columns [e.g. 32] by studying distant strata [e.g. 33], flow channels, debris flows, and formations such as the Marker Band recently visited by the rover [e.g. 34-35] or yardangs that may not be accessible [e.g. 34].

Atmospheric Observations: Passive observations of the sky by *ChemCam* were used to derive the abundance of the water vapor column, variation in oxygen abundance, and some aerosol properties [37]. Seasonal measurements of water vapor are broadly in agreement with orbital and *in situ* measurements, but suggest a lower local abundance than at the regional scale with a minimum in northern spring [37-38]. Comparison with daytime *REMS* temporal measurements supports the hypothesis of substantial diurnal interactions between the surface and the atmosphere. *ChemCam* has also found year-to-year variations in ice aerosol opacity and season-to-season variations in dust aerosol particle size [37-38].

On-going Science: The *ChemCam* instrument is working well. The number of measurement points per target has been reduced but these measurements are still almost daily. It has been used continuously in the transition zone between the clay unit and the Mg sulfate unit where the rover is currently located. These recent observations will be presented at this conference [16, 34-35, and many more#].

References[1]: [1] Vasavada A. (2022) *Space Sci Rev, 218,* 14. [2] Wiens R. and Maurice S. (2015) *Elements, 11,* 33. [3] Maurice S. et al. (2016) *J. An. At. Spectrom., 31,* 863. [4] Wiens R. (2013) *NASA Planet. Data Sys.,* 10.17189/1519485. [5] Bedford C. et al. (2019) *Geo. Cosmochim. Acta, 246,* 234. [6] Cousin A. et al. (2017) *Icarus, 288,* 265. [7] Sautter V. et al. (2016) *Lithos, 254-255,* 36. [8] Bowden D. et al. (2023) *Met. Planet. Sci.,* 10.1111/maps.13933. [9] Mangold N. et al. (2016) *JGR, 121,* 2015JE004977. [10] Anderson R. et al. (2015) *Icarus, 249,* 2. [11] Le Deit L. et al. (2016) *JGR, 121,* 2015JE004987. [12] Mangold N. et al. (2019) *Icarus, 321,* 619. [13] Frydenvang J. et al. (2020) *JGR, 125,* e2019JE006320. [14] L'Haridon J. et al. (2020) *JGR, 125,* e2019JE006299. [15] Dehouck E. et al. (2022) *JGR, 127,* e2021JE007103. [16] Rapin W. et al. (2023) *LPSC 54,* this conf. [17] Nachon M. et al. (2017) *Icarus, 281,* 121. [18] Frydenvang J. et al. (2017) *GRL, 44,* 4716. [19] Gasda P. et al. (2022) *JGR, 127,* e2021JE007097. [20] Forni O. et al. (2015) GRL, 42, 1020-1028. [21] Fraeman A. et al. (2020) *JGR, 125,* e2020JE006527. [22] Lanza N. et al. (2014) *GRL, 41,* 5755. [23] Rapin W. et al. (2016) *EPSL, 452,* 197. [24] Turner S. et al. (2021) *Met. Planet. Sci., 56,* 1905. [25] David G. et al. (2021) *Icarus, 365,* 114481. [26] Cousin A. et al. (2015) *Icarus, 249,* 22. [27] David G. et al. (2022) *GRL, 49,* e2022GL098755. [28] Johnson J. et al. (2016) *Am. Min., 101,* 1501. [29] Fraeman A. et al. (2020) *JGR, 125,* e2019JE006294. [30] Johnson J. et al. (2018) *GRL 45,* 9480. [31] Cousin A. et al. (2017) *JGR, 122,* 2144. [32] Rapin W. et al. (2021) *Geology, 49,* 842. [33] Le Mouélic S. (2021) *LPSC 52,* #1408. [34] Gasda P. (2023) *LPSC 54,* this conf. [35] Dietrich W. et al. (2023) *LPSC 54,* this conf. [36] Dromart G. et al. (2021) *EPSL, 554,* 116681. [37] McConnochie T. (2018) *Icarus, 307,* 294. [38] McConnochie T. (2022) *Mars Atm. Model. Obs. conf.,* #3403.

* ChemCam team: https://www.msl-chemcam.com/chemcam/team-bios/
§ Data guidelines: https://openplanetary.github.io/blog/tools/chemcam.html
# See Cousin, Das, Davis, Dietrich, Dimitracopoulos, Essunfeld, Gasda, Hoffman, Lasue, Loche, Manelski, Nellessen, Newsom, Pilleri, Rammelkamp, Rapin, Schröder, Turner
1 All ref.: https://www.msl-chemcam.com/results/publications/peer-reviewed/