INVESTIGATION OF MAGMATIC ACTIVITIES ON EARLY MARS USING IGNEOUS MINERAL CHEMISTRY IN GALE CRATER, MARS.
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Introduction: One objective of rover missions is exploring the geological context of the surroundings. Over the years, igneous petrology and sedimentology have been disconnected, the first investigating magmatic processes and volcanic activities, and the second seeking environmental conditions in the past and assessing the habitability of the planet. Although different, one is related to the other: igneous rocks are altered and broken down, leading to the formation of sedimentary rocks, which can in turn be used to back out the nature of their magmatic source. The *Curiosity* rover that landed in the 3.7 Gyr old impact crater Gale is traveling through sedimentary rocks [1]. About fifty float rocks have been observed, and several of them with ambiguous texture and composition have been classified as igneous or sedimentary depending on studies such as Jake_M [2-3]. The composition of several unambiguous igneous rocks has been analyzed [4-6] but their heterogeneity at a larger instrumental (measurement size < 2 cm) scale prevents the measurement of a bulk composition as performed on Earth. An original approach avoiding these two last issues is to consider igneous mineral chemistry analyzed within igneous and sedimentary rocks to assess magmatic processes that could have formed them. Most *Curiosity* data are used to explore ancient environmental conditions, and a significant number of compositional analyses are under-explored for constraining magmatic activities. We will present how we can make use of sedimentary data for investigating igneous processes in the vicinity of Gale crater.

Geological Context: We focus on the first 750 martian days, corresponding to measurements in a coherent lacustrine sedimentary unit called Bradbury, because all sedimentary rocks were sourced from the same watershed and appear to have a consistent source with minimal alteration [2-3]. Igneous detrital minerals including feldspar and pyroxene, are observed in sedimentary rocks. Monte Carlo models showed that minimal cation loss is observed based on the composition of all Bradbury rocks, implying negligible weathering [3]. Although clay minerals are detected in few rocks [7], chemical compositions of rocks can be explained by a mixture of primary igneous minerals [3]. Variation of composition within Bradbury rocks can be explained by mineral sorting and one distinct source component. While a common magmatic source is suggested, Bradbury sediments likely come from several volcanic eruptions from a single magmatic chamber [9-10]. The occurrence of alkali minerals like sanidine and K-rich rocks throughout Bradbury supports the presence of a potassic component, likely trachytic, while plagioclase and a mafic composition suggest a basaltic component [8-9].

Instruments: Mineral chemistry can be estimated by three instruments onboard *Curiosity*. The CheMin instrument enables detection of mineral assemblages using X-ray diffraction (XRD). Using Rietveld refinement, each mineral is identified according to their 1D XRD pattern [11]. Note that distinction between pyroxene minerals is challenging with the CheMin instrument due to overlapping peaks on XRD patterns and low angular resolution of the instrument [12]. Then, using least square regression and optimization algorithms based on unit-cell parameters, mineral chemistry has been estimated by [11]. Plagioclase composition has been estimated using the $NaAlSi_3O_8$-$CaAl_2Si_2O_8$ system and alkali feldspar is based on the $NaAlSi_3O_8$-$KAlSi_3O_8$ system (stars in Fig.1). Two mudstone samples (John Klein and Cumberland) and one sandstone sample (Windjana) were analyzed by CheMin at Yellowknife Bay and Kimberley, respectively.

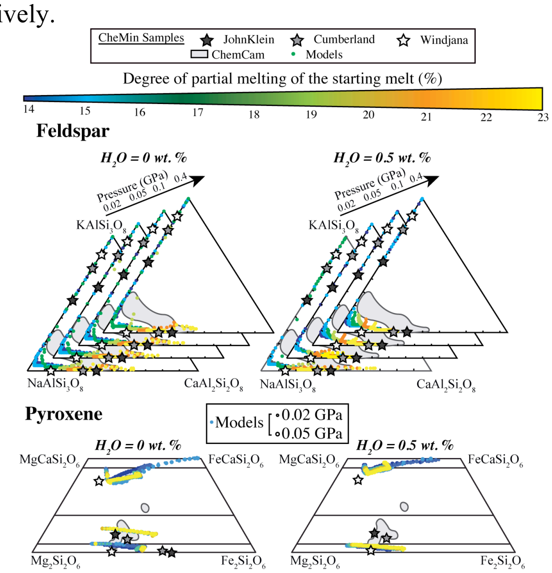

Figure 1. Ternary diagrams of feldspars (top) and pyroxene (bottom) quadrilateral. Stars correspond to CheMin composition and the gray patches to ChemCam composition. The colored dots are the composition of feldspar and pyroxene that crystallized during fractional crystallization at FMQ+1

of a melt extracted at distinct melting degree during the adiabatic ascent of a primitive mantle composition, without any water (left panels) and with 0.5 wt.% of water (right panels) at distinct pressure.

The ChemCam instrument enables the analysis of the chemical compositions of rocks at hundreds of micrometer scale (350-550 µm) using laser induced breakdown spectroscopy (LIBS), which may provide the composition of minerals when they are larger than the beam spot (>550 µm) [13]. Within >5000 LIBS points, we performed a typical stoichiometric filtering allowing us to distinguish 56 feldspar and 10 pyroxene mineral compositions (grey patches in Fig. 1).

Finally, the Alpha Particle X-ray Spectrometer (APXS) analyzes the composition of rocks with a 1.6 cm diameter spot size. Monte Carlo mass balance modeling allowed [3] to decipher a feldspar range varying between An_{30} and An_{40} (Fig. 1).

Discussion: Although there could be a more complex history and other ways to form the whole compositional range of igneous minerals analyzed within the Bradbury formation, we are presenting here simple magmatic pathways commonly occurring on Earth using the thermodynamical softwares pMELTS and rhyoliteMELTS [14]. The objective is to find reasonable igneous processes that produce minerals that parallel the compositions of feldspar and pyroxene analyzed by the *Curiosity* rover. As commonly observed for mid-ocean ridge basalts, the adiabatic ascent of a primitive mantle composition [15] partially melting at 2 GPa has been modeled, followed by the extraction of a liquid at distinct degrees of partial melting, which undergoes fractional crystallization at an oxygen fugacity +1 log unit above the fayalite-magnetite-quartz (FMQ) buffer within the crust (0.02-0.4 GPa) with H_2O = 0-0.5 wt. %. These latter conditions correspond to those recorded within igneous clasts from the Noachian martian breccia NWA 7034 and paired and within Gale igneous rocks (colored dots in Fig. 1) [16-17]. To check the reliability of these 2-step models, we also tested fractional crystallization at similar conditions (FMQ+1; P=0.02-0.4 GPa; H_2O = 0-0.5 wt. %) of starting compositions corresponding to that of magmas with distinct melting degrees obtained from isobaric experiments at 2 GPa [18]. Mineral compositions obtained from both models are similar.

As shown on Fig. 1, the whole range of observed feldspar compositions cannot be reproduced by fractionation of one magma only. Indeed, while alkali feldspar and Na-plagioclase likely crystallized from fractional crystallization of a low-degree melt (here <15%), plagioclase and pyroxene can only be formed by fractional crystallization of a higher degree melt (here >19%). The corresponding liquid descent lines are broadly in agreement with compositions estimated by ChemCam corresponding to float igneous rocks (Fig. 2) [4-6].

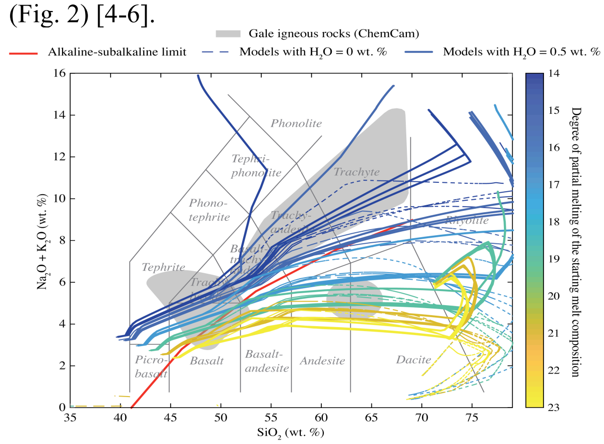

Figure 2. Silica versus alkali content. Lines show the liquid lines of descent from magmas with distinct degrees of melting. Gray patches represents the composition of Gale igneous rocks [4-6].

Trachytic to rhyolitic magmas crystallize alkali feldspar, and andesite to dacite magmas likely form plagioclase. Therefore, at least two starting magmas at distinct melting degrees, which could easily come from a single mantle source, are necessary to explain the whole compositional range of feldspar and pyroxene analyzed within Bradbury rocks.

Conclusion: Because rocks from the Bradbury formation are likely originating from the same magmatic source with minimal weathering as supported by several studies using different approaches, igneous mineral chemistry analyzed by CheMin and ChemCam allows us to back out reasonable magmatic pathways that could have crystallized them. Fractional crystallization of at least two starting magmas originating from distinct melting degrees of a single mantle source can explain the whole range of feldspar and pyroxene composition. Both alkaline and sub-alkaline liquids can be produced, with compositions corresponding to those of the igneous rocks analyzed by ChemCam within the Bradbury formation, highlighting the complexity of Mars magmatism.

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