COMPLEXLY ZONED CRYSTALS IN THE NAKHLITE AND CHASSIGNITE METEORITES AND IMPLICATIONS FOR PETROGENESIS.

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Introduction: The nakhlite and chassignite martian meteorite suite shares crystallization (~1.3 Ga) and ejection ages (~11 Ma), and is comprised of 34 samples, making it the largest single-origin suite of rocks from Mars [1]. Absent of field context, the relative emplacement histories of the nakhlites (clinopyroxene-rich basalts) and chassignites (dunites) are poorly constrained. They may have formed intrusively as sills, or extrusively as lavas, or both [1,2]. The nakhlite cumulus phases (olivine and pyroxene) may have formed together from one magma as phenocrysts, or separately with one phase xenocrystic (from a foreign magma) or antecrystic (from a related magma) [1–3]. In this study, we seek to discern relative formation conditions for the cumulus phases in both subclasses to better constrain their petrogenetic histories.

Cumulus phases of both the nakhlites and chassignites have largely reequilibrated to changing magma compositions [3], and so do not retain zoning of rapidly diffusing elements such as Mg or Fe. However, slowly-diffusing elements (P in olivine, Cr in pyroxene) do preserve zonation [4,5]. In olivine, highly-incompatible P is more readily incorporated during periods of rapid crystallization [4]. In pyroxene, Cr is compatible, but Cr will be taken up preferentially by other late-stage minor phases and be depleted in pyroxene, or it may be enriched during periods of mafic recharge [5]. Thus, Cr preserves changes in magma chemistry in an open or fractionating system [5]. We find that there are likely multiple generations of cumulate phase formation in the nakhlites, but the chassignite olivine likely formed in a single event.

Methods: Major and minor element mapping (e.g., Cr, P, Ti, Al, Mg, Fe) was done with the electron probe microanalyzer (EPMA) *JEOL* JXA-8200 Superprobe at Rutgers University. Maps were conducted with a 15 kV accelerating voltage, and a 300 nA beam current. We used a 2 μm spacing and a dwell time of 500 ms. Some minerals were mapped in their entirety and others in strips to reduce analytical time, using methods from [6]. Mapping has been completed for chassignites Chassigny and Northwest Africa (NWA) 2737, and for nakhlites NWA 11013, NWA 10645, and Caleta el Cobre (CeC) 022.

We quantitatively analyzed major and minor element abundances in the mapped minerals along traverses with the *JEOL* JXA-8900 EPMA at the University of Nevada, Las Vegas (UNLV) using a 15 kV accelerating voltage, 300 nA beam current, and a beam diameter of 1 μm. Trace elements were analyzed for points using the *Thermo Fisher Scientific* iCAP Qc inductively coupled plasma mass spectrometer with the *Elemental Scientific* Excimer NWR193 laser ablation unit (LA-ICP-MS) at UNLV. We used a 6.7 J/cm^3 fluence, a 15 Hz rep rate, and a consistent spot size for individual minerals that was appropriate for the zoning observed in maps (20-50 μm).

Results: Phosphorous abundances were mapped in phenocryst olivine in the chassignites and nakhlites. Abundances of Cr were mapped in nakhlite pyroxene.

Phosphorous in olivine. Chassigny contains olivine with oscillatory P-zoning (Fig. 1b). Olivine P-maps in chassignite NWA 2737 reveal rapidly undercooled skeletal or hopper morphologies in some olivine grains but oscillatory zoning in others (Fig. 1d). Other elements, such as Mg, are entirely homogenous throughout both samples, obscuring grain boundaries.
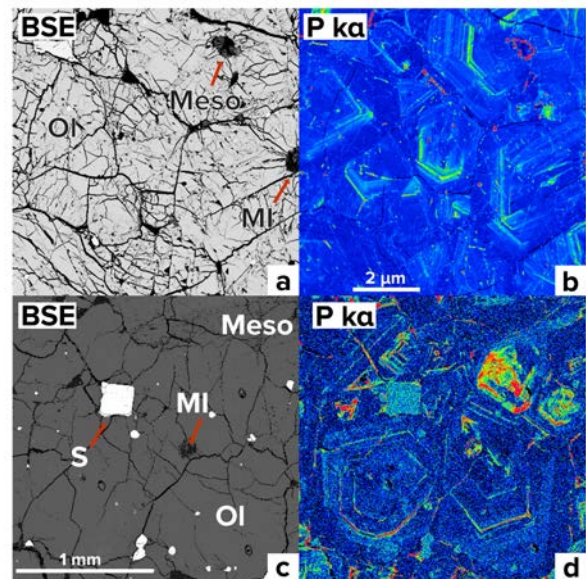

Fig. 1. Chassignite olivine zoning. a) Backscattered electron (BSE) image of Chassigny; b) P-map of Chassigny; c) BSE image of NWA 2737; d) P-map of NWA 2737. Ol = olivine; Meso = mesostasis; MI = melt inclusion.

Analyzed nakhlite olivine displays oscillatory zoning outside of possible relict cores (Fig. 2). Olivine that is ~1–2 mm in diameter contains subhedral cores (Fig. 2b). The relict cores in megacrystic olivine (total

> 2 mm diameter) are euhedral, but the rims of the cores have been rounded (Fig. 2d). Olivine cores are P- and Mg-enriched while rims are P- and Fe-enriched (Fig. 3).
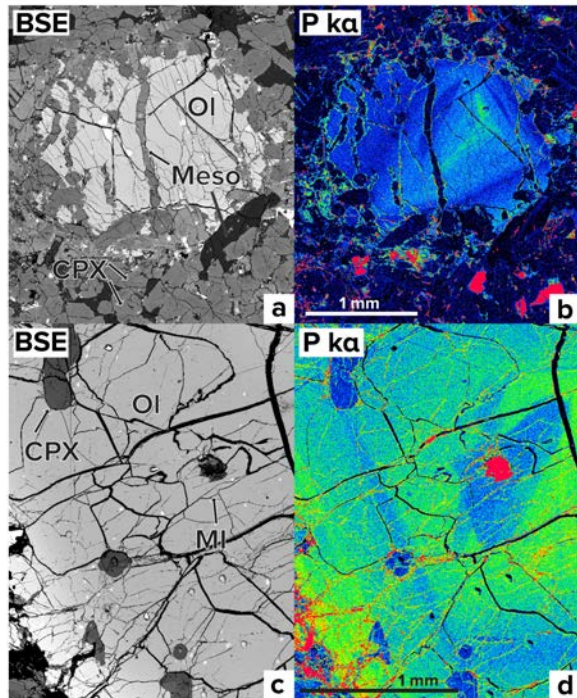

Fig. 2. Nakhlite olivine zoning. a) Backscattered electron (BSE) image of CeC 022; b) P-map of CeC022; c) BSE image of NWA 10645; d) P-map of NWA 10645. CPX = clinopyroxene.
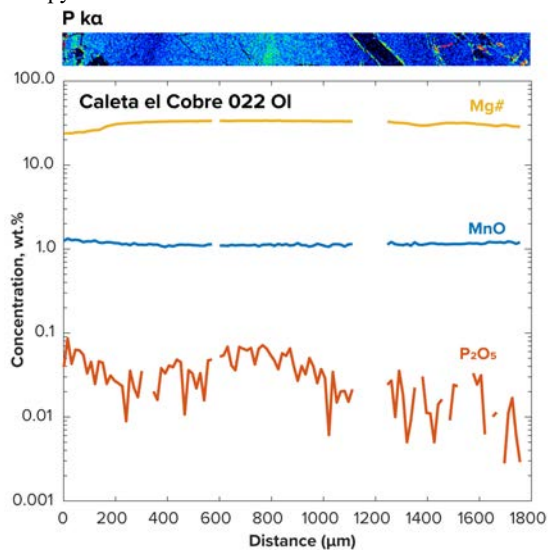

Fig. 3. Quantitative traverse data in nakhlite CeC 022 olivine. Detection limit for P is 109 ppm (1σ).

Chromium in pyroxene. In analyzed nakhlite pyroxene, Cr is typically heterogeneously distributed throughout cores and is sharply depleted around the rims (Fig. 4–5). Additionally, pyroxene rims are depleted in Mg, and enriched in Fe, Al, and Ti. Zoning of elements other than Cr appears relatively diffuse (Fig. 5).
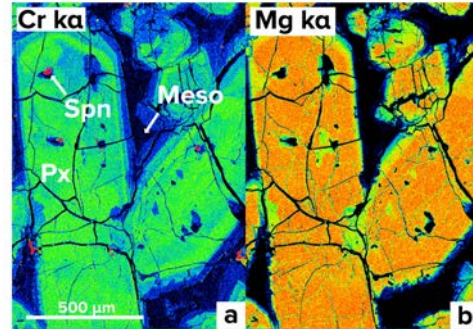

Fig. 4. Nakhlite pyroxene zoning. a) Cr-map of NWA 10645; b) Mg-map of NWA 10645. Px = pyroxene; Spn = spinel.
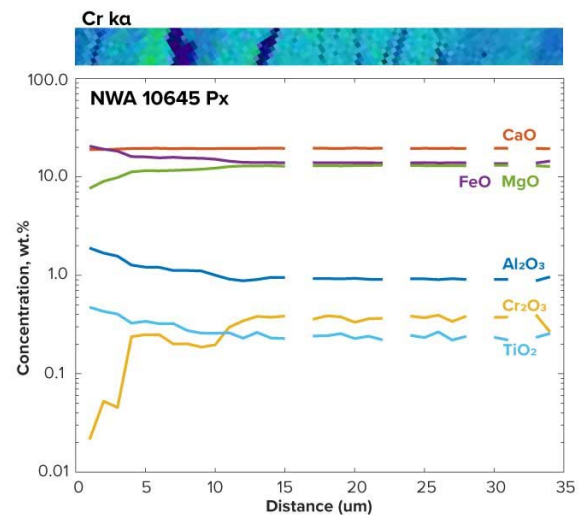

Fig. 5. Quantitative traverse data in nakhlite NWA 10645 pyroxene.

Discussion and Conclusions: Chassignite olivine formation may have occurred first during undercooling prior to transitioning into oscillating rapid growth periods. Nakhlite olivine underwent multiple stages of crystallization including core formation and overgrowth periods. Analyzed nakhlite pyroxene likely underwent Cr and MgO depletion during formation and removal of late-stage phases (e.g., spinel, olivine, pyroxene). Additional strip maps and quantitative traverses will be conducted for nakhlites NWA 817, Miller Range (MIL) 090032, Nakhla, and Governador Valadares. The effects of shock on zoning will be carefully considered, so as to isolate primary formation effects.

References: [1] Udry A., and Day J. M. D. (2018) *GCA*, *238*, 292–315. [2] Stockstill K. R. et al. (2005) *Met. & Planet. Sci.*, *48*, 2371–2405. [3] Goodrich C. A. et al. (2013) *Met. & Planet. Sci.*, *48*, 819–853. [4] Milman-Barris M. S. et al., (2008) *Cont. to Min. and Pet*, *155*, 739–765. [5] Ubide T. and Kamber B.S. (2018) *Nat. Comm.*, *9*, 326. [6] Shearer C.K. et al. (2013) *GCA*, *120*, 17–38.