UNRAVELING THE ORIGIN AND PETROLOGY OF THE MARTIAN CRUST WITH A HELICOPTER.

V. Payré[1], A. Udry[2], A. A. Fraeman[3], W. Rapin[4], C. C. Bedford[5], and R. C. Wiens[5]. [1]Department of Earth and Environmental Sciences, University of Iowa, IA, USA (valerie-payre@uiowa.edu), [2]Department of Geosciences, University of Nevada Las Vegas, NV, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, CA, USA, [4]Institut de Recherche en Astrophysique et Planétologie, Toulouse, France, [5]Department of Earth, Atmospheric and Planetary Sciences, Purdue University, IN, USA.

Introduction: Remote sensing observations, rover analyses, and martian meteorite measurements reveal a martian crust composition more complex than a homogeneous mafic crust (SiO_2 < 52 wt.%). Noachian igneous rocks with compositions from basaltic to trachytic and dioritic were discovered by the *Curiosity* rover [1]. Visible/near infrared (VNIR) spectral observations with the Compact Reconnaissance Imager for Mars (CRISM) detected feldspar-bearing outcrops excavated in Noachian terrains with evolved (defined here as SiO_2 > 52 wt.%) compositions [2-3]. The Northwestern Africa (NWA) 7034 martian brecciated meteorite and its paired rocks contains 4.49 Ga igneous clasts of mafic and evolved composition with monzonitic clasts [e.g., 4]. Such igneous diversity contrasts from the mafic and ultramafic igneous rocks found by the Mars Exploration Rovers (MER) and in younger martian meteorites (≤ 2.4 Ga; [5]).

The discovery of evolved materials in Noachian times raises questions about the petrology of the martian crust, thought to be homogeneously basaltic. The lack of a regional- to global-scale overview of centimetric to millimetric textural and chemical data of Noachian igneous rocks yet prevents the characterization of the early martian crust and its formation. This abstract will review the detections of evolved rocks in Noachian terrains and present the advantages of a future mid-air deployed helicopter mission to unravel the petrology and formation of the martian crust.

Evolved Crustal Components: In Gale crater, the *Curiosity* rover analyzed a set of Noachian alkaline and sub-alkaline igneous rocks from mafic to felsic compositions [1]. These two suites cannot have formed the same way: the alkaline suite was produced from an alkali-rich parental magma through fractional crystallization, crustal assimilation, and/or mantle metasomatism, while the subalkaline suite likely formed through partial melting of mafic materials in hydrous conditions as observed on Earth [6-7]. The isotopic analyses of zircons in NWA 7034 revealed that a possible andesitic crust was extracted from the mantle as soon as 20 Myr after the solar system formation, suggesting that a sub-alkaline crust was formed very early after the formation of the planet [4]. The occurrence of sub-alkaline diorites in Gale crater thus raises questions about whether they are remnant of that early crust. VNIR CRISM spectral signals in exposed Noachian regions reveal the presence of feldspar-bearing outcrops. Feldspar is a mineral difficult to observe with VNIR; Fe must be present to generate a diagnostic spectra absorption at 1.3µm, and this absorption is easily masked by the presence of other minerals [8-9]. Detecting feldspar spectral signal with CRISM could thus suggest an evolved outcrop. Combining feldspar detections with thermal data from the Thermal Emission Imaging System (THEMIS) orbital instrument show that, especially in one of the oldest martian regions Terra Sirenum/Cimmeria (TSC), feldspar outcrops are indeed, of evolved compositions, but their alkali content cannot be assessed (Fig. 1). To date, >200 outcrops on Mars exhibit feldspar VNIR signals, and some of them are associated with low-Ca pyroxene (LCP: pigeonite and orthopyroxene; [10]; Fig. 2). High-degree of partial melting in a thin lithosphere in early Mars could favor the crystallization of LCP, possibly leading to residual alkali melts if fractional crystallization occurs [11]. Yet, the relationship between feldspar and LCP is ambiguous, as clear geologic relationship between these two minerals is not always observed. No LCP-rich rock has been found in Gale crater, but the martian meteorite Allan Hills (ALH) 84001 is a ~4.1 Ga orthopyroxene cumulate with compositions matching orthopyroxene minerals in 4.48 Ga basaltic and noritic clasts of NWA 7034 [12].

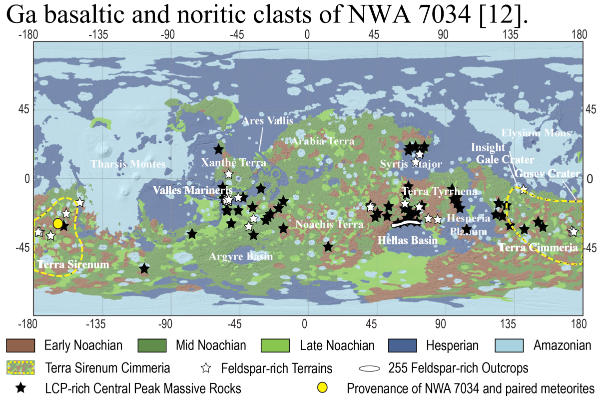

Fig. 1. Geological map modified from Tanaka et al. (2014) with the location of feldspar sites and LCP-rich central crater peak massive rocks. K-Th-rich terrain in TSC (yellow dashed line) is illustrated.

To summarize, evolved feldspar-bearing outcrops are scattered in Noachian terrains, suggesting the presence of an evolved crust characterized by alkaline and sub-alkaline rocks, as well as LCP. Mafic rocks might be part of the Noachian crust, but geophysical and seismic data from the *Insight* lander support the presence of a crust lighter than being basaltic only [6], supporting the occurrence of an evolved component below the mafic surface observed from orbit.

The relationship between feldspar and LCP and their petrology is unknown, preventing a characterization of the petrology of the early martian crust. Whether such evolved crust is primary, i.e., extracted from the magma ocean, or secondary, i.e., formed following modifications of the primary crust through magmatic/impact processes, and which processes formed it are unknown.

Future Missions: Deciphering the petrology of the martian crust is not only essential to constrain its formation and evolution, but also more broadly to provide insights into the formation of terrestrial crusts. Characterization of the crustal petrology requires imaging and chemical/mineralogical analyses both a centimeter to micrometer-scale as well as a meter to kilometer regional scale. Imaging will reveal the geological context of crustal outcrops, including the relationship between LCP- and feldspar-bearing lithologies and their texture, as well as information regarding crystallinity, indicating the eruptive conditions and the intrusive or extrusive nature of the body. Mineralogical and chemical analyses of major elements will classify the type of igneous rocks. Further mineralogical measurements will provide important insights regarding the magmatic conditions and processes that formed the outcrops. A helicopter mission would be ideal platform to provide a regional coverage with high-resolution data.

The proposed Mars Science Helicopter can carry up to 5 kg payload [13], which would permit a miniaturized VNIR spectrometer for cm-scale mineralogical mapping [14] and a micro-LIBS coupled with a micro-imager for chemical analyses at <100 µm scale and micro-scale imaging [15]. Such helicopter could travel kilometers to detect promising feldspar and LCP terrains, and document their geologic relationship, and measure their texture and composition at a micron scale.

Fifty microns scale-LIBS analyses would allow chemical mapping over 10 x 10 grids of major, minor, and trace elements that the ChemCam and SuperCam LIBS instruments (on board of the *Curiosity* and *Perseverance* rover, respectively) could not detect. Several trace elements including Rare Earth Elements (REE) (e.g., Rb, Sr, Ba, Cr, Ni, La, Ce, Eu, Gd, Dy, Nd, Pr, and Sm) have been indeed detected using a similar LIBS system on laboratory samples [e.g., 16-17]. Because the µLIBS spot size should be in the 50-100 µm range covering up to 30 x 30 grids, grains in a similar size range could be analyzed, even if they represent <1% of the bulk. REE-rich minerals, which have a diluted LIBS signal when analyzed with >350 µm LIBS spot size, could be individually analyzed if >50-100 µm in size. Overall, regional measurements of the composition and micro-textures on Noachian magmatic rocks could help constrain their formation, understand the nature of their source, and decipher whether the evolved crust is primary or secondary.

Landing Sites: Feldspar- and LCP- bearing outcrops that were detected with CRISM in Noachian terrains are mainly excavated by impacts, fractures, faults, or erosion [3]. The TSC region is one of the oldest terrains of Mars that encompasses the ejection site of NWA 7034, Gale crater where evolved rocks were also found, and feldspar and LCP-bearing excavated outcrops [3]. This region is enigmatic by its geochemical and magnetic anomalies, making it a possible ancient evolved crustal component. Valles Marineris is a canyon exposing a 7 km pile of crust with LCP and feldspar-bearing rocks near the lower part of the walls. Finally, Hellas basin is a 2,300 km impact crater of 6.5 km deep crustal profile, exhibiting layers of LCP and feldspar.

The petrology of these feldspar outcrops varies depending on studies: anorthosites, granites, feldspar cumulates, basalts, and evolved rocks. The presence of LCP has been attributed to either orthopyroxene cumulates, basalts, norites, and gabbros. *In-situ* measurements at the regional scale are now required to discriminate between the different petrology to unravel the magmatic processes and crustal formation. A helicopter traveling through such complex ancient regions would enlighten the relationship between LCP and feldspar observed in orbital data, providing crucial insights regarding the long-standing enigmas on the origin of terrestrial crusts.

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