THE PETROGENESIS OF QUARTIER: AN EVOLVED OLIVINE CUMULATE ROCK IN THE SÉITAH FORMATION.

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Introduction: One of the main units on the floor of Jezero Crater (Mars) is the ~3.9 Ga Séitah formation, which may extend beyond the crater as part of a regional olivine-bearing unit [*1*, *2*]. The Perseverance rover made detailed observations at three outcrops in the Séitah formation: Bastide, Brac, and Issole [*1*, *3*]. Observations on Brac and Issole outcrops include PIXL X-ray Fluorescence (XRF) map scans and multicolor Micro-Context Camera (MCC) optical images of abraded rock surfaces [*4*]. Quartier is the name of the abraded patch in the Issole outcrop from which MCC and XRF data were acquired [*1*, *3*]. The MCC images cover the entire patch, while the XRF scans are of two smaller areas, Quartier 1 and 2. Here, we describe rock textures and mineral chemistry in Quartier 2, as this area exposes more igneous features (Figure 1) [*3*]. From this map scan, we estimate the bulk rock composition and a range of magma compositions (with crystallization paths) that could have been parental to Quartier.

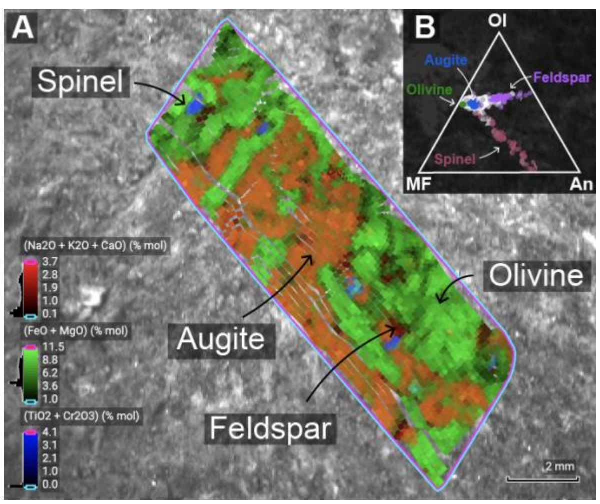

Figure 1. A. *RGB image from PIXLISE showing main phases in Quartier. Red – (Na_2O + K_2O + CaO); Green – (FeO + MgO); Blue – (TiO_2 + Cr_2O_3). Oxides are given in mol%.* ***B.*** *Ternary plot showing mixing trends for olivine (green), augite (blue), spinel (red), feldspar (purple). Corners Ol and An are olivine and anorthite coordinates projected from diopside [*5*], and MF is FeO + MgO – CaO – 3×K_2O – 3×Na_2O, with oxides as mol%.*

Petrography and textural analysis: Phase identification and mixing between phases in Quartier was done via interpretation of XRF compositional data. Primary phases are olivine, clinopyroxene, Fe-Cr-Ti-spinel, and minor proportions of feldspar (Figure 1). Secondary phases (products of aqueous alteration) include perchlorates, sulfates, carbonates, and a low-(Fe-Mg)-silicate [*6*]. Most olivine crystals are elongated, with observed lengths from less than 1 mm up to 8 mm. They display a variety of morphologies such as tabular, skeletal (i.e., hopper), and dendritic that are consistent with rapid crystal growth due to magma undercooling [*7*]. Olivine is commonly enclosed by clinopyroxene crystals of variable size, which define a poikilitic texture typical of cumulate rocks. A similar texture is seen in the Dourbes abrasion of the Brac outcrop [*3*]. Spinels and feldspar are also interstitial to the olivine. Analysis spots where spinel and feldspar are dominant represent variable mixtures with other primary and secondary phases.

Mineral chemistry: The compositions of olivine and augite were estimated from analyzed spots that best match ideal stoichiometric relationships, such as molar SiO_2/(FeO+MgO)~0.5 and coordinates in projection space [*5*]. Final compositions were obtained after removal of perchlorates and sulfates following the method of [*6*]. For analysis spots with Fe-Cr-Ti-minerals, we assumed their composition is a linear mixture of spinel with different proportions of average olivine and augite. A system of mass balance equations was solved to calculate the proportion of each phase in the mixture and the composition of spinel. The composition of feldspar spots was extrapolated to stoichiometric feldspar, following mixing lines in ternary diagrams.

Olivine and augite are more Fe-rich in Quartier than in Dourbes [*3*]. The average olivine composition is $Fo_{43\pm3}$ and augite is $Wo_{36\pm6}En_{38\pm2}Fs_{26\pm5}$. Spinel compositions are low in Al_2O_3 and have systematic variations in FeO*, TiO_2, and Cr_2O_3 that define mixing relationships between ulvöspinel and chromite endmembers. Feldspar-rich spots have low totals and show mixing with olivine, clinopyroxene, and secondary phases. The approximate feldspar is An_5–Ab_{77}–Or_{18}.

A first attempt at estimating an expanded whole-rock composition for Quartier: Inferences about the origin and evolution of Quartier and other igneous cumulates requires knowledge of their chemistry. A bulk composition of the scan area can be obtained from PIXL analysis by integration of XRF data from all the analyzed spots. However, this composition may not be representative of the Issole outcrop (or even the abraded patch), as local variability in mineral proportions can lead to sampling bias. To account for this, a range of possible bulk compositions corresponding to wider areas of the patch in the multispectral images was estimated using a *Random Forest* algorithm of image classification with the phases identified in the XRF scan as training datasets [*8*]. We assumed that only the primary phases described above crystallized from the parental magma and the remaining phases resulted from secondary alteration and introduction of aqueous fluids. The XRF scan area includes 60% olivine, 36% augite 2% spinel, and 2% feldspar, but MCC images show that the whole abraded patch has 78% olivine and 18% pyroxene. These differences in mineral abundances translate into relatively large variations in FeO and CaO, but a small change in bulk Mg# (from 44 to 47). The bulk composition is thus dominated by olivine and augite abundances, as the spinel and feldspar spots represent mixtures with these phases.

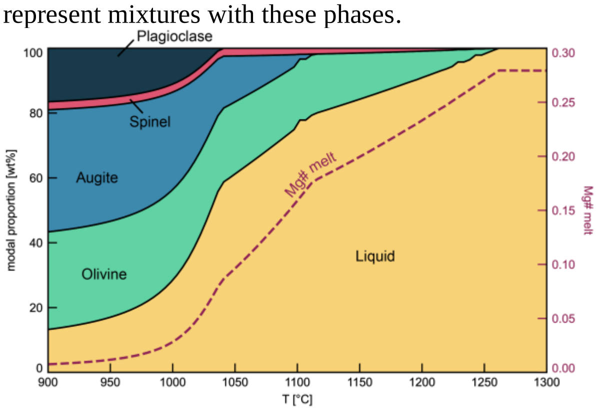

Figure 2. *Modal box of phases produced during fractional crystallization of a magma in equilibrium with olivine in Quartier. The compositional system is Na_2O-K_2O-CaO-FeO-MgO-Al_2O_3-SiO2-TiO_2-O_2. The proportion of cumulus olivine is ~50% and the $Fe^{3+}/\Sigma Fe$ is assumed to be 0.01.*

Magmas in equilibrium with Quartier: A family of potential magma compositions in equilibrium with the olivine in Quartier was estimated following a mass balance approach. We assumed an FeO-MgO bulk distribution coefficient between olivine and melt (K_D) of 0.35 [*9*], different proportions of olivine coexisting in equilibrium with the melt, and variable $Fe^{3+}/\Sigma Fe$ ratios. For each of the calculated magmas, we estimated the olivine liquidus temperature using thermodynamic modeling and empirical thermometers based on parametrization of experimental data.

Modeling these systems using the Perple_X thermodynamic package [*10*] with the activity-composition models of [*11*] yields olivine on the liquidus with compositions similar to that of Quartier at temperatures of ~1260 °C [*10*, *11*]. These temperatures are also comparable to those obtained with olivine-liquid thermometers (~1240 °C) for the same liquid compositions [*12*, *13*]. Valid thermodynamic solutions require ~40-50% of cumulus olivine in equilibrium with a silicate melt with Mg# ~30 at low $Fe^{3+}/\Sigma Fe$ (i.e., <0.05; fO_2 < QFM–2). More primitive or evolved magmas would result in lower K_D values or augite/spinel as phases in the liquidus. The crystallization sequence is olivine → augite/spinel → feldspar, where the appearance and proportion of spinel is controlled by the oxidation state. The predicted feldspar is calcic to intermediate plagioclase, which conflicts with the measured feldspar composition in Quartier. Thus, the measured feldspar composition likely reflects post-magmatic equilibration or crystallization from a less calcic magma composition.

Summary and conclusions: Quartier is an igneous cumulate rock that crystallized from a more Fe-rich magma than Dourbes and then experienced significant subsolidus re-equilibration and interaction with fluids. Preserved igneous textures in Quartier are consistent with rapid olivine growth due to magma undercooling followed by crystallization of augite, spinel, and feldspar from intercumulus magma. Olivine and augite are relatively homogeneous in composition and their modal abundances dominate the bulk composition. Extending this bulk composition to an area larger than the XRF scan increases the olivine proportion relative to augite, which results in lower CaO and TiO_2, higher FeO, and similar Mg#. Thermodynamic modeling and liquid thermometry indicate temperatures of olivine crystallization of ~1240–1260 °C. A magma that crystallizes olivine with the composition of that in Quartier would require low $Fe^{3+}/\Sigma Fe$ (fO_2 < QFM–2) and subtraction of ~40-50% of cumulus olivine from the whole-rock composition.

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