

## THE SULFATE UNIT AT GALE CRATER: WHAT TO EXPECT THERE AND HOW TO EXPLORE IT.

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**Introduction:** Gale Crater was selected as landing site for the Curiosity rover because of a sequence of clay, hematite and sulfate signals detected from orbit on the slopes of Mount Sharp [1]. The transition in minerals is expected to shed light in the changing environmental conditions over the first one billion years on Mars, a time frame when life arose on Earth.

As of sol 2985, the rover has traversed ~23km from its landing site and climbed across the first two areas, closing in on the sulfate unit. Here, we will speculate, what the rover might encounter in that unit, based on earlier sulfate detections in previous rover missions and in-situ sulfates already seen in Gale Crater. We will discuss, how the rover can efficiently explore the sulfate unit and how optimal drill samples for SAM and Chemin might be selected, in particular by the use of the APXS [2].

**Method:** The APXS is an arm-mounted X-ray spectrometer using a combination of PIXE and XRF to quantify 16 standard elements, among them sulfur, with high precision, good accuracy and low detection limits. Starting with Na, elements are quantified by their characteristic X-ray peaks. Their usual oxides are normalized to 100%, assuming a homogeneous and water and carbonate free sample. The assumption that sulfur is fully oxidized as SO<sub>3</sub> in the overwhelming number of cases can be confirmed by quantification of the invisible elements – essentially oxygen – using the APXS scatter peak method [3] or other mineralogical results like CheMin or Moessbauer. Identifying and quantifying sulfate candidates is straight forward using APXS results in many cases through mass balance or elemental correlations; however, detailed structural information, including the hydration state is not possible. These details require dedicated drill campaigns of several weeks for CheMin and SAM.

We will first discuss possible settings the sulfate unit could represent, based on already encountered sulfate deposits from MSL and MER.

**Soils:** The unconsolidated material (soil) at all landing sites, including Pathfinder and Viking, shows similarity in overall composition – interpreted as average martian crust- and a significant abundance of sulfur, about 5% SO<sub>3</sub>. Sulfur correlates well with chlorine and zinc in soils (fig 1), and with the Fe<sup>3+</sup>/Fe<sub>T</sub> content from Moessbauer on MER. These phases likely represent the fine Martian dust [4] and are usually linked to the amorphous component in CheMin XRD, since the amount of crystalline sulfates in a few soils cannot account for the SO<sub>3</sub> abundance from APXS.

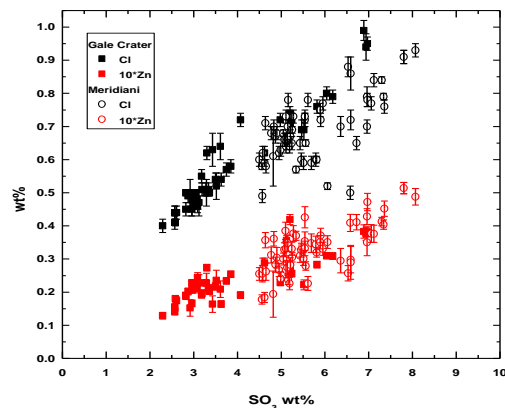


Figure 1 S vs Cl and Zn in soils

**Meridiani Planum:** The dominant bedrock at Meridiani is the Burns Formation, a sandstone with up to 25% SO<sub>3</sub> from APXS and hematite and jarosite from Moessbauer. Over the traverse of ~45km, the bedrock is remarkably homogeneous, with some variations with depth in impact craters, interpreted as dissolved Mg-sulfates caused by changing ground water levels. The observed 1:1 molar decrease in Mg and S is one example for the application of bulk chemistry deduced mineralogy [2]. Plotting the sulfur content against the major possible cations in fig 2 reveals that no single cation can be identified in the Burns formation; however, Mg and Fe are clearly not diluted by the addition of sulfur, although Fe is also attributable to hematite in the bedrock. Abraded interiors have the highest sulfate content, while brushed and as-is surfaces have lower values due to soil/dust cover or preferential abrasion of sulfate minerals from the rock surface, which ultimately could be a source of sulfur in the global soil.

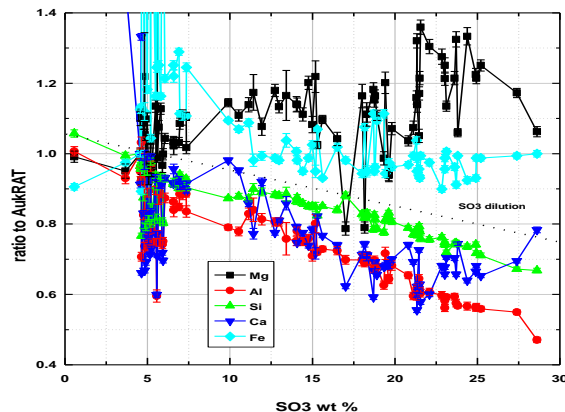
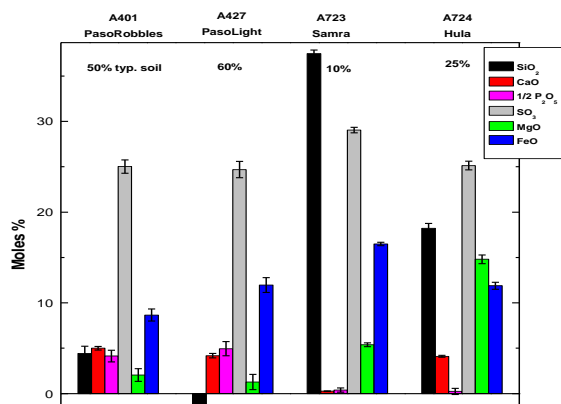


Figure 2 S vs Major Elements in Burns Formation

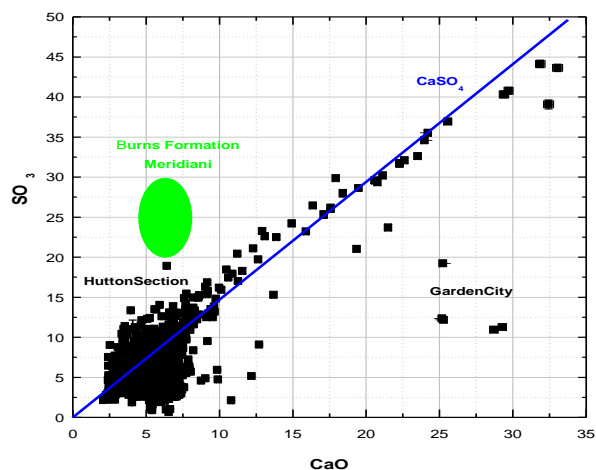
**Gusev Crater:** The Gusev Plains' rock population was dominated by mafic, primitive, olivine bearing rocks like Adirondack [5]. The Rock Abrasion Tool enabled to grind several mm into the rock, where  $\text{SO}_3$  values went down to  $\sim 1\%$ . A variety of sulfates (Mg and Ca) were encountered, typically covered by dust of lower sulfur content. Trenches showed minor excess  $\text{MgSO}_4$ . The largest extent of sulfates was found in whitish subsurface soils exposed by the rover wheels with  $\text{SO}_3$  exceeding 30%. Mass balance showed that after removing an easily quantifiable amount of mixed in usual soil, the remaining material is a varying mixture of  $\text{Fe}^{3+}$ , Mg and Ca sulfates with excess  $\text{SiO}_2$ . These soils were interpreted as remnants of acidic leaching, indicative of fumarolic activity. The scatter peaks indicated large excess of oxygen, equivalent to  $\sim 15\%$  bound water in these soils [3].



**Figure 3** Excess sulfates and silica in PasoRobbles soils

**Gale Crater** showed the same soil composition, warranting a reliable cross calibration of MER APXS and other instrument findings to the MSL mission. The bedrock at YellowKnifeBay, containing  $\sim 20\%$  clays is notably low in sulfate with  $\sim 1\%$   $\text{SO}_3$ . Sulfates at Gale are so far dominated by late stage  $\text{CaSO}_4$  veins and with some  $\text{CaSO}_4$  cement. When all samples are plotted against CaO in fig 4, a clear 1:1 molar trend of CaO and  $\text{SO}_3$  is obvious. The largest veins were found at GardenCity, accompanied by a high Ca phase with enrichments in Ge and Mn, but no  $\text{SO}_3$  [6]. Local  $\text{MgSO}_4$  containing pebbles and concretions were identified in the Murray and Stimson formations through rasters. Minor amounts of Fe-sulfates (e.g. jarosite), detected by CheMin, show excess sulfate over CaO as expected. One bedrock sample, HuttonSection (sol 2694), shows high 18%  $\text{SO}_3$  without any sufficiently elevated cation candidate, possibly resembling the Burns formation.

**Summary and Discussion:** The capability of the APXS to quantify the sulfur content in-situ was crucial for MER and MSL and will allow a flexible and optimized approach to explore the upcoming sulfate unit. Based on the landed results so far, several scenarios can be postulated as what could be expected:



**Figure 4**  $\text{CaSO}_4$  at Gale Crater and comparison to Burns Formation

- Burns formation type of sulfates
- Pure and clearly identifiable sulfates as found at Gusev, possibly from fumarolic activity
- Similar lacustrine bedrock to Murray with different morphology or lower dust cover that obfuscates the sulfate signal seen from orbit
- Higher abundance of Mg or Fe sulfates, occasionally evident in low concentration in the Murray and Stimson formation
- None of the above and no elevated sulfur.

It is worthwhile noting that the Burns formation at Meridiani is not giving a consistent sulfate signal from Orbit, thus entering with a rover the first sulfate unit identified from orbit will help reconciling orbit and rover science.

As done so far on MSL, the APXS will be one of the instruments to select suitable drill samples for in detail characterization. While the APXS sample diameter matches that of the drill, its sampling depth is only the topmost 10 to 100 micrometer. From the experience from Meridiani, brushes or even better mini-drills would be beneficial to expose a homogenized deeper layer of the bedrock. These are quicker to accomplish than a full drill campaign. It is possible that high sulfur deposits might be in amorphous phases, as observed in the soils.

**References:** [1] Milliken, 2010, GRL, [2] Gellert, Clark, (2015) Elements, 11(1), [3] Campbell et al, 2008, JGR, Vol 113, E6, [4] Berger et al, 2016, GRL, Vol 43, [5] Gellert et al, 2004, Science, Vol 305, [6] VanBommel et al, 2017, XRS, Vol 46.

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