ChemCam Top Science Highlights

of the first 3 Mars years

The ChemCam team

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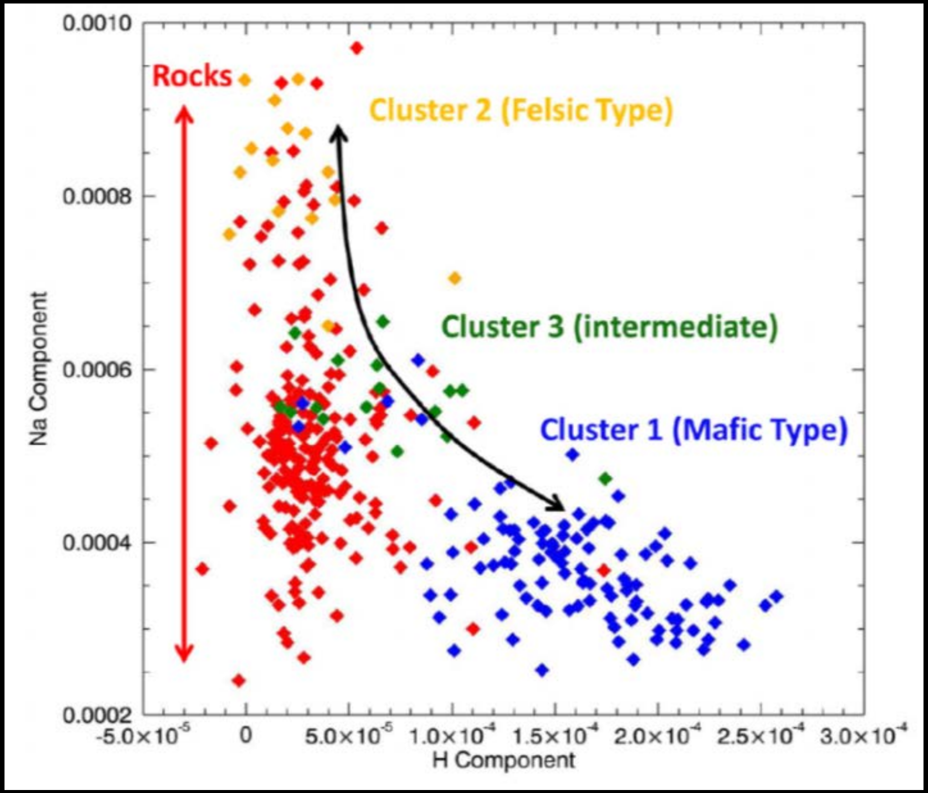
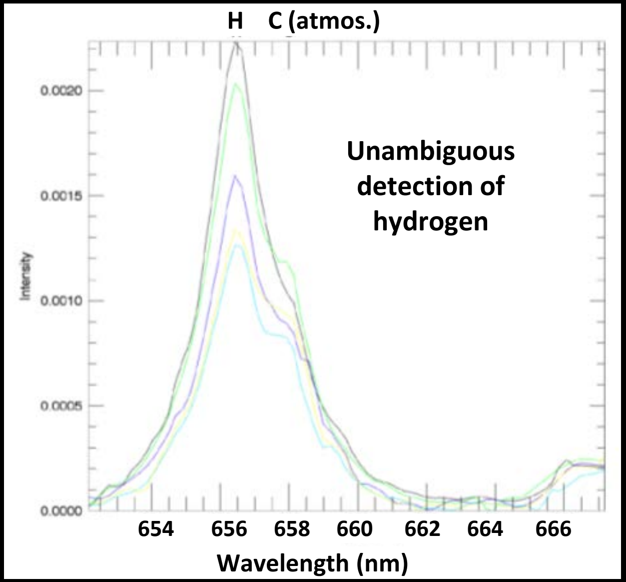
The ChemCam team has exceeded our highest expectations at Gale crater !

1.

Hydrated soil and dust

With the very first laser shot on Mars we discovered that the soil and even the wind-blown dust is hydrated. The SAM instrument quantified the amounts, but ChemCam has shown the ubiquity of water in the soils and has helped constrain the mineral component in the soil containing the water.



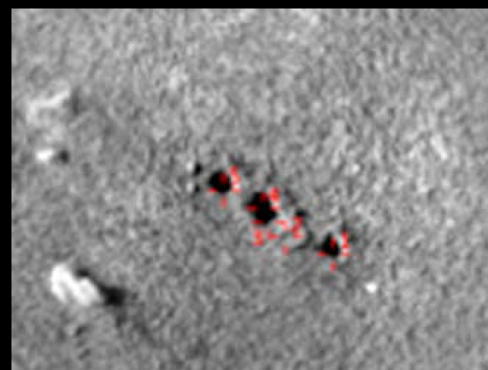


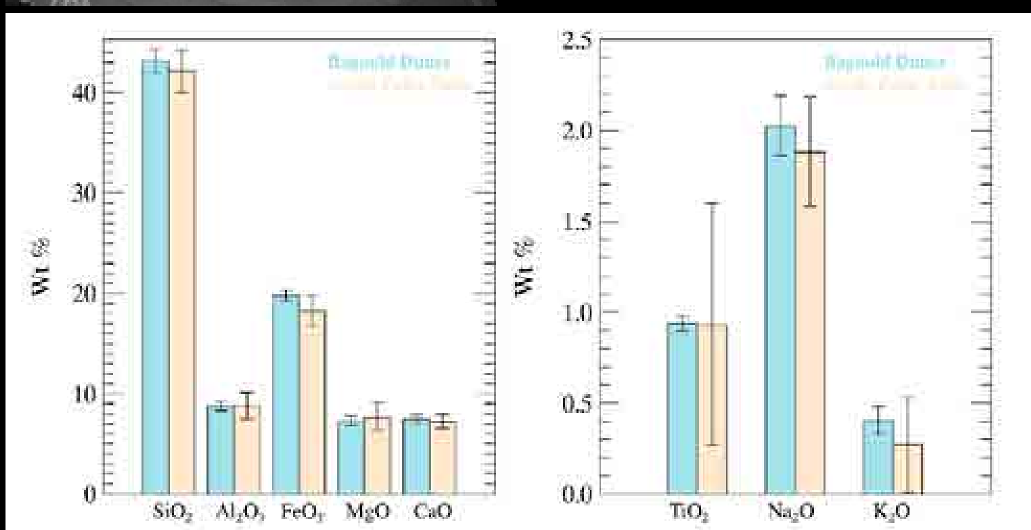
- Schroeder S., et al. (2015) First analysis of the hydrogen signal in ChemCam LIBS spectra. Icarus, 249, 43-61; http://dx.doi.org/10.1016/j.icarus.2014.08.029.

- Meslin P.-Y. et al. (2013) Soil diversity and hydration as observed by ChemCam at Gale crater, Mars. Science 341, DOI: 10.1126/science.1238670.

Composition and multiple phases in soils

ChemCam provides the first microbeam analysis of soils (incl. sand dunes), showing for the first time that all soils we have analyzed so far consist of multiple components including contributions from the local rock types. We can correlate these components with characteristic grain sizes and detect changes between soils.





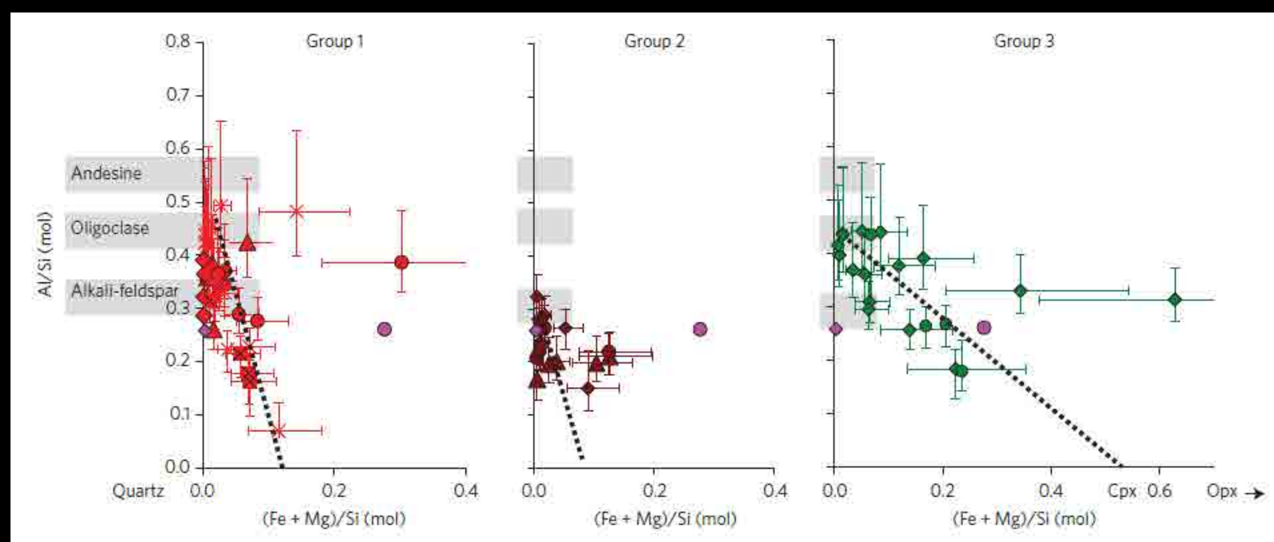
- Meslin P.-Y. et al. (2013) Soil diversity and hydration as observed by ChemCam at Gale crater, Mars. Science 341, DOI: 10.1126/science.1238670.
- Cousin A. et al. (2013) Compositions of sub-millimeter-size clasts and fine particles in the Martian soils at Gale: A window in tot the production of soils. Icarus, in press.
- Cousin A., et al. (2017) Geochemistry of the Bagnold Dune Field as observed by ChemCam, and comparison with other Aeolian deposits at Gale crater. JGR Planets 122, 10.1002/2017JE005261

3.

Felsic igneous rocks (1/2)

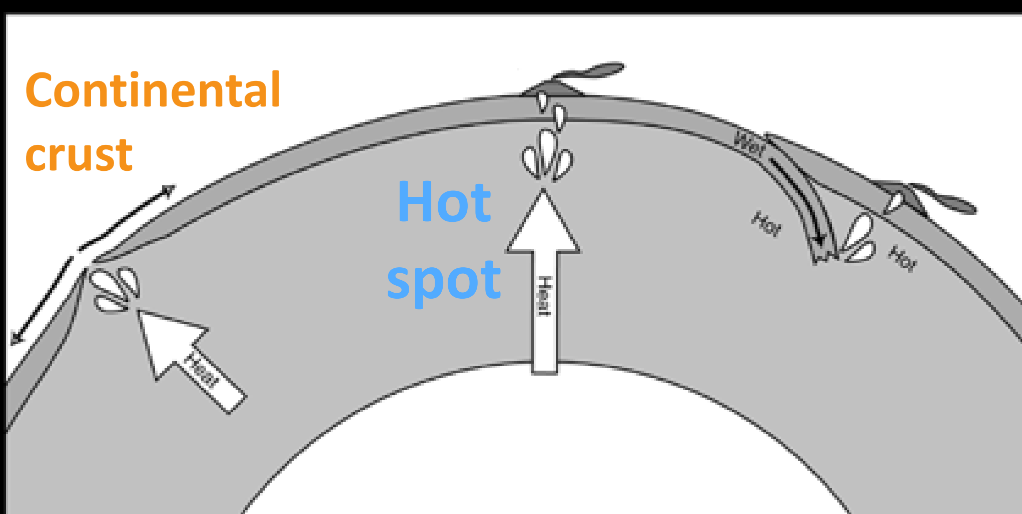
In the first Mars year ChemCam yielded the first felsic (high-silicium, high-aluminum) rock compositions in float rocks found along the traverse, such as trachytic and dacitic chemistry, with identification of feldspars (incl, alkali feldspars). The implication is that the igneous rocks of Mars are more diverse in composition, coming from much more evolved magmas, than previously thought.

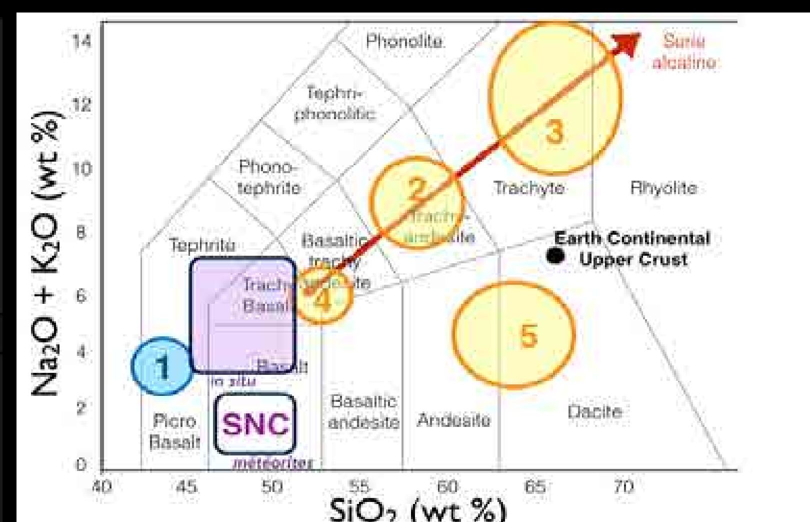
• Sautter V.et al. (2013) Igneous mineralogy at Bradbury rise: The first ChemCam campaign. J. Geophys. Res., 119, 30-46, DOI: 10.1002/2013JE004472.
• Sautter V., et al. (2015) Direct evidence for silica-rich crust in the southern hemisphere of Mars: Implications for Noachian magmatism. Nature Geoscience 8, 605-609, DOI:10.1038/NGEO2474.
• Sautter V., et al. (2016) Magmatic complexity on early Mars as seen through a combination of orbital, in situ, and meteorite data. Lithos254-255, 36-52.
• Cousin A. et al. (2017) Classification of igneous rocks analyzed by ChemCam at Gale crater, Mars. Icarus 288, 265-283.
• Mangold N., et al. (2017) Classification scheme for sedimentary and igneous rocks in Gale crater, Mars. Icarus 284, 1-17, doi:10.1016/j.icarus.2016.11.005.



Felsic igneous rocks (2/2)

ChemCam classification of many feldspar-rich magmatic rocks (effusive & intrusive) with a wide range of Mg numbers for basalts, and correlation with texture acquired by the RMI, demonstrates the existence of evolved magmatism and yields the new insight into the ancient Martian crust.



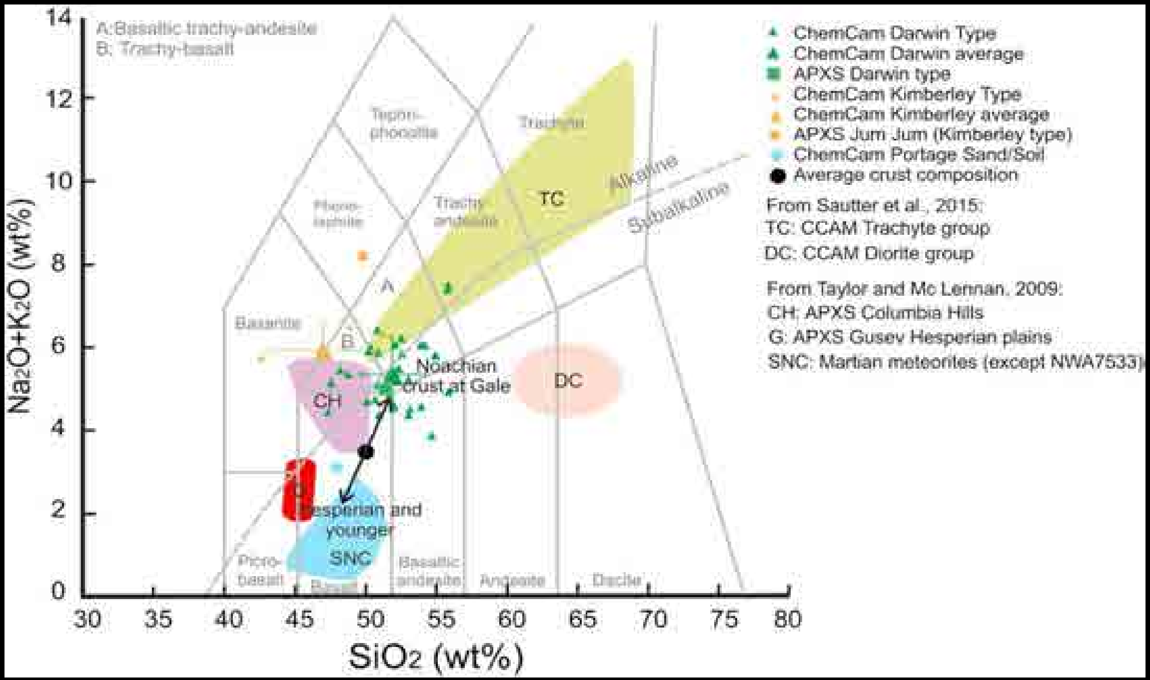


4.

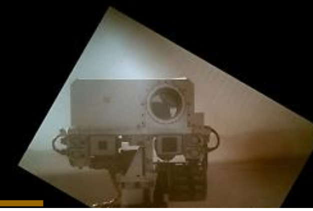
Conglomerates as a probe for crustal diversity

Conglomerates have been analyzed on 40 locations along the rover traverse. They provide an evidence for fluvial flows inside Gale crater. They also display a diversity in pebble compositions, from basaltic to alkali-rich compositions. Taken as a whole they show that the local crust in Gale rim is more alkali-rich and more felsic than younger locations where the crust has been sampled previously.

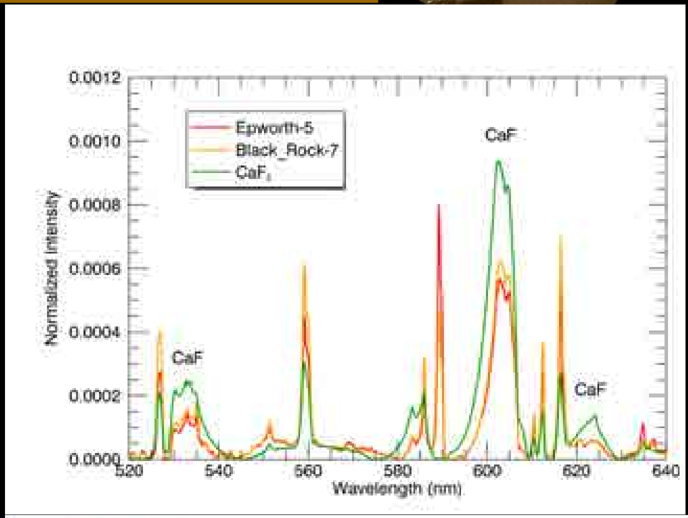
• Williams R. et al. (2013) Martianfluvial conglomerates at Gale Crater. Science 340, 1068-1072, DOI: 10.1126/science.1237317.
• Sautter V., et al. (2015) Direct evidence for silica-rich crust in the southern hemisphere of Mars: Implications for Noachian magmatism. Nature Geoscience 8, 605-609, DOI:10.1038/NGEO2474.
• Mangold N., et al. (2016) Composition of conglomerates analyzed by the Curiosity rover: Implications for Gale crater crust and sediment sources. JGR. Planets121, 353-387, doi:10.1002/2015JE004977.

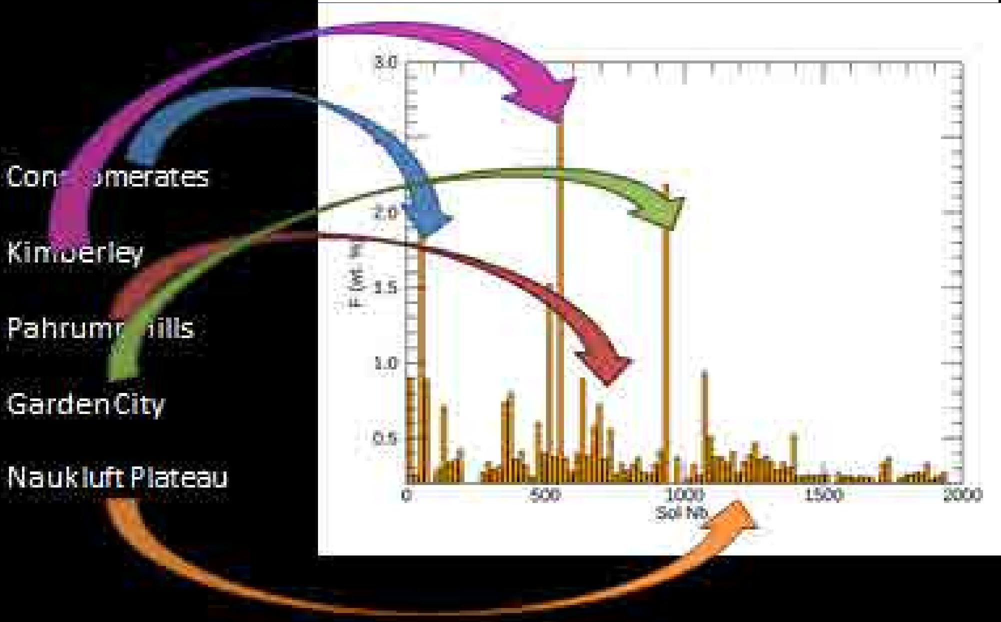


First Mars fluorine chemistry



- Fluorine has been detected for the first time on Mars as early as Sol 14 in the Goulburn conglomerate through its CaF molecular emission
- F is ubiquitous on Mars (more than 1000 detections)
- F is found in various settings: conglomerates as micas, fluvial systems as phyllosilicates, associated to concretions and diagenetic features like sulphate veins, and Mg rich concretions as apatite, associated to the dark veins as fluorite.
- According to the phases, fluorine gives fruitful indications on the origin of magmatic sources, the history of alteration and constrains on the fluids temperatures.

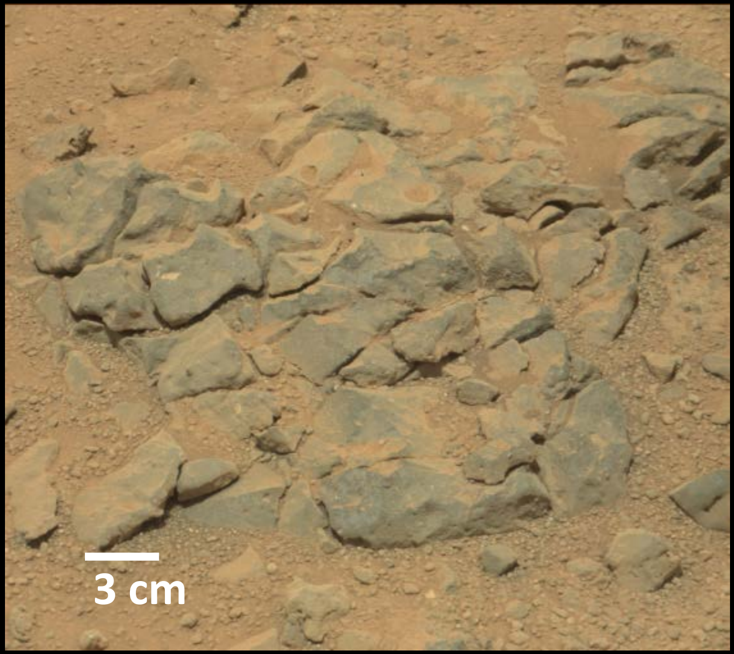




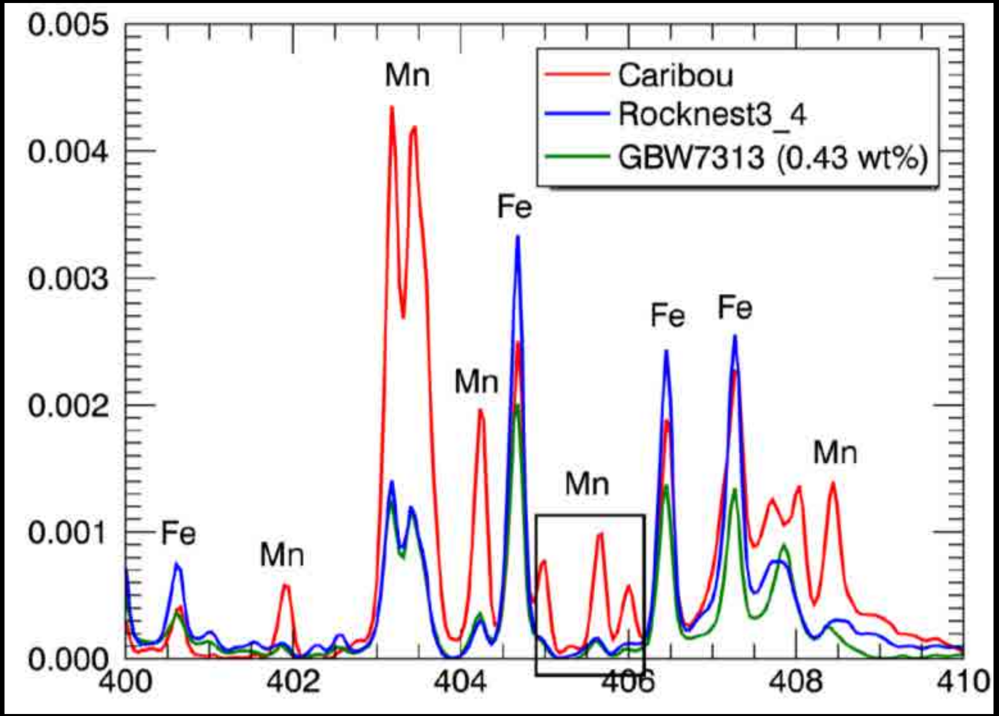
- Forni O., et al. (2015) First detection of fluorine on mars: Implications on Gale crater's geochemistry. Geophys. Res. Lett., 42, doi:10.1002/2014GL062742.

First manganese-rich phases

The production of high manganese concentrations requires a highly oxidizing environment, which currently does not exist on Mars. The discovery by ChemCam of a number of Mn-rich phases has powerful implications for the paleo-atmosphere of Mars.



Caribou Sandstone with High-Mn Mineral

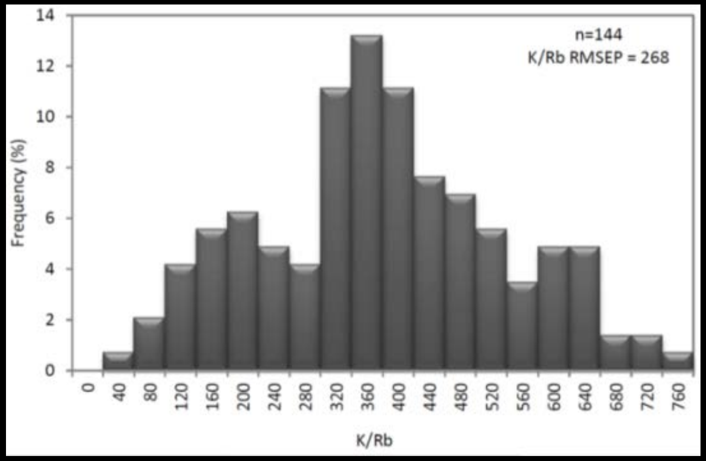


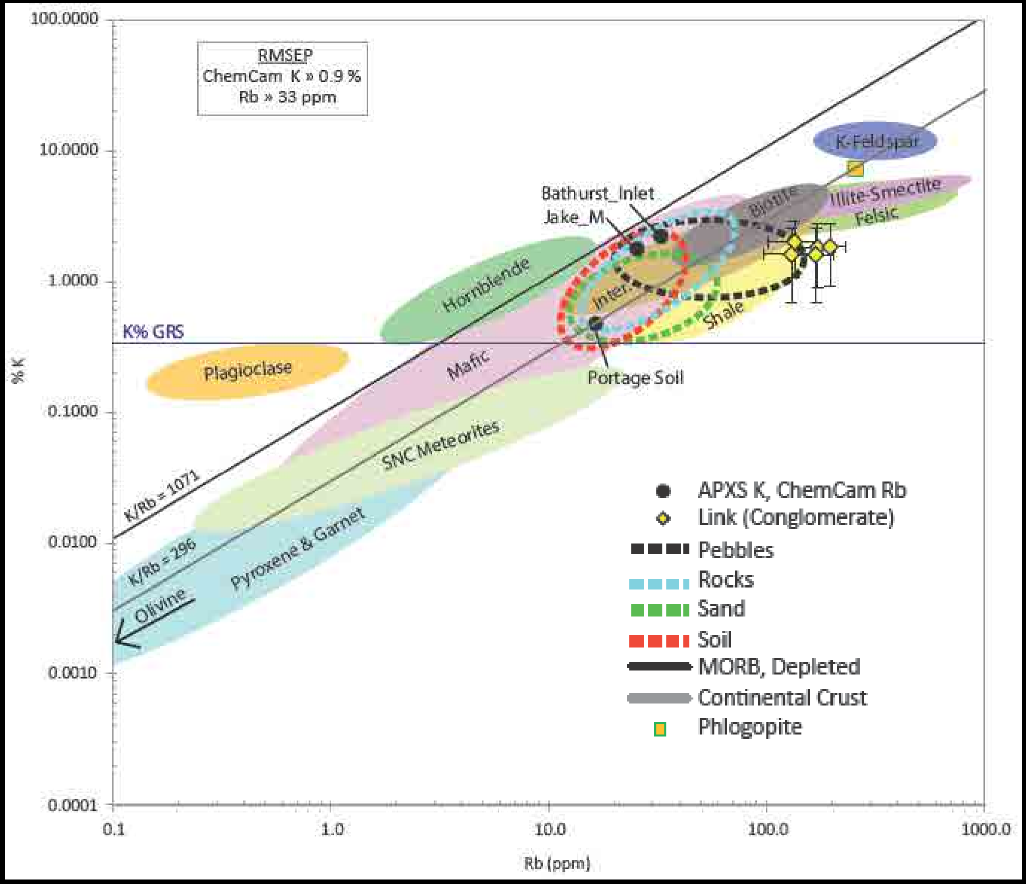
- Lanza N.L., et al. (2014) High manganese concentrations in rocks at Gale crater, Mars. Geophys. Res. Lett., 41, 5755-5763, doi:10.1002/2014GL060329.
- Lanza N.L., et al. (2016) Oxidation of manganese in an ancient aquifer, Kimberley formation, Gale crater, Mars. Geophys Res. Letters 43, 7398-7407, doi:10.1002/2016GL069109.

First Li, Rb, Sr, and Ba on Mars

LIBS is highly sensitive to the alkali and alkaline-earth elements, so much so that our detection limit for lithium is ~5 ppm. These elements have generally never been seen on Mars before and they each have implications for Mars geochemistry. Lithium is a strong indicator of alteration; Rb, Sr, and Ba each tend to be sequestered in different minerals: Rb in anorthoclase, Sr in albite and more so in anorthite, etc. The global Rb/K ratio has important implications for planetary origins.

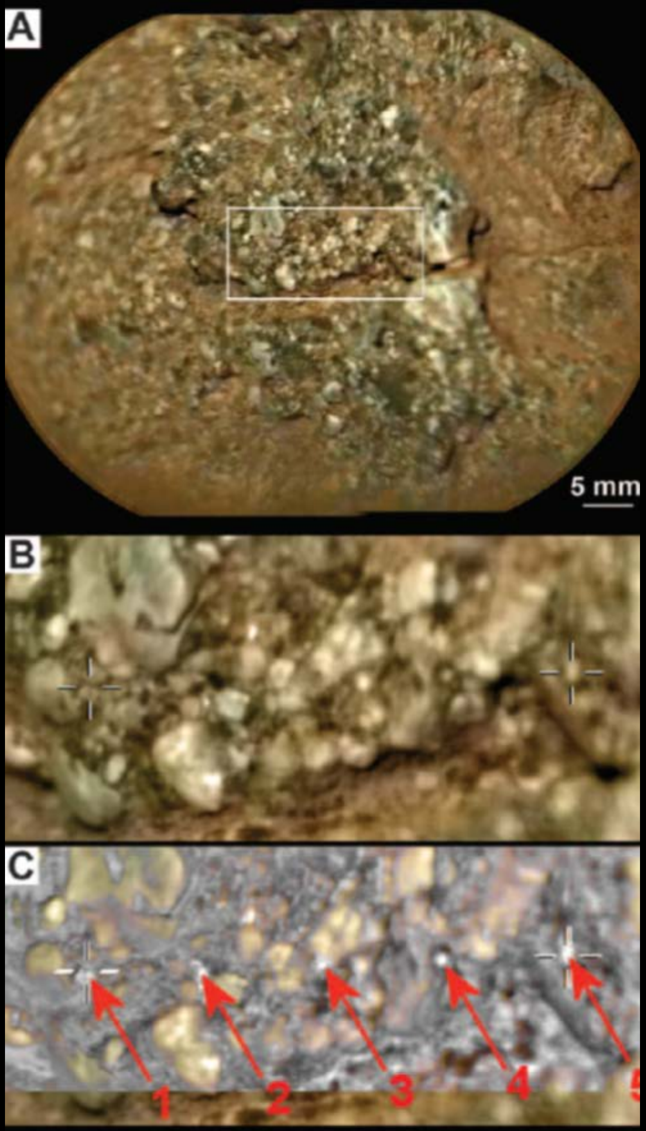
- Ollila A.M. et al. (2014) Trace element geochemistry (Li, Ba, Sr, and Rb) using Curiosity's ChemCam: Early results for Gale crater from Bradbury Landing Site to Rocknest. J. Geophys. Res., 119, 255-285, doi:10.1002/2013JE004517.
- Payre V., et al. (2017) Alkali trace elements with ChemCam: Calibration update and geological implications of the occurrence of alkaline rocks in Gale crater, Mars. J. Geophys. Res. 122, doi: 10.1002/2016JE005201.



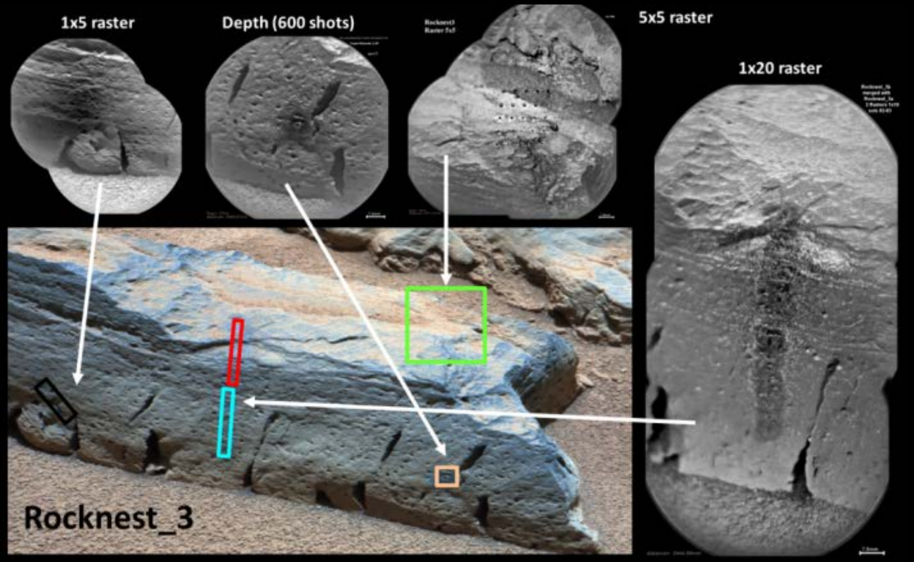


8.

Fe-rich cements in sediments



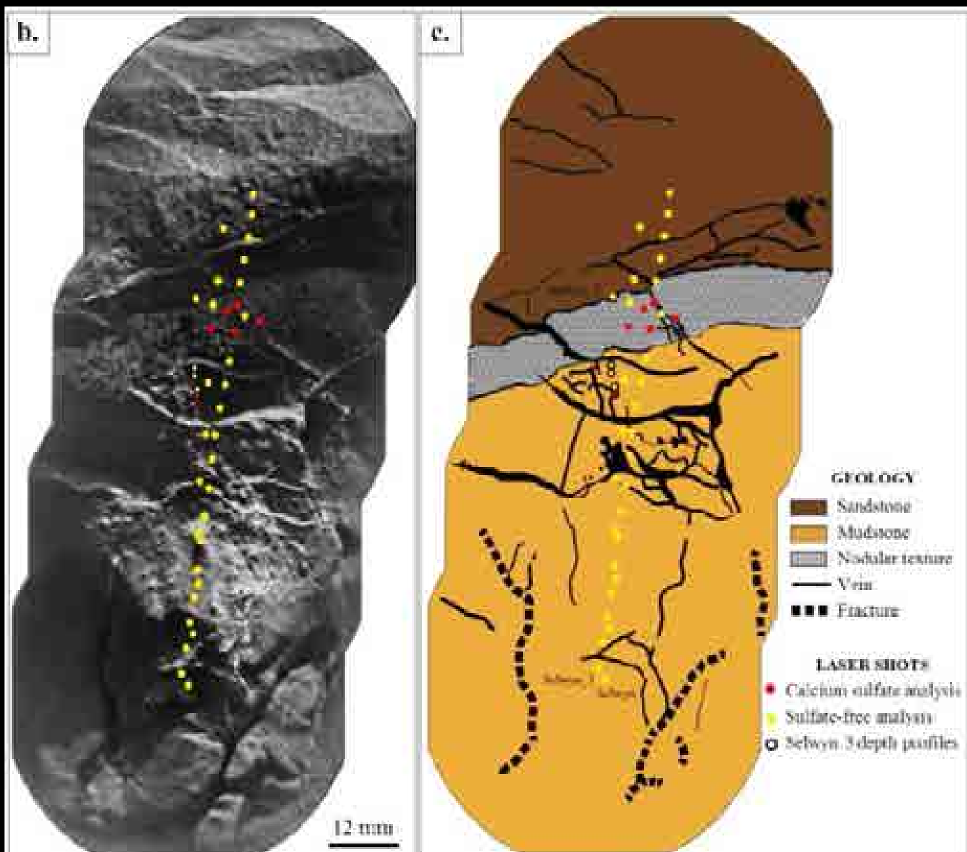
The micro-beam LIBS technique allows us to probe small areas, looking for interstitial material. In the first Science paper on conglomerates we reported that one observation point showed the beam profiling through a Fe-rich hydrated phase which we interpret to be an iron-rich cement binding the conglomerate clasts. We have evidence for this cement in the Rocknest rocks as well .



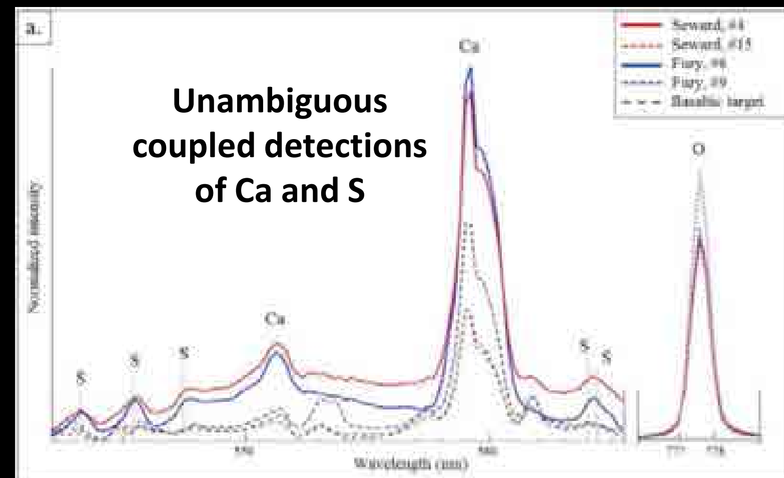
- Williams R. et al. (2013) Martian fluvial conglomerates at Gale Crater. Science 340, 1068-1072, DOI: 10.1126/science.1237317.
- Blaney D., et al. (2014) Chemistry and texture of the rocks at “Rocknest”, Gale crater: Evidence for iron-rich cements. J. Geophys. Res., 119, 2109-2131, DOI: 10.1002/2013JE004590.

Ubiquitous Ca-sulfate veins

ChemCam was the first to observe the composition of veins in the Yellowknife Bay lacustrine sediments as being calcium sulfates. We were also able to show that the veins were variably hydrated such as in bassanite and gypsum.



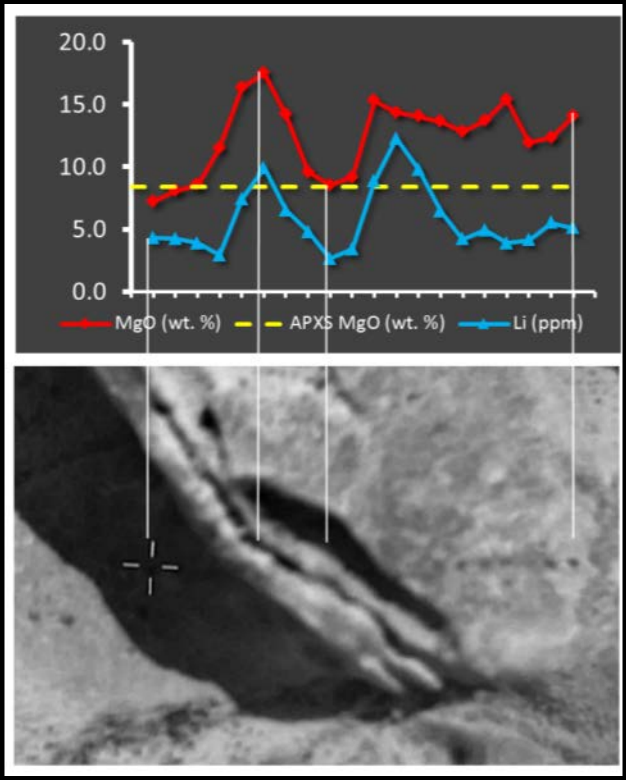
Cross-section through multiple sulfate veins



- Nachon M. et al. (2013) Calcium sulfate veins characterized by the ChemCam instrument at Gale crater, Mars. J. Geophys. Res.
- Rapin W., et al. (2017) Quantification of water content by laser induced breakdown spectroscopy on Mars. Spectrochim. Acta B 130, 82-100, doi:10.1016/j.sab.2017.02.007.
- Schwenzer S., et al. (2016) Fluids during diagenesis and sulfate vein formation in sediments at Gale crater, Mars. Met. Planet. Sci. 1-28, doi:10.1111/maps.12668

Diversity in diagenetic features

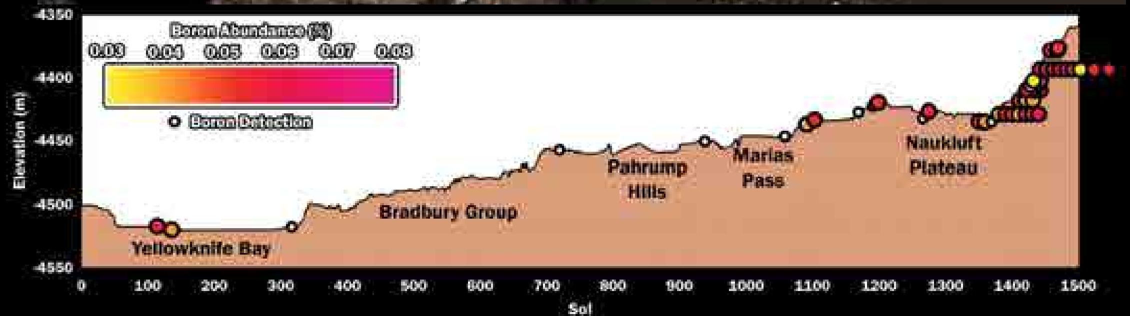
ChemCam provides constraints on diagenetic features composition in fluvial and lacustrine sediments. fine-scale geochemical constraints within the Yellowknife Bay formation: Mg and Li variations are correlated at the site of the raised ridge. A t Pahrump Hills, concretions with enhanced S and Mg (or Fe) were interpreted as Mg-sulfates (or Fe-sulfates such as jarosite) showing episodes of acidic fluid circulation while at Garden City, observations of Ca with F suggest mineralization by fluorite.



- McLennan S.M. et al. (2013) Elemental geochemistry of sedimentary rocks in Yellowknife Bay, Gale Crater, Mars. Science, 9 December, DOI:10.1126/science.124473.
- Leveille R.J. et al. (2014) Chemistry of fracture-filling raised ridges in Yellowknife Bay, Gale crater: Windows in to past aqueous activity and habitability on Mars, Icarus.
- Nachon M., et al. (2016) Chemistry of diagenetic features analyzed by ChemCamat Pahrump Hills, Gale crater, Mars. Icarus, doi:10.1016/j.icarus.2016.08.026.

Discovery of Boron in Fractures

Boron was found in an increasing number of Ca-sulfate fractures as Curiosity drove to higher elevations. Boron is an indicator of desiccation, and its presence could be indicative of evaporite beds higher in the strata, or of its incorporation in clays and then re-release and concentration by groundwater. Boron is also important for habitability: ribose, the principal constituent of RNA, is stabilized in water by the presence of boron.

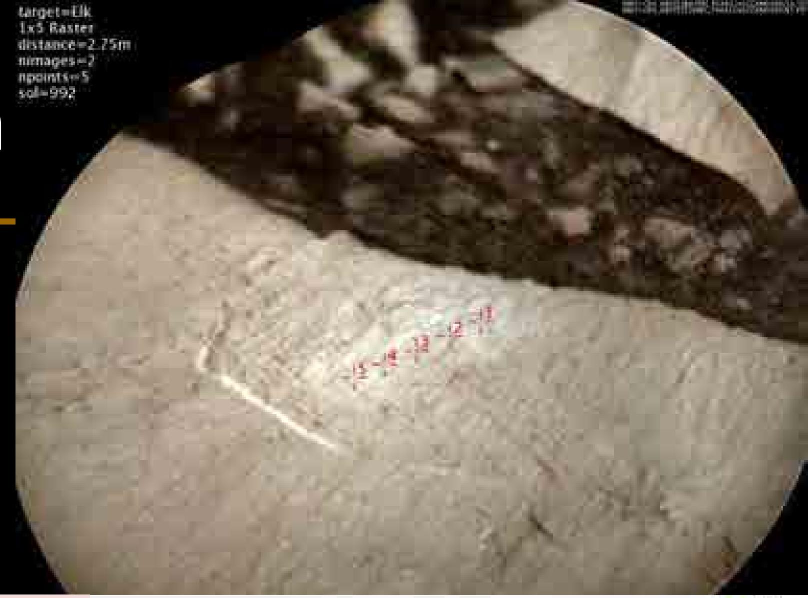


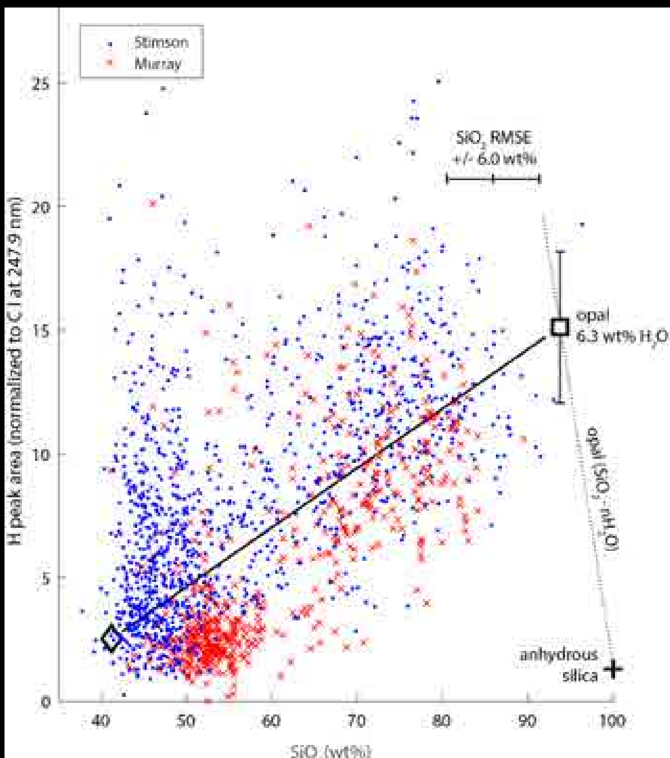
• Gasda P.J., et al. (2017) In situ detection of boron by ChemCam on Mars. Geophys. Rev. Lett. 44, doi:10.1002/2017GL074480.

12.

Discovery of Deposited Silica

On Earth, evidence of some of the earliest life forms is found associated with silica deposits such as chert or opal. On Sol 992, ChemCam discovered nearly pure silica in finely laminated layers (Elk target at right). The team stopped and turned around the rover to investigate in detail. The CheMin instrument identified the mineral form as tridymite, although ChemCam also identified opal, based on hydration.



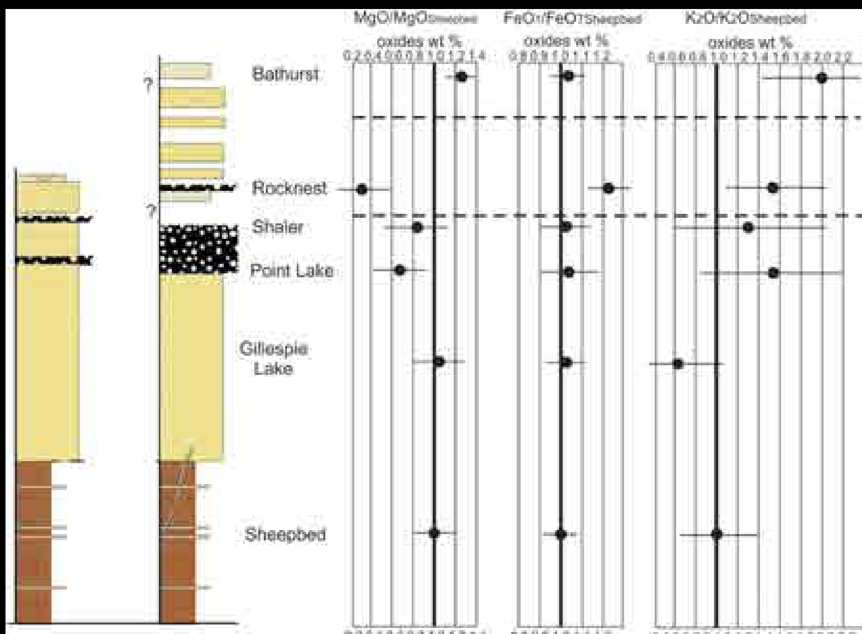


- Frydenvang J., et al. (2017) Discovery of silica-rich lacustrine and eolian sedimentary rocks in Gale crater, Mars. Geophys. Res. Lett. DOI: 10.1002/2017GL073323.
- Rapin W., et al. (2017) In situ analysis of opal in Gale crater, Mars, submitted.

13.

Chemostratigraphy of Yellowknife Bay sediments

ChemCam used > 30,000 shots and > 100 of super-high resolution images to characterize the Yellowknife Bay sediments far more comprehensively than with any other instrument. Using large aggregates of observations provides high confidence in the relative differences in these units. In the Shaler outcrop alone, only ChemCam was able to cover the whole area, as the rover was not allowed to drive up the outcrop for arm-deployed sampling.



- Mangold N. et al. (2014) Chemical variations in Yellowknife Bay Formation sediments analyzed by the Curiosity rover on Mars. J. Geophys. Res., 2015,
- Anderson R.B. et al. (2014) ChemCam Results from the Shaler Outcrop in Gale Crater, Mars, Icarus, 2015.

RMI LIBS

Stratigraphy	Texture	Chemistry	Interpretation
Glenelg member Bathurst	Faint layering, mm thick lamination. Sandstone to siltstone.	High alkali, distinct strong K/Na ratio. Similar to floats found in hummocky plains.	Eolian or volcaniclastic. Unknown cementation. May not be part of YKB sediments.
Glenelg member Rocknest	Layered sandstone or massive texture with flow features.	High Fe and alkali. Mg depleted. Similar composition of both textures.	Unknown depositional origin. Cement with Fe-oxides. Disturbance by late event may explain the massive textures.
Glenelg member Shaler	Laminated sandstone with cross-bedding, locally siltstone. Lateral variations with pitted texture.	Close to Sheepbed and Gillespie Lake composition except higher K. Locally low Mg in pitted texture.	Fluvial sediments. Local alteration during diagenesis forming pitted texture.
Glenelg member Point Lake	Pitted texture locally large vugs with glassy texture. Layering not obvious. Many cracks.	High alkali. Low Mg. Glassy texture contains points with high K, Na (feldspar-like)	Diagenetically modified sediments with enhanced alkali content and dissolution features.
Gillespie Lake member	Fine-grained to pebbly sandstone. Strong induration, poor layering. Many cracks and filled veins.	Similar to Sheepbed. Unidentified hydrated phases.	Fluvial sediments. Cementation by aqueous fluids.
Sheepbed member	Local layering visible. Mudstone to siltstone. Many filled veins and open cracks	Homogeneous mafic composition except diagenetic features.	Lacustrine sediments. Early in situ diagenetic alteration. Late diagenetic episode with calcium sulfate veins.

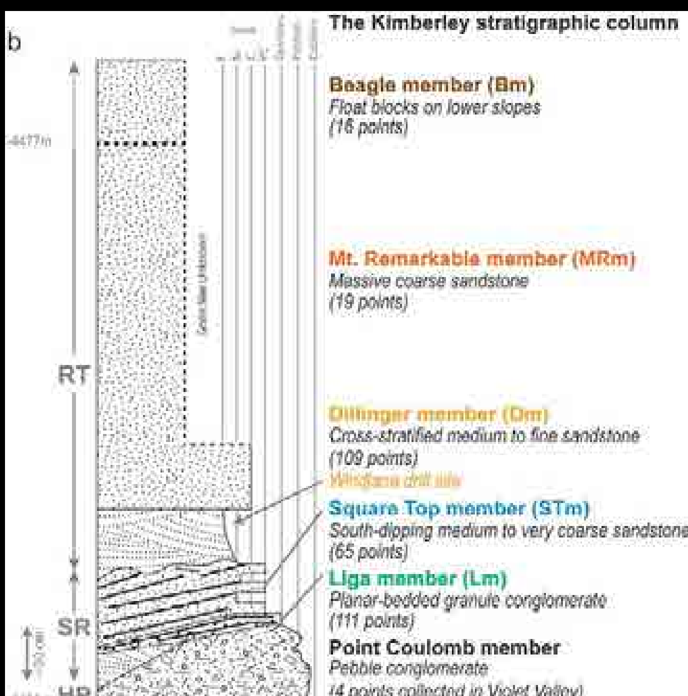
Chemostratigraphy of potassic rocks at Kimberley

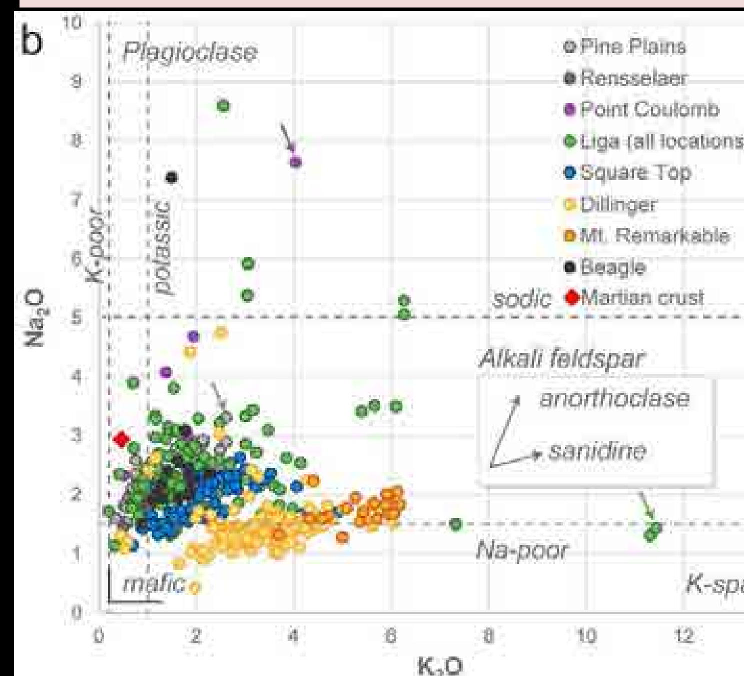
The combined analysis of ChemCam data with stratigraphic and geographic locations reveals that the mean K2O abundance increases upward through the stratigraphic section. The occurrence of these potassic sedimentary rocks provides additional evidence for the chemical diversity of the crust exposed at Gale Crater.

- Le Deit L., et al. (2016) The potassic sedimentary rocks in Gale crater, Mars, as seen by ChemCam on boardCuriosity. Geophys. Res. Planets. 121, doi:10.1002/2015JE004987.

- Treiman A.H., et al. (2016) Mineralogy, provenance, and diagenesis of a potassic basaltic sandstone on Mars: CheMinX-ray diffraction of the Windjanasample (Kimberley area, Gale crater), J. Geophys. Res. Planets 121, 75-106, doi:10.1002/2015JE004932.

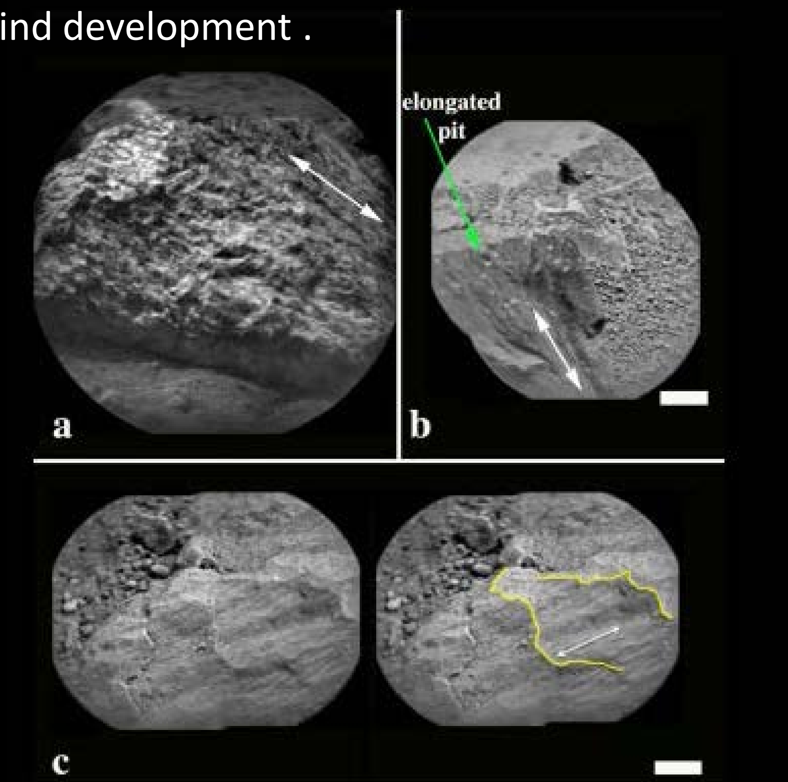
- Rice M.S., et al. (2016) Geologic overview of the Mars Science Laboratory Rover mission at The Kimberley, Gale crater, Mars. J. Geophys. Res., 10.1002/2016JE005200.

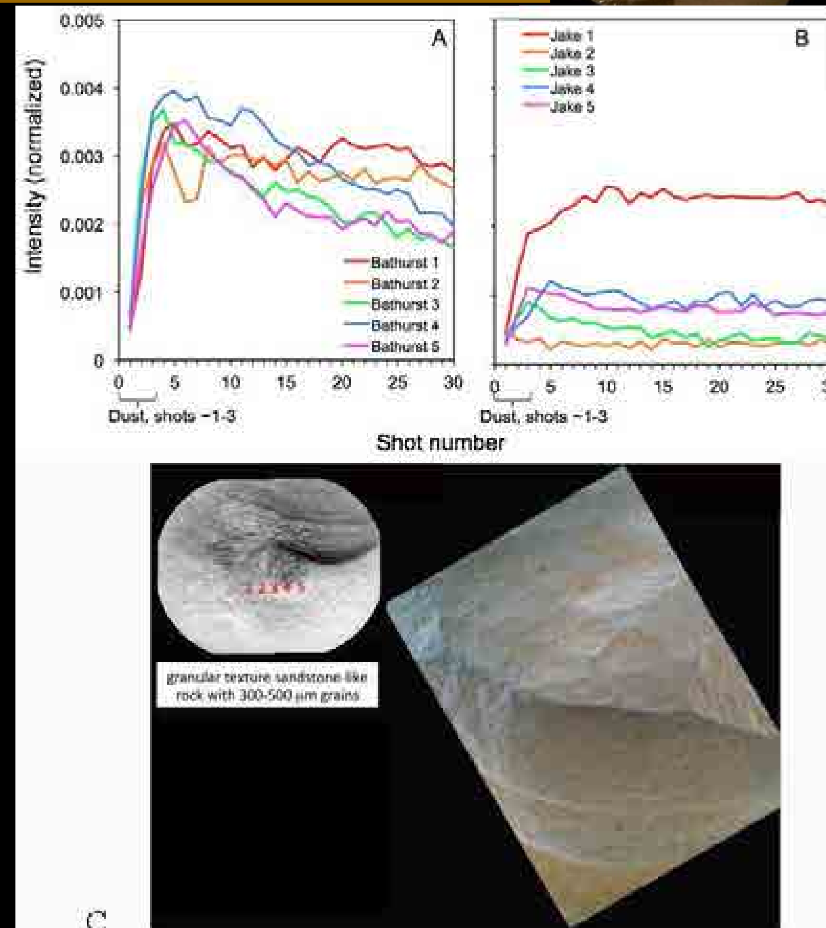




Rock abrasion

The high resolution of ChemCam's RMI shows rock textures in fine detail formed from sand wind abrasion . Using lithium as a proxy for surface coatings or rinds, LIBS depth profiles on abraded rocks like Jake, have an Li peak that remains constant with depth, suggesting a lack of surface alteration, with the possibility that the rate of abrasion exceeds that of rind development .

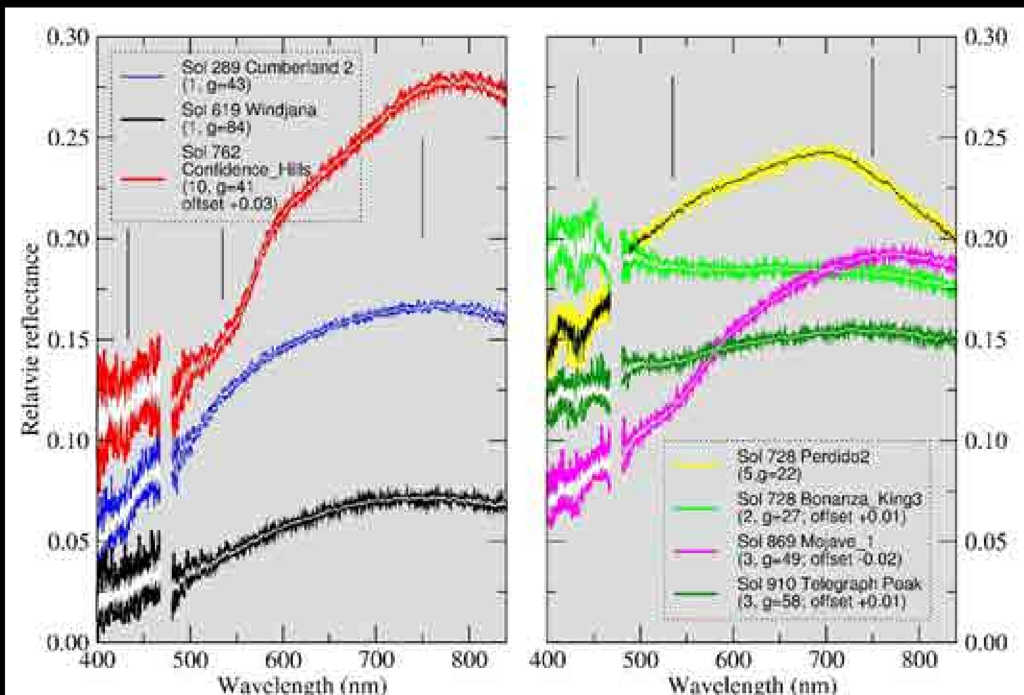


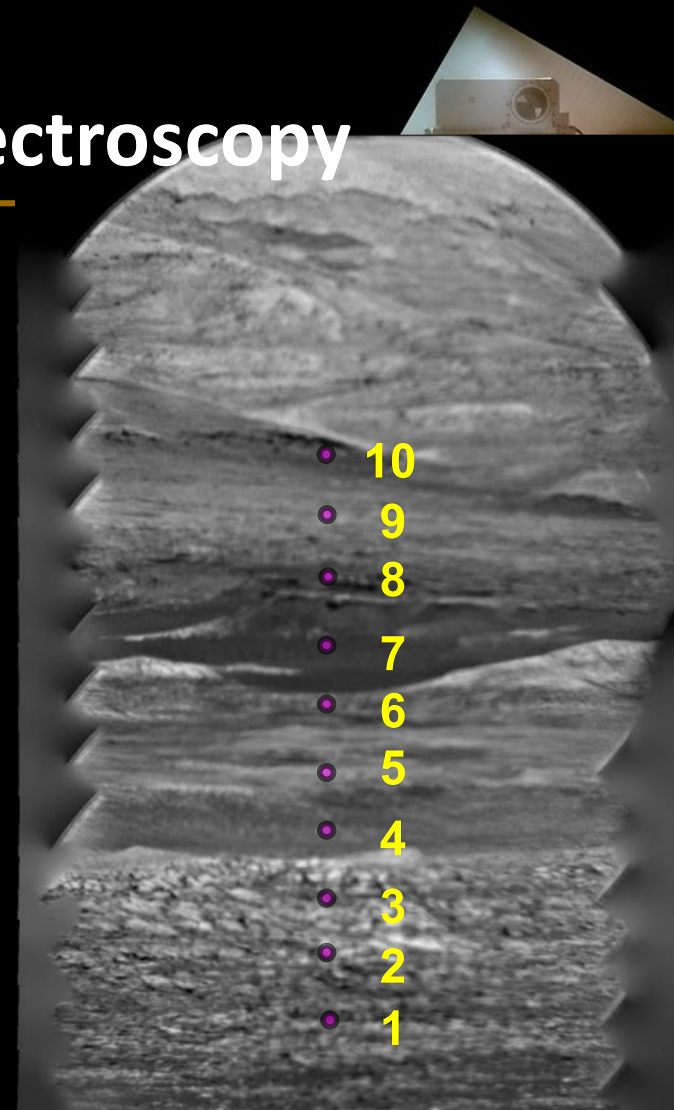


• Bridges N., et al. (2014) The rock abrasion record at Gale Crater: Results from the first 100 sols of MSL. J. Geophys. Res., 119, 1374–1389, doi:10.1002/2013JE004579.

High-resolution reflectance spectroscopy

While the spectral range only covers the 0.4-0.9 micron range, spectral features consistent with hematite, pyroxenes/olivine, and ferric sulfate have been observed.

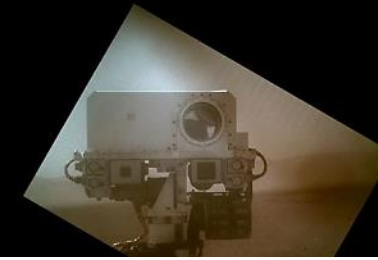


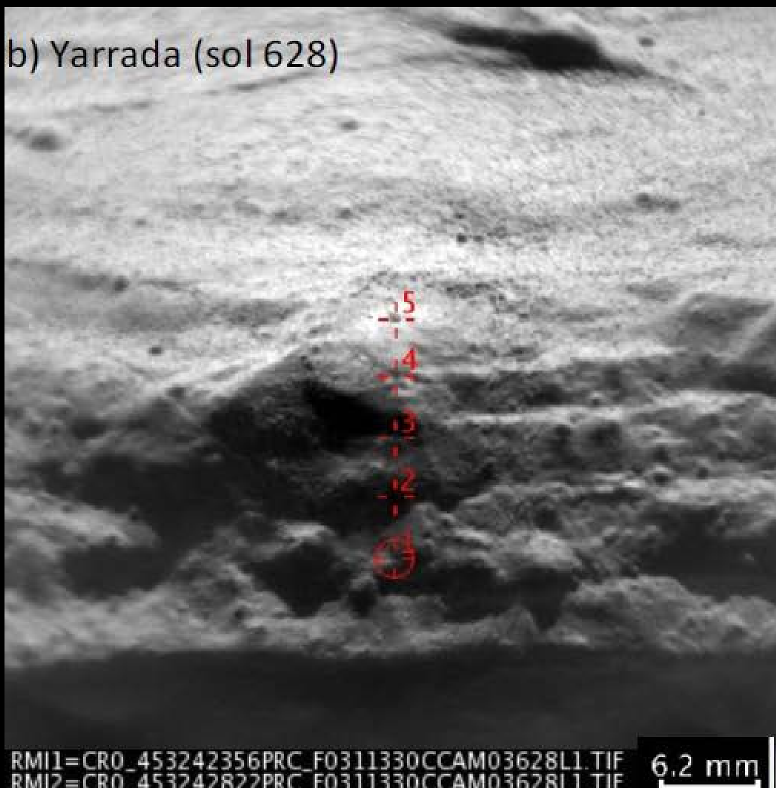


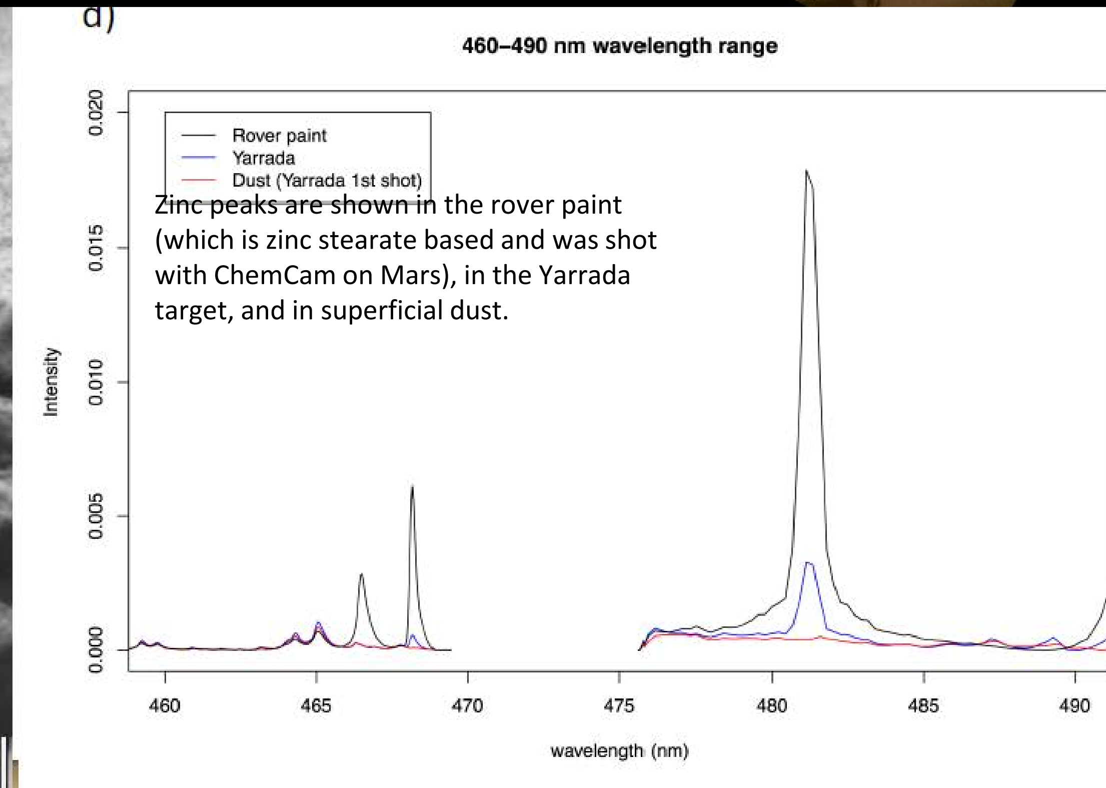
Observations of ~5 km distant dunes and ridges also exhibit features consistent with hematite and pyroxene/olivine.

- Johnson, J.R. et al. (2014), ChemCam Passive Reflectance Spectroscopy of Surface Materials at the Curiosity Landing Site, Mars, Icarus, DOI: 10.1016/j.icarus.2014.02.028
- Johnson J.R., et al. (2016) Constraints on iron sulfate and oxide mineralogy from ChemCam visible/near-infrared reflectance spectroscopy of Mt. Sharp basal units, Gale crater, Mars. Am. Mineral., 101, 1501–1514.
- Johnson J.R., et al. (2018) Visible/near-infrared spectral diversity from in situ observations of the Bagnold Dune Field sands in Gale crater, Mars. J. Geophys. Res. Planets, 122, 2655-2684, doi:10.1002/2016JE005187.

Observation of Enriched Cu & Zn







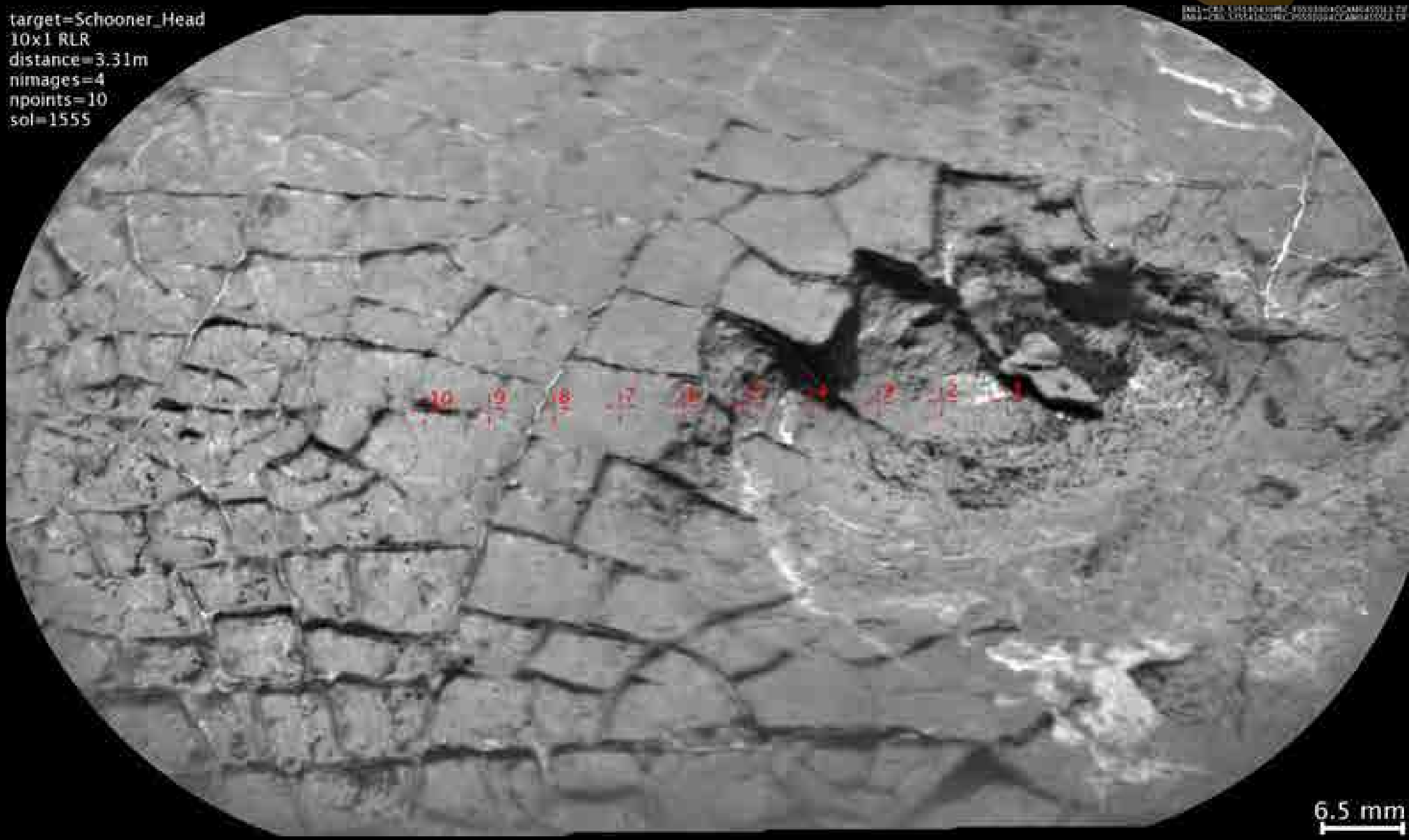
Enrichments of these elements is curious. Mars is generally depleted in copper, and the presence of enriched copper along with sanidine at the Kimberley suggests the possibility of a porphyry deposit.

- Lasue J., et al. (2016) Zinc detection with ChemCam LIBS at Gale crater, Mars. J. Geophys. Res. 121, 338–352, doi:10.1002/2015JE004946.
- Payre V., et al. (2018) Copper enrichments in Kimberley formation, Gale crater, Mars, Icarus, submitted.

18.

Observation & Analysis of Mud Cracks

Observation of mud cracks at higher elevations in the Murray formation indicate that the lake in this part of Gale crater dried out at least once. Lack of typical playa chemistry hints that most of the time the lake was deep, in spite of these mud cracks.



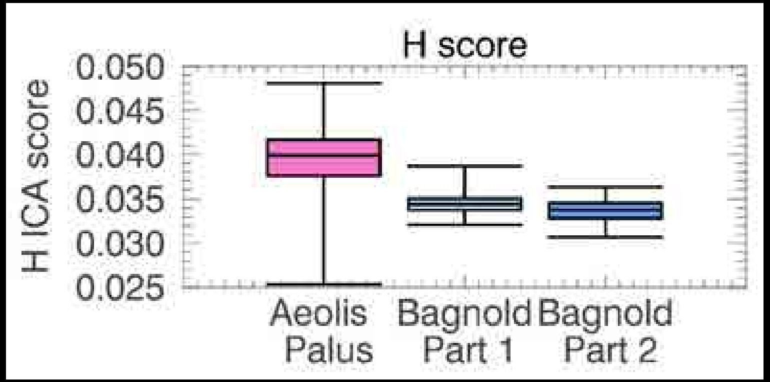
- Stein N., et al. (2017) Desiccation cracks provide evidence of lake drying on Mars, middle Murray Formation, Gale Crater. Geology, doi:10.1130/G40005.1.

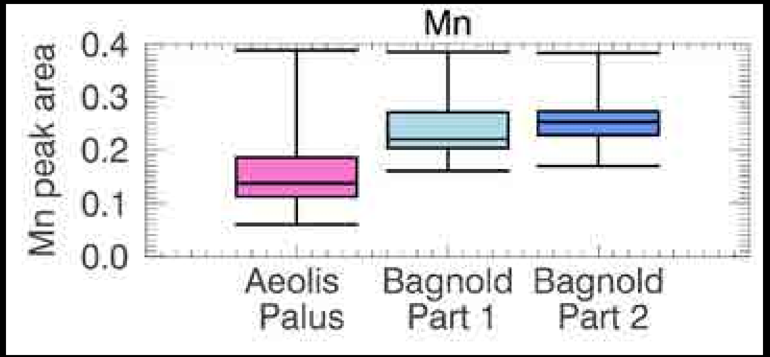
18.

In situ analysis of active dunes

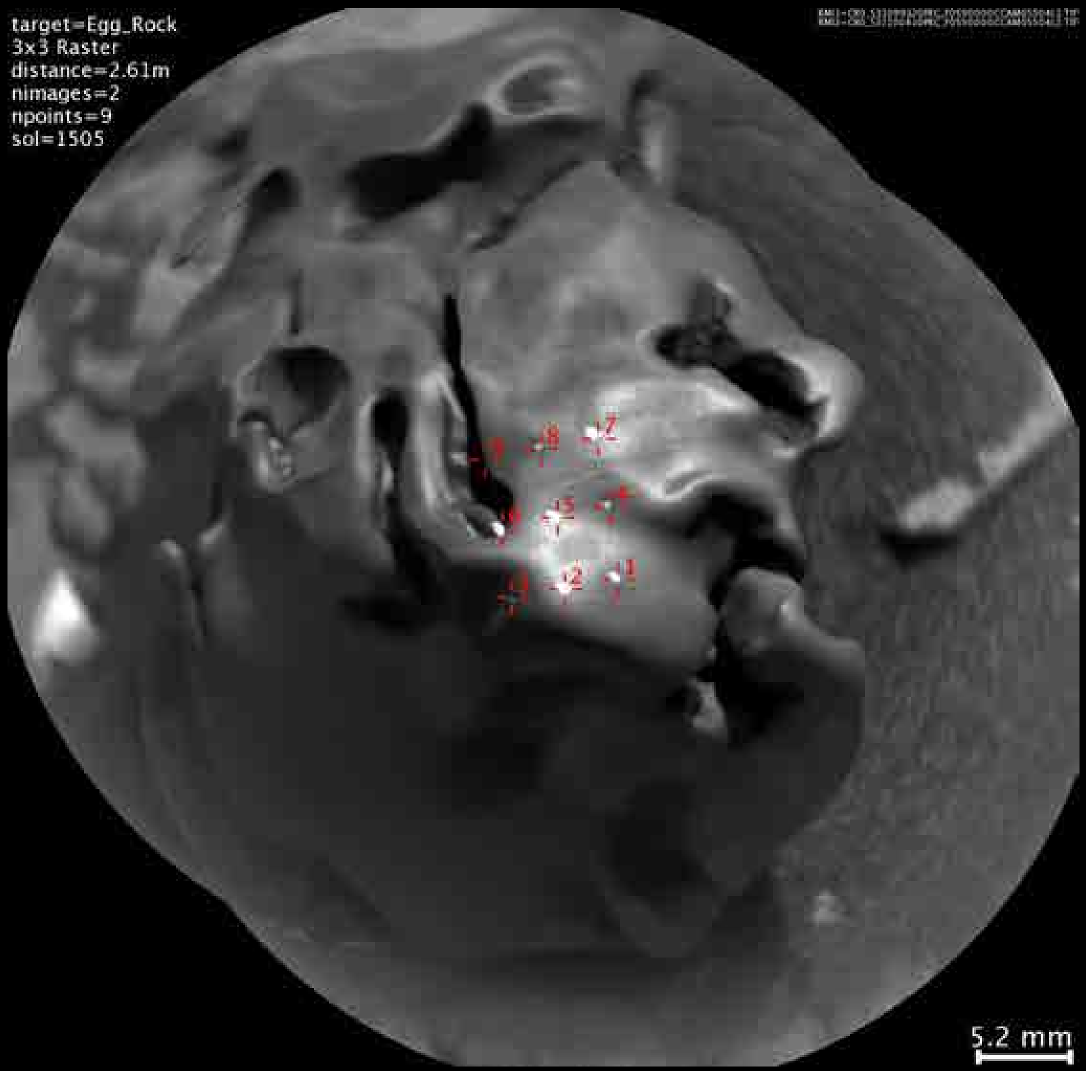
ChemCam performed the first in situ analysis of an active dune. Bagnold Dunes are overall similar to Aeolis Palus soils in terms of major elements chemistry (slight enrichments in FeO, and Ca0 ; Depletion in volatils H, S, and Cl; enrichments in Mn, Cr, Sr). Dunes seem to be enriched in mafic minerals. Longitudinal dunes are more enriched in pyroxenes compared to barchan dunes.

- Cousin A., et al. (2017) Geochemistry of the Bagnold Dune Field as observed by ChemCam, and comparison with other Aeolian deposits at Gale crater. JGR Planets 122, 10.1002/2017JE005261.
- Ehlmann B.L., et al. (2017) Chemistry, mineralogy, and grain properties at Namib and High Dunes, Bagnold dune field, Gale crater, Mars: A synthesis of Curiosity rover observations, J. Geophys. Res., 122, 2510-2543, doi:10.1002/2017JE005267.
- Johnson J.R., et al. (2018) Visible/near-infrared spectral diversity from in situ observations of the Bagnold Dune Field sands in Gale crater, Mars. J. Geophys. Res. Planets, 122, 2655-2684, doi:10.1002/2016JE005187.



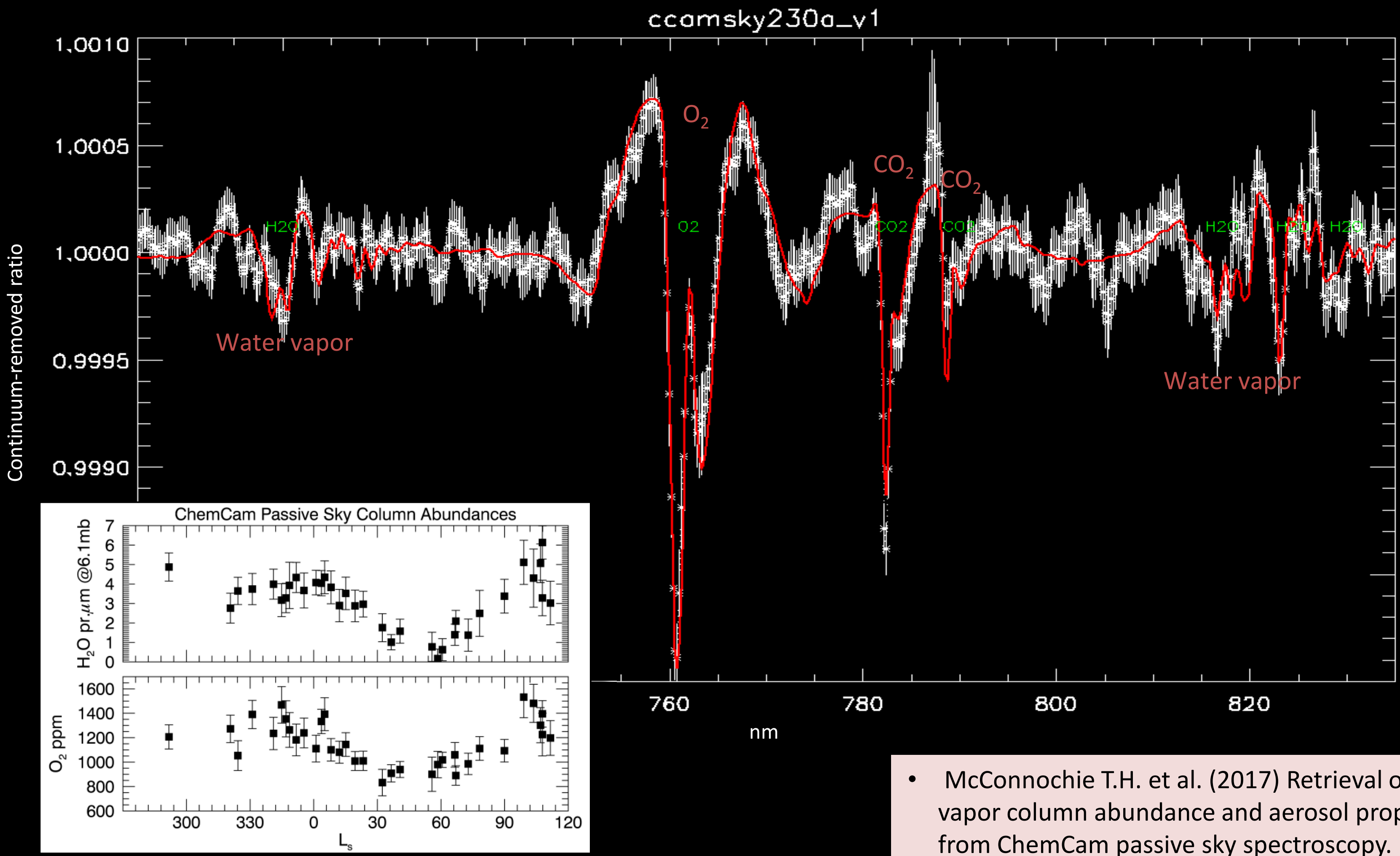


TBD meteorites



Atmospheric H_2O, O_2 abundances

ChemCam passive-mode sky observations measure the H_2O, O_2, and CO_2 columns.



- McConnochie T.H. et al. (2017) Retrieval of water vapor column abundance and aerosol properties from ChemCam passive sky spectroscopy. Icarus, doi:10.1016/j.icarus.2017.10.043.

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45. Rapin W., et al. (2017) Quantification of water content by laser induced breakdown spectroscopy on Mars. Spectrochim. Acta B 130, 82-100, doi:10.1016/j.sab.2017.02.007.
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58. McConnochie T.H. et al. (2017) Retrieval of water vapor column abundance and aerosol properties from ChemCam passive sky spectroscopy. Icarus, doi:10.1016/j.icarus.2017.10.043.
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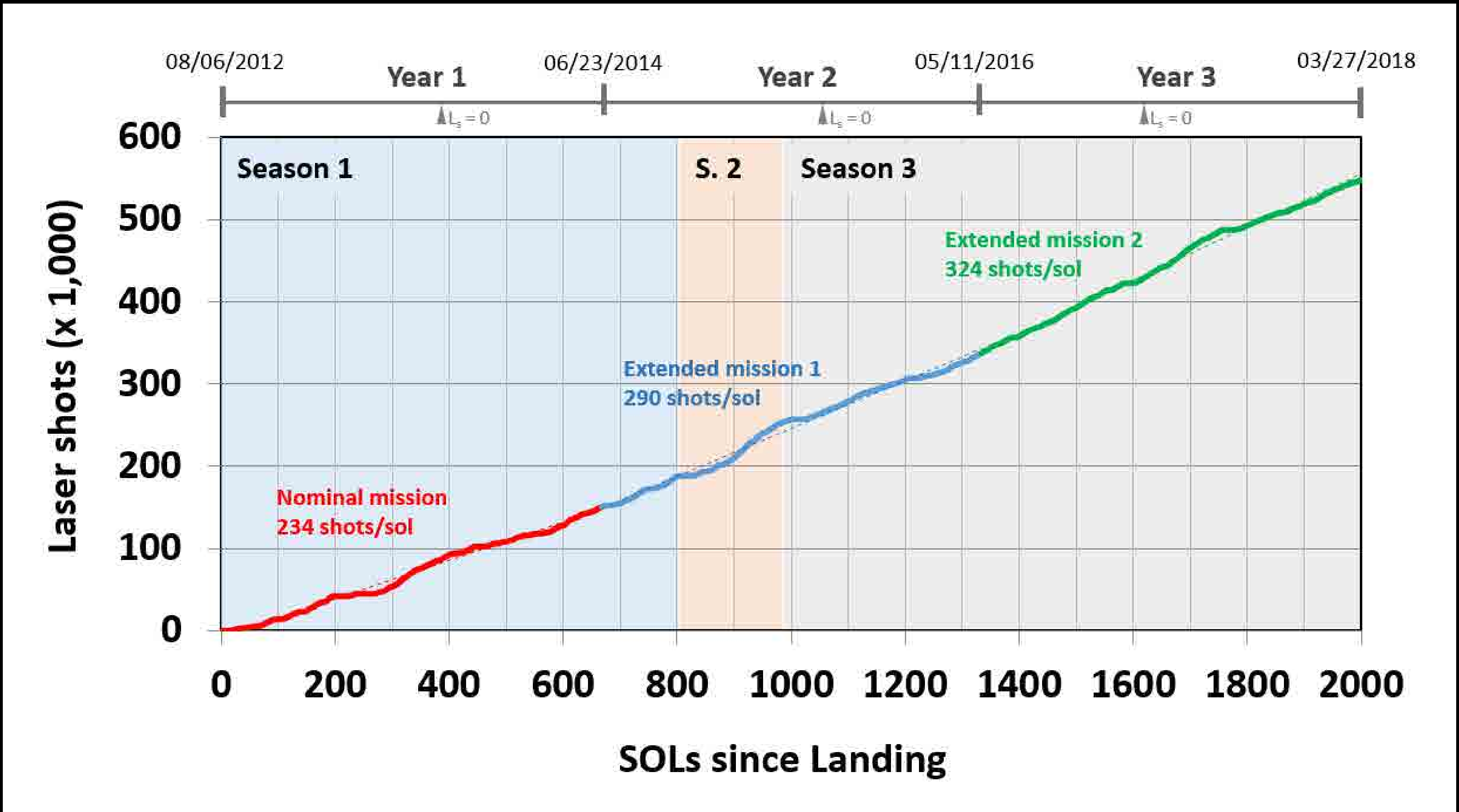
Supplementary material

ChemCam capabilities and instrument status

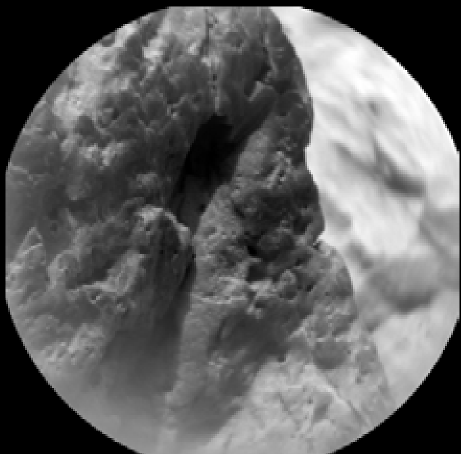
Instrument Status

ChemCam is doing great!

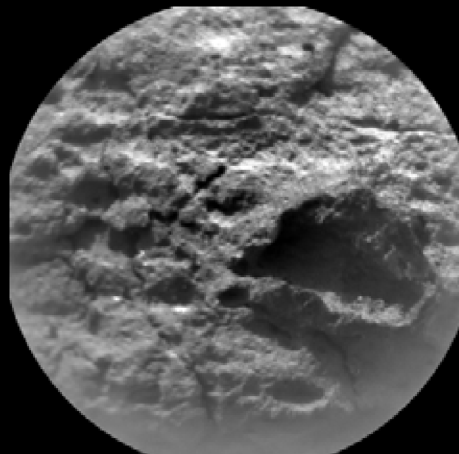


Variety of fine scale textures

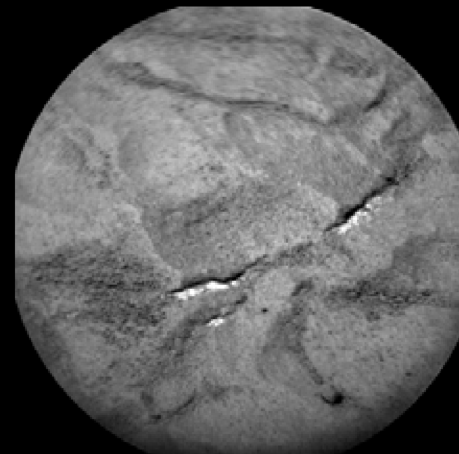
Pointing_test (sol 100)



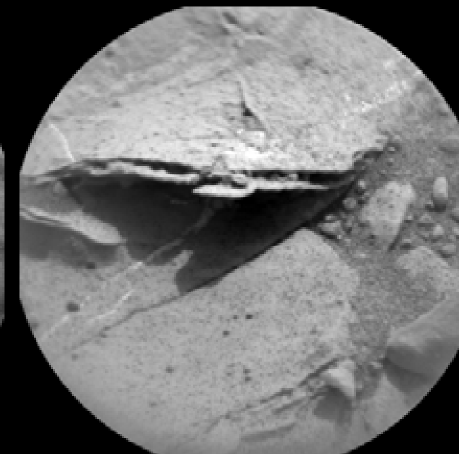
Athole_point (sol 302)



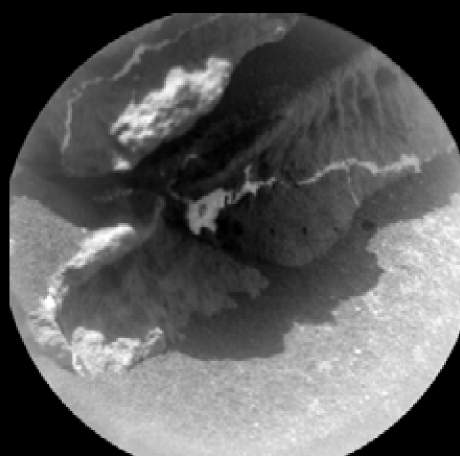
Beachrock (sol 126)



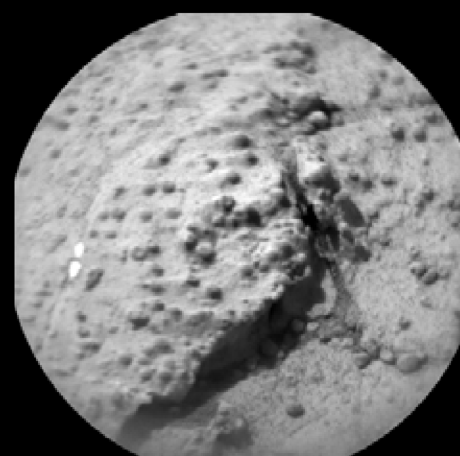
John_Klein_RP3 (sol 165)



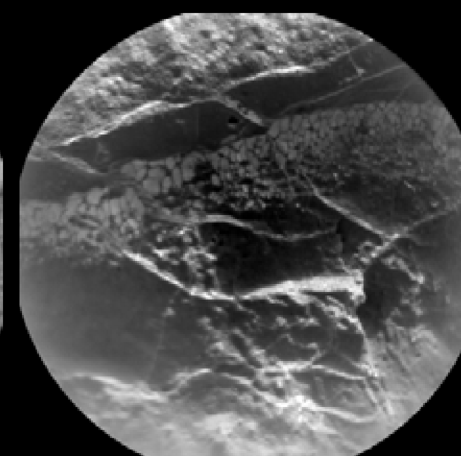
Denham (sol 326)



Fabricius_Cliffs (sol 322)

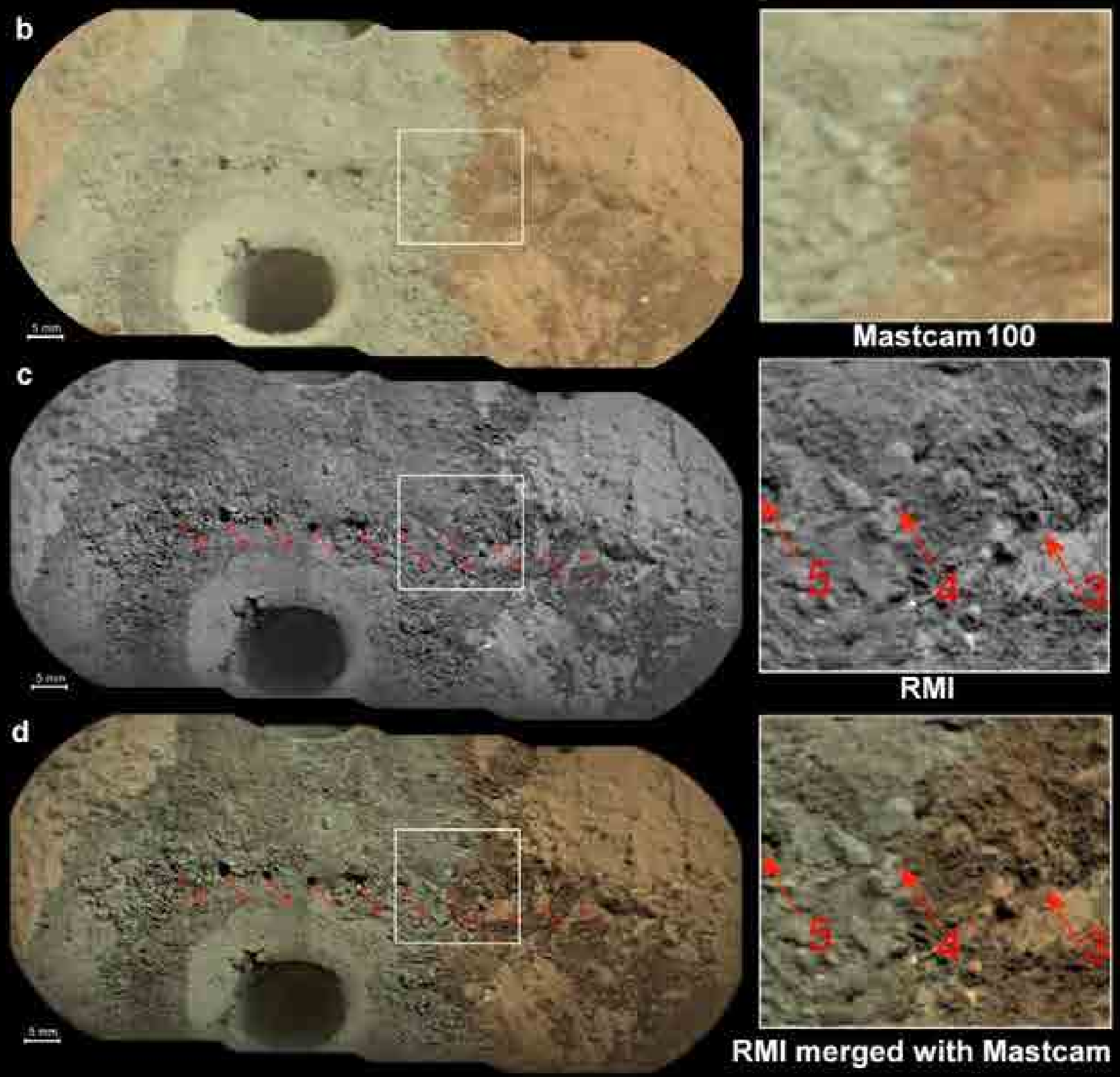


Cumberland (sol 187)



Selwyn (sol 157)

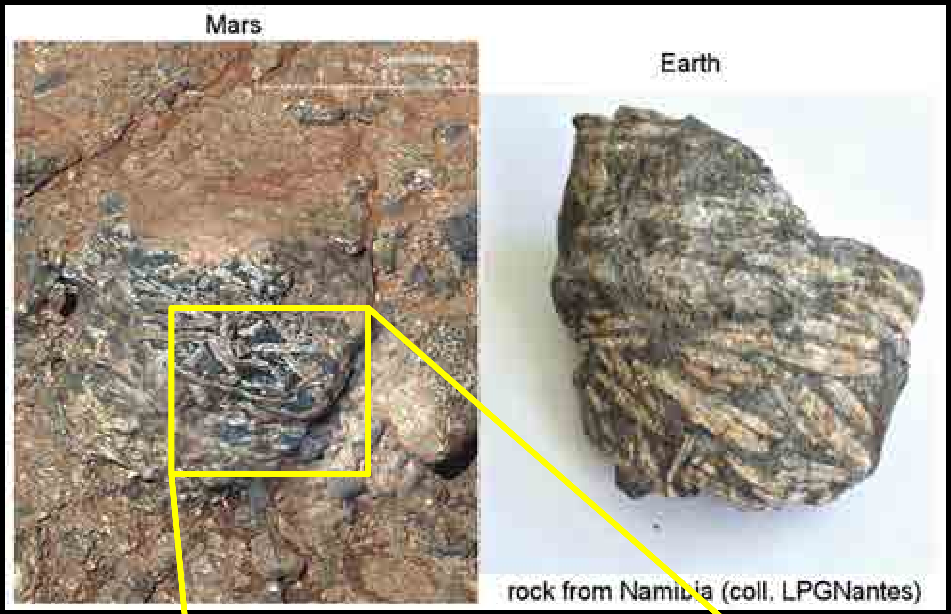
High res. Color images



Drill Tailings
sol 183

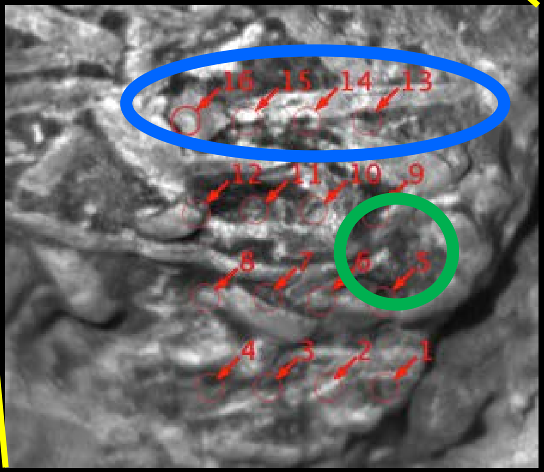
- Le Mouelic S. et al. (2013) The ChemCam Remote Micro-Imager at Gale crater: Review of the first year on Mars. Submitted to Icarus.

Probing small scales



Mastcam & ChemCam merged images

"Harrison" sol 514 :
Rock rich in light-colored elongated crystals, in a grey matrix, plus a darker interstitial phase.

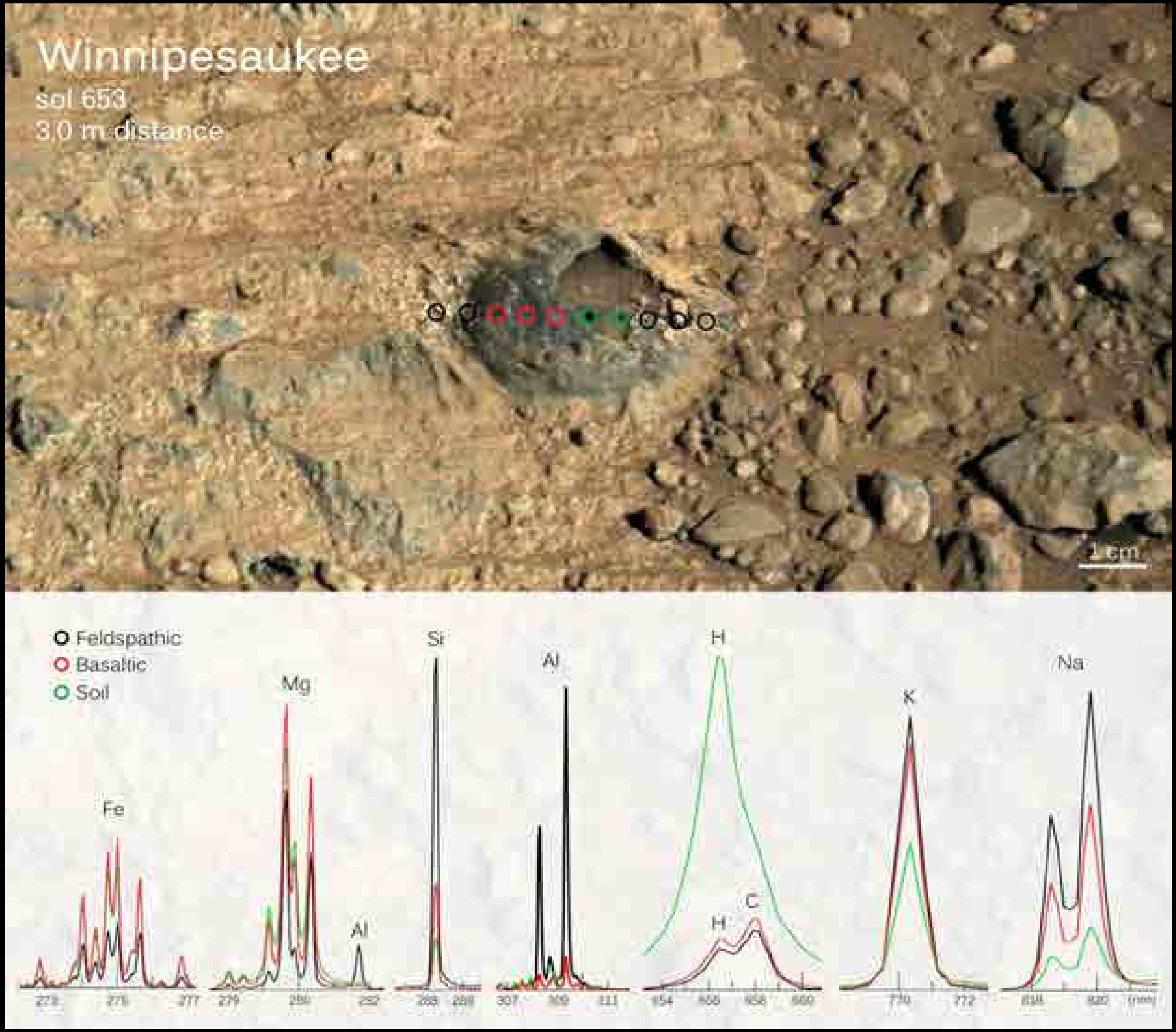


1 cm

Rich in Si, Al, Na, K (lighter phase)
Rich in Fe, Mg, Ca (darker phase)

Conclusion : Feldspar and pigeonite are dominant phases; preliminary evidence for secondary phases

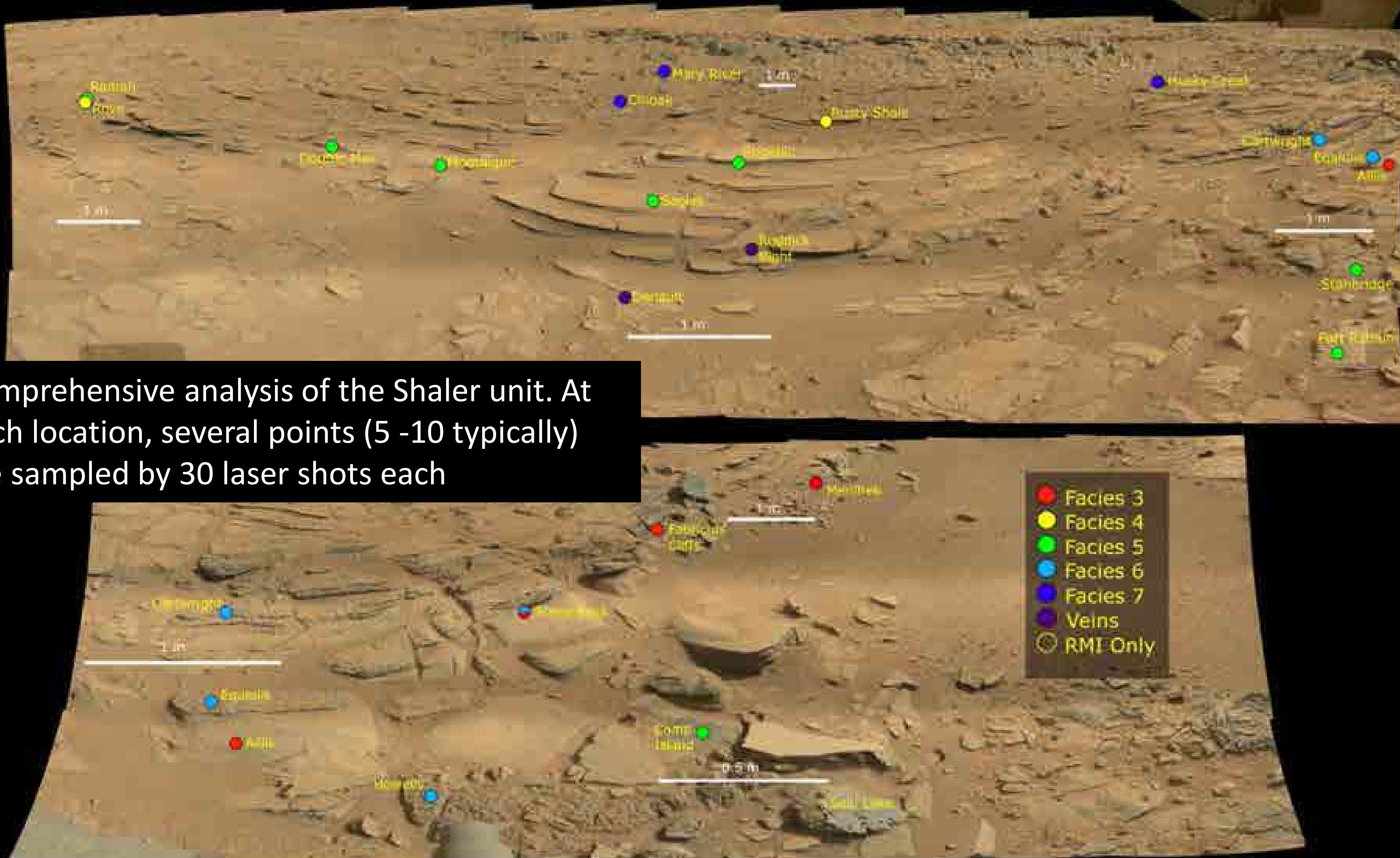
Chemical and morphological gradients



Combination of RMI and color M100 Mastcam

Three distinct types of material were analyzed: the bedrock (listed as feldspathic, high Si, Al, Na); on each side of the structure the “shell” material (mafic, high Fe and Mg), and dust accumulation (high H) inside the void space.

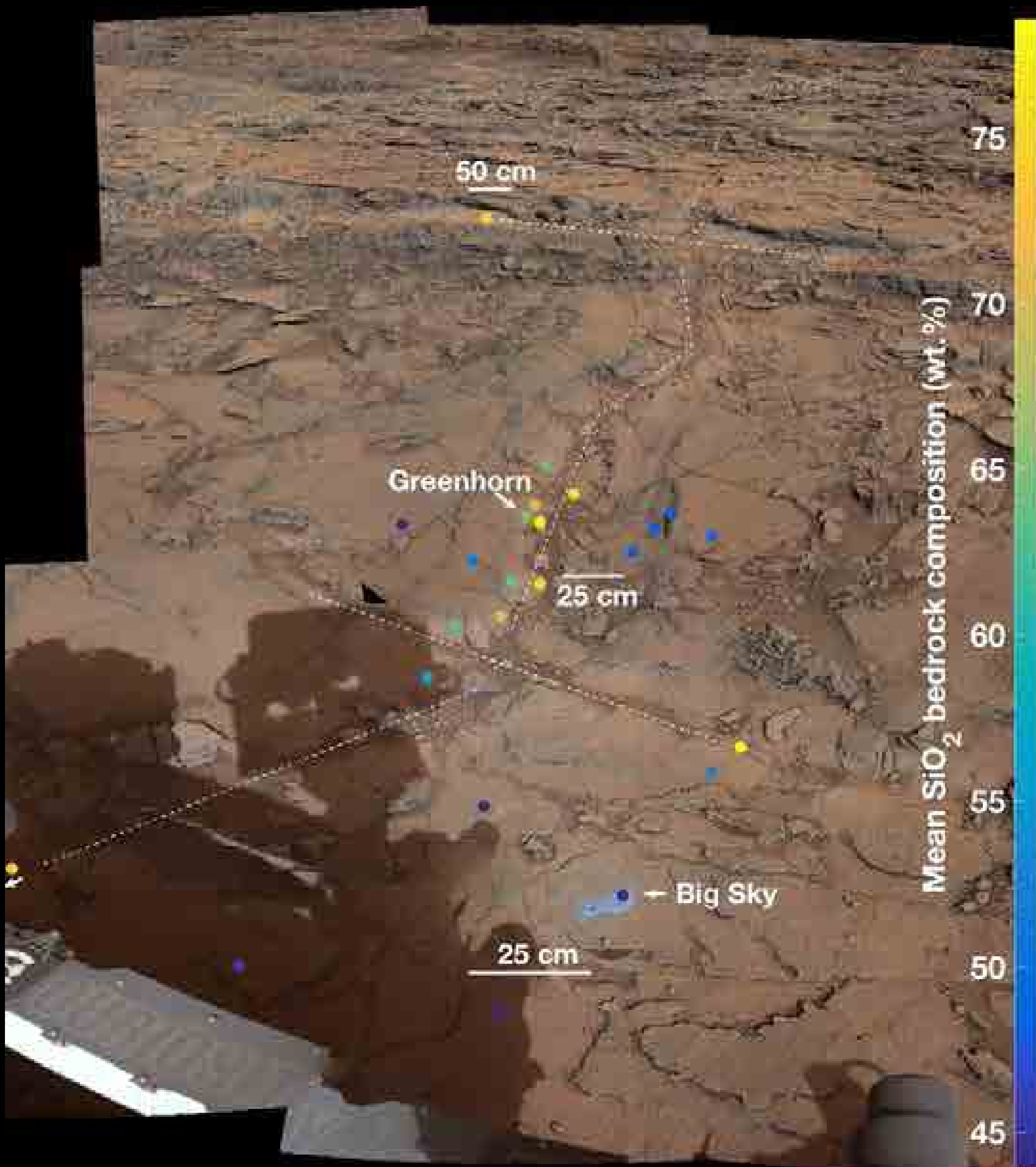
Fine scale survey of large areas (1/2)



Comprehensive analysis of the Shaler unit. At each location, several points (5 -10 typically) are sampled by 30 laser shots each

- Anderson R.B. et al. (2015) ChemCam Results from the Shaler Outcrop in Gale Crater, Mars.Icarus, 249, 2-21.

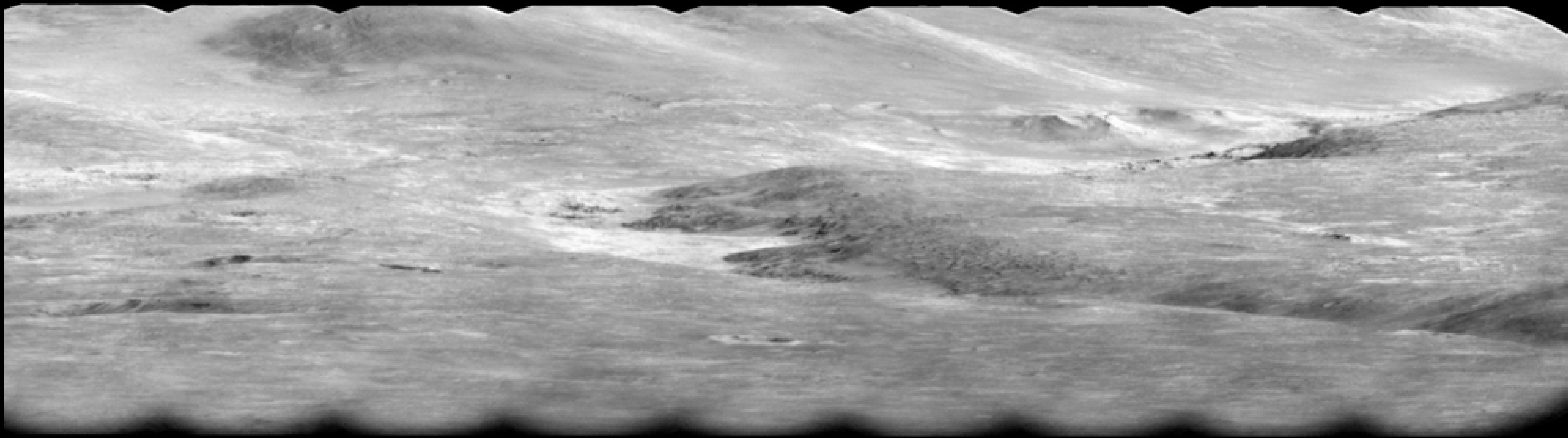
Fine scale survey of large areas (2/2)



Annotated map of the Greenhorn high-silica halo. It shows how ChemCam can track cm-scale variations in bedrock chemistry over large areas because of its speed and remote sensing ability.

- Frydenvang J., et al. (2017) Discovery of silica-rich lacustrine and eolian sedimentary rocks in Gale crater, Mars. Geophys. Res. Lett. DOI: 10.1002/2017GL073323.

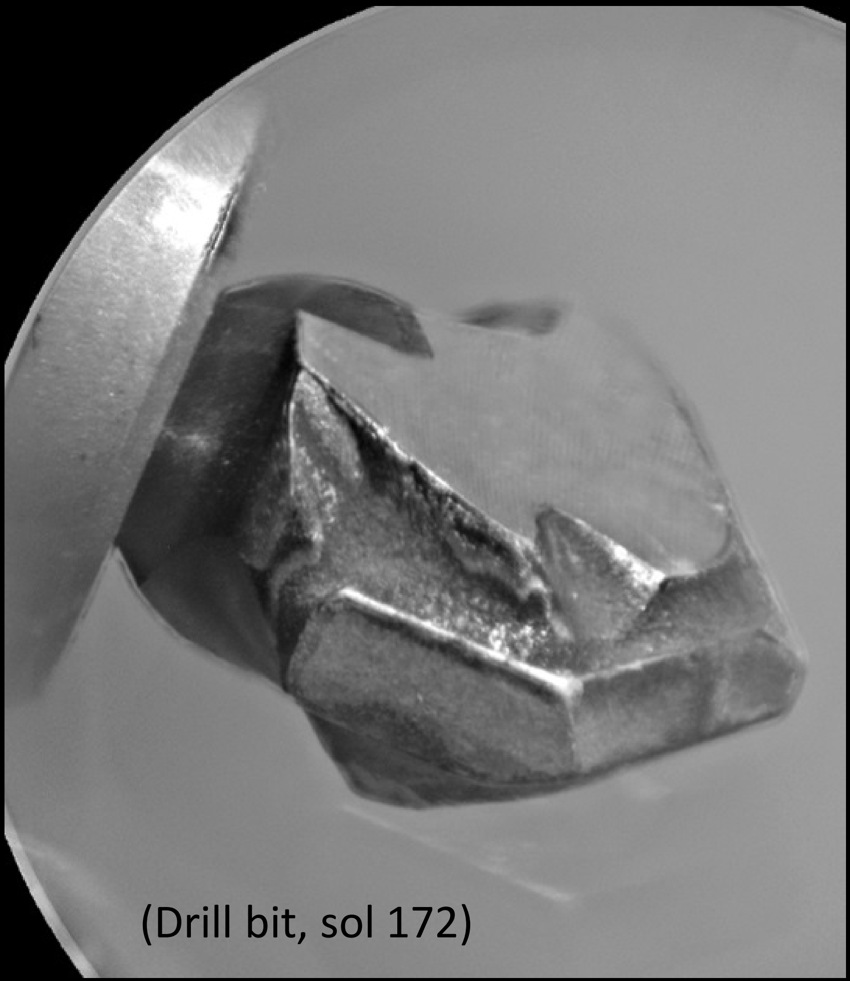
Long-Distance Imaging



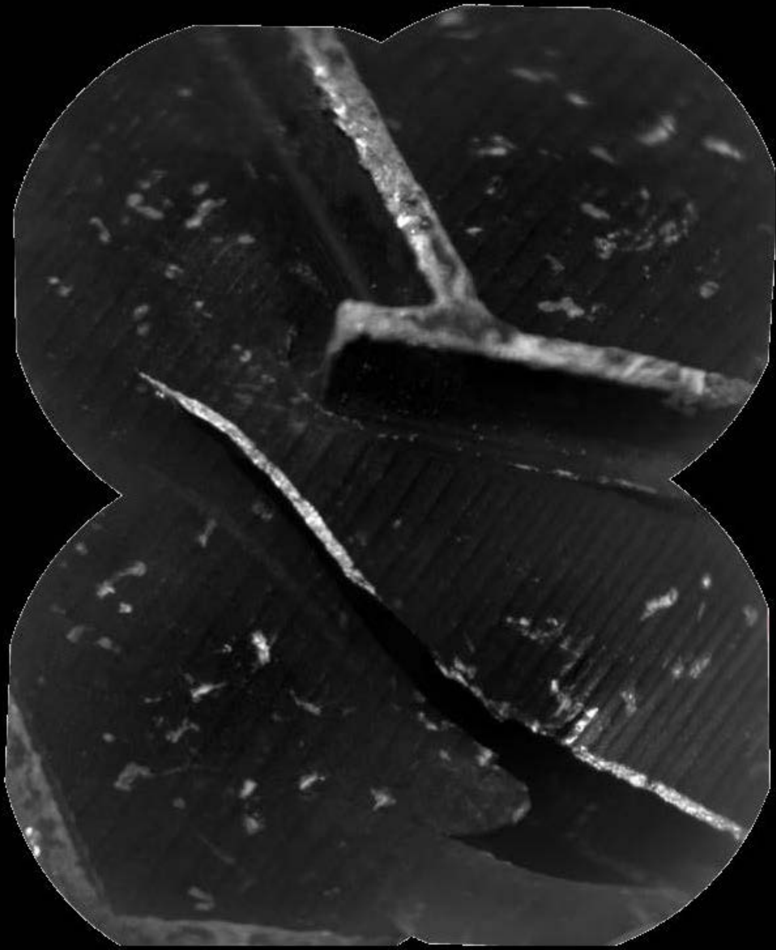
Peace Vallis campaign - RMI - sol 1300

Assisting rover operations

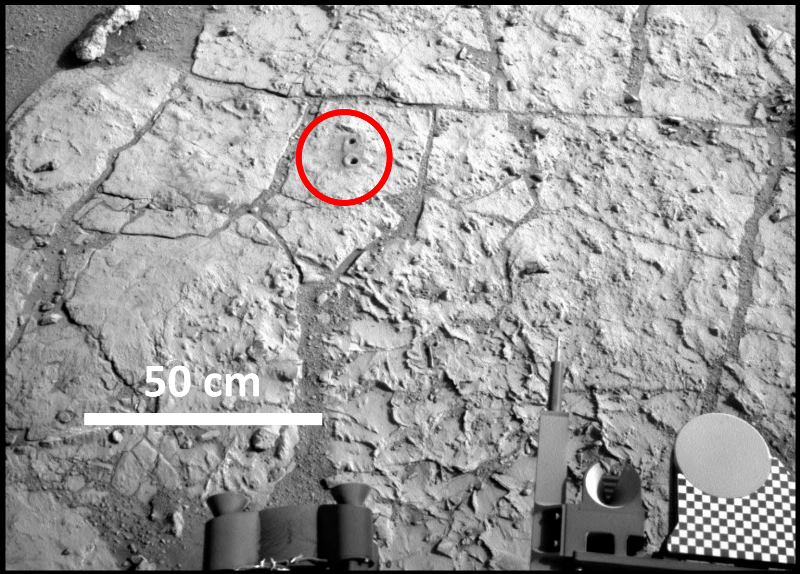
(Wheel inspection, sol 520)

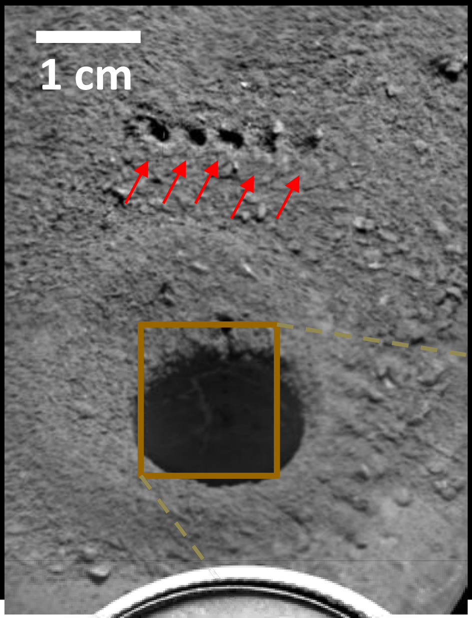


(Drill bit, sol 172)

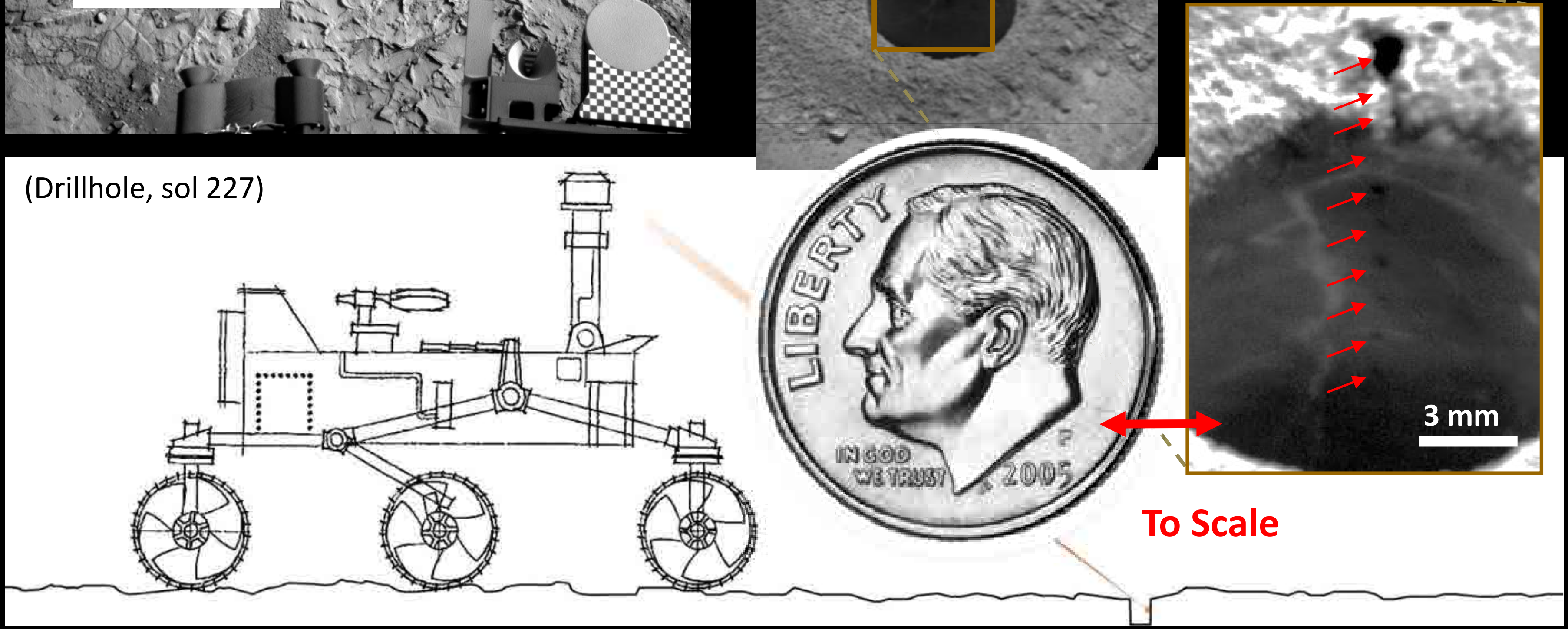


Fine pointing

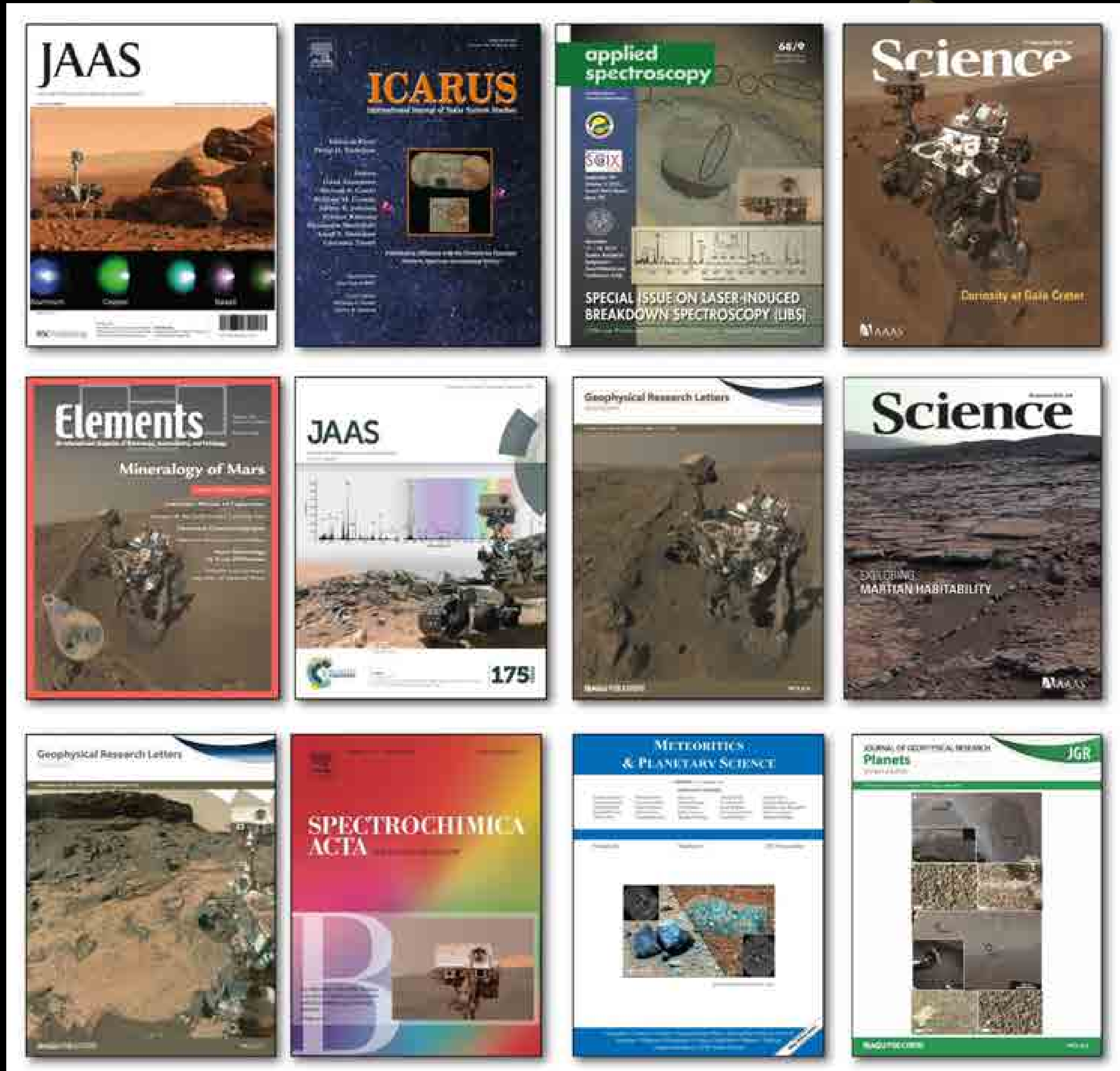


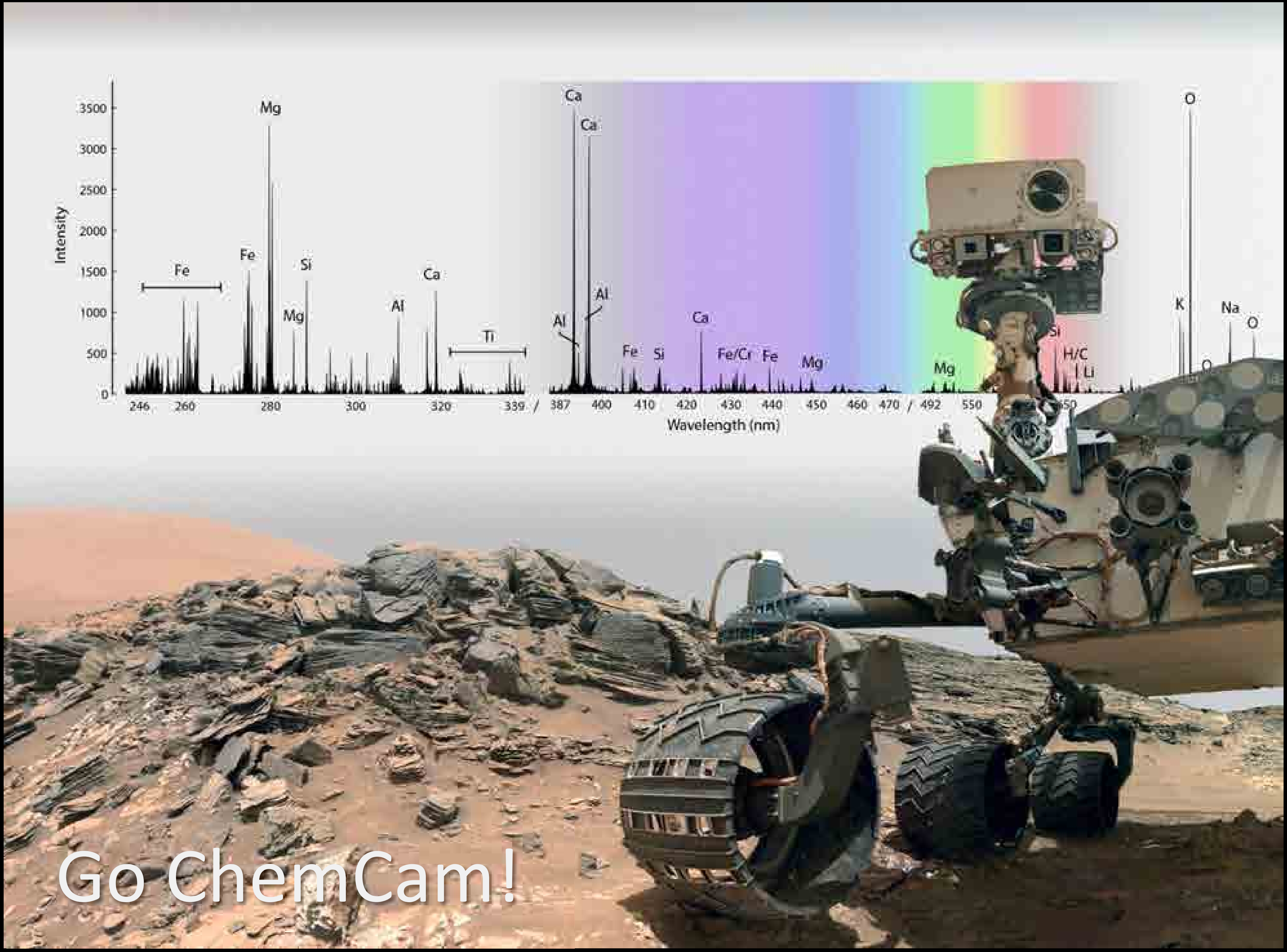


Good to
±0.5 mrad



Magazine Covers

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Wavelength (nm)
Go ChemCam!