**NICKEL-COPPER DEPOSITS ON MARS: ORIGIN AND FORMATION.**

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**Introduction:** After its landing in February 2021 in the Jezero crater, the Perseverance rover identified two distinct magmatic formations called Máaz and Séítah on the crater floor [1]. The Máaz formation is thought to consist of different lava flows and/or possibly pyroclastic flows originating from the same parental magma and/or the same magmatic system [2]. They are not petrogenetically linked to the underlying Séítah formation which is the deep ultramafic member of a cumulate series derived from the fractional crystallization and slow cooling of the parent magma at depth [3, 4, 5]. In this paper, we will present observations of high-grade nickel and copper geological samples obtained by the SuperCam instrument [6, 7, 8] on-board Perseverance that support this hypothesis since high nickel concentration can only derive from processes affecting ultramafic rocks [9]. Therefore, it puts constraints on the nature of the original protolith and demonstrates that the presence of ultramafic rocks is likely in the source region of these rocks. Nickel was detected by the several Alpha Particule X-ray Spectrometer (APXS) experiments on board the Opportunity and Curiosity rovers. [10] reported values of Ni enrichment of about 4000 ppm in concretions. In Jezero crater, no Ni enrichments have been observed with the PIXL instrument in the olivine-rich abraded patches at the detection limit of about 300 ppm [11].

We will describe SuperCam's Ni-rich data up to sol 913, giving the Ni quantification and its relationship with the other major and minor elements to try to constrain the processes that led to its enrichment and to the alteration of these rocks.

**Data and methodology:** To perform our analyses, we use the data from the SuperCam instrument--mainly the LIBS that gives chemical information and VISIR data that provides mineralogical information. Since each LIBS observation usually consists of 30 laser shots, shot-to-shot correlation between elements can bring useful insights into the mineral phases. Major-element Oxide Composition (MOC) data are derived from multivariate regression methods [12]. SuperCam passive reflectance spectra cover the 0.39–0.85 μm (VIS) and 1.3–2.6 μm (NIR) ranges, which allow the identification of a wide variety of minerals, especially hydrated species [13]

**Results:** All the Ni enrichments in Jezero have been observed in Al-rich, light-toned float rocks along the traverse. The LIBS spectra as well as the MOC compositions of the Al-rich rocks exhibit some very peculiar properties. For the major elements the targets are strongly depleted in Fe, Mg, Ca, and Na and strongly enriched in Ti, and Al (on average >25.0 $Al_2O_3$ wt. %). No S was detected by LIBS in the targets. For the minor elements the targets are strongly enriched in Ni and Cr. Ba and Sr are also locally enriched but Mn is depleted in comparison to other rocks. The VISIR spectra also exhibit some peculiar features, in particular the detection of spinel in the Dolgoi_Island target (Sol 657) and the detection of kaolinite in target Chignik (Sol 680) [14].

*Ni enrichment:* Ni is identified by its emission lines at 302.3 nm and 310.2 nm. Almost all of the Al-rich targets exhibit the signature of Ni, which is unusual. A preliminary quantification of this element was performed based on observations of Fe-Ni meteorites and corresponding calibration with the ChemCam instrument in Gale crater [15], in which the Ni content varied between 4.0 and 24.0 wt. %. A calibration was possible between the two instruments since the spectrometers in the UV range where the main lines of Ni are present are nearly identical. This preliminary calibration gives a Ni content up to 9.0. ± 1.0 wt. % in the Jezero target Finch_Lake (Sol 784), point #1, and half of the points contain more than 0.5 wt.% Ni. This is the first time that nickel at the 1+ wt % level is found at the surface of Mars [16]. This is one order of magnitude larger than the Ni content found in martian meteorites with at most 788 ppm in Northwest Africa (NWA) 2737 [17] although Ni-enriched pyrrhotite has been identified in shergottites [18].

*Cu detection:* Cu is identified by two lines at 324.8 nm and 327.5 nm. Cu has the strongest detection in Finch_Lake point #10 and is present in other high Ni points. From the shot-to-shot perspective, Cu is also strongly correlated with Ni. When compared to the SuperCam on-board Calibration targets LJMN10106 and NTE010301, we estimate the Cu content to be at most around 2000 ppm [19].

**Discussion:** On Earth, the joint presence of a high proportion of Ni and Cu is diagnostic of the so-called

Ni-Cu-PGE (Platinum Group Element) sulphide deposits. They are thought to derive from magma that has experienced high degrees of partial melting. This magma must then be rapidly transported to the crust to reduce the possibility of Ni removal from the magma by crystallization of olivine or segregation of sulphide from the silicate magma [20]. Ni-Cu sulphide ore deposits are found at the base of mafic and ultramafic bodies. All their host rocks, except the Sudbury Igneous Complex, are thought to be mantle-derived melts. The Sudbury Igneous Complex is the product of complete melting of continental crust in a gigantic impact [21]. In the case of mantle-derived magmas, a high degree of partial melting of the mantle is needed to extract compatible elements (Ni and PGE) from mantle rocks (mainly olivine) into the silicate magma. Ni and Cu are deposited from an immiscible sulphide liquid in rapidly crystallising ultramafic extrusive rocks. Pentlandite ($(Fe,Ni)_9S_8$) is the major Ni sulphide while chalcopyrite ($CuFeS_2$) is the major Cu sulphide. Sulphur saturation can occur as a result of cooling deep-sourced melts enriched in mantle-derived sulphides or by the assimilation of sulphide-rich sedimentary host rocks. Due to the high density of the sulphide phase, deposits are typically located at the base of flows [22]. On Mars, the study by [23] first investigated the potential of Martian magmatic systems to host metal-rich sulphide mineralisation. Critical mineral system parameters and processes for Ni-Cu±(PGE) sulphides in mafic to ultramafic magmatic systems include: (1) melting from an appropriate mantle source, which supplies metals and sulphur to the system, (2) an active lithosphere-scale pathway, which ensures the delivery of high-flux melt from deep mantle reservoirs to uppermost crustal regions, (3) sulphide saturation, which can be achieved by a wide range of mechanisms, (4) physical processes that concentrate sulphides, and (5) sulphide preservation [24]. However, he most efficient way to reach sulphide saturation and sulphide liquid segregation in a sulphide-undersaturated silicate melt is the addition of sulphur in amounts that exceed the capacity of the magma to dissolve it ([22], [24]). The Martian crust is recognised to be extremely rich in sulphur with abundances estimated to be typically 2 orders of magnitude higher than those of igneous and sedimentary rocks on Earth ([25], [26]). Hence, the assimilation of crustal sulphur appears to be the most promising and feasible mechanism to promote sulphide supersaturation in Martian magmas. The Martian crust has long been viewed as dominated by mafic rocks. Recent discoveries, however, altered this view. Crustal materials that spectrally resemble anorthositic rocks have been identified by [27] and [28]. Fragments of feldspar-rich lithology (potentially anorthosites) have been documented using LIBS on-board MSL Curiosity at the Gale Crater landing site [29]. The widespread occurrence of silica-rich rocks may be also inferred from monzonitic clasts in the regolith breccia NWA 7034, NWA 7533 and paired samples [30]. Finally, comparison of the density of Martian basalts with geophysical constraints on the density of the Martian crust suggests a buried felsic crustal component [31]. Given these large uncertainties, it is unconstrained but possible that Martian mantle melts significantly interacted with crustal silica-rich reservoirs to reach sulphide supersaturation. However, the fact that the high nickel float rock might result from the intense oxidative alteration of orthomagmatic sulphides ([32], [33]) embedded in an evolved basement is further sustained by the presence of the Isidis mega-breccias [34] which have similar mineralogical associations as observed from orbit. This supports the idea that these float rocks might originate from a giant impact similar to the Sudbury Impact Complex in which 40 percent of the total Ni-Cu-PGE inventory is related to quartz diorite in offset dikes and Sudbury breccia belts [22].

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