

**CHEMICAL HETEROGENEITIES AMONG MELT INCLUSIONS IN NAKHLITES AND CHASSIGNITES.** A. M. Ostwald<sup>1</sup>, A. Udry<sup>1</sup>, J. Gross<sup>2,3</sup>, and J. M. D. Day<sup>5</sup>. <sup>1</sup>University of Nevada, Las Vegas, Las Vegas NV, 89154; ostwald@unlv.nevada.edu, <sup>2</sup>Rutgers University, Piscataway NJ, 08854; <sup>3</sup>NASA, Johnson Space Center, Houston TX, 77058; <sup>5</sup>Scripps Institution of Oceanography, La Jolla CA, 92037.

**Introduction:** Comprised of 29 known unpaired samples, the martian nakhlite and chassignite meteorite suite shares crystallization (~1.3 Ga) and ejection ages (~11 Ma), making it the largest single origin suite of samples from Mars [1]. Despite their possible shared provenance, there are few constraints on nakhlite and chassignite relative petrogenesis. Previous work attempting to determine the petrogenetic history of the nakhlites has focused on the relationship between the two cumulus phases, olivine and augite. Some studies find that the two nakhlite cumulus phases originate from the same parental magma [1,2]. Other studies suggest that olivine is xenocrystic [e.g., 3].

One common method to address petrogenesis of cumulate samples, such as the nakhlites or chassignites, is to study their parental melt compositions, or the composition of the magma prior to accumulation [2,3]. Parental melt compositions may be determined from analysis of melt inclusions, or pockets of trapped melt [2,3]. No studies yet use a consistent set of techniques to analyze both nakhlite and chassignite melt inclusions. To further constrain nakhlite and chassignite petrogenesis, we examined trace element abundances and distributions in melt inclusions in chassignites Chassigny and Northwest Africa (NWA) 2737, as well as nakhlites Caleta el Cobre (CeC) 022, Miller Range (MIL) 090030, MIL 090032, NWA 10645, and Gobernador Valadares.

**Methods:** Trace element analysis was conducted on melt inclusions using the *Thermo Fisher Scientific* iCAP Qc inductively coupled plasma mass spectrometer and *Elemental Scientific* NWR UP213 laser ablation (LA-ICP-MS) system at Scripps Institution of Oceanography. A 3.5 J/cm<sup>2</sup> fluence and 5 Hz rep rate was used with spots of beam sizes between 100 and 50 µm to homogenize large (~50–100 µm diameter) and small melt inclusions (<50 µm diameter), respectively. All analyses were bracketed with NIST 610, NIST 612, BHVO-2g, BCR-2g, and BIR-1g standards. Data were reduced using the *iolite4* trace elements scheme [4].

Preliminary trace element mapping was conducted on a melt inclusion in chassignite NWA 2737 at UNLV using an iCAP Qc ICP-MS and NWR193 laser ablation system. A 12 J/cm<sup>2</sup> fluence, 10 Hz rep rate, 12 second scan speed, and a 24 µm square spot was used for all analyses. Maps were processed on *iolite4* using a NIST610 raster taken with the same beam settings in the same session for semi-quantitative data reduction [4].

**Results:** Bulk rare earth elements (REE) for all of the melt inclusions analyzed are roughly parallel with each other and the bulk (Fig. 1). Melt inclusion values for La/Lu range from ~15 to 140. Other trace elements, when ratioed and compared, are also variable and do not fall within bulk rock values (Fig. 2). Pyroxene-hosted melt inclusions in nakhlites display the most scatter, while olivine-hosted nakhlite melt inclusions fall close to one another (Fig. 2).

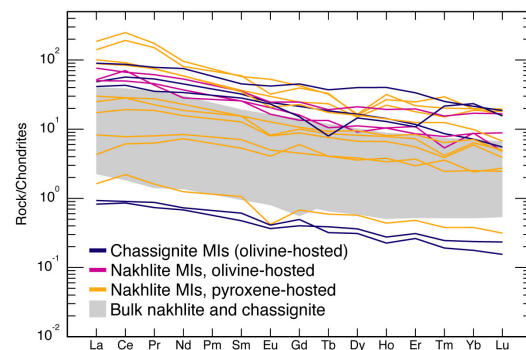


Fig. 1: CI-normalized [5] REE abundances in nakhlite and chassignite melt inclusions (MI).

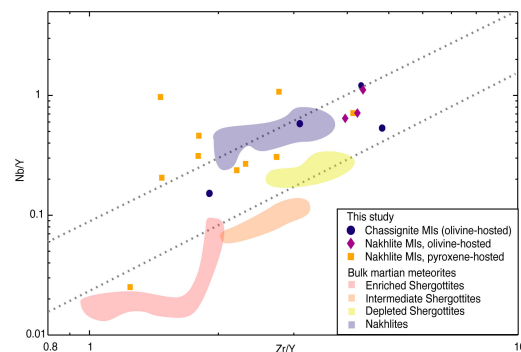


Fig. 2: Zr/Y and Nb/Y diagram with melt inclusion data (points), bulk nakhlites and shergottites (envelopes) and Icelandic ranges (dashed lines). Adapted from [6].

Trace element mapping of a polycrystalline melt inclusion in chassignite NWA 2737 reveals significant heterogeneities between the different inclusion phases (Fig. 3). Glass, which contained low Mg and high Al relative to mineral phases, may have a heterogeneous distribution of the REE throughout (Fig. 3). Furthermore, Nb, Y, and Zr are heterogeneously distributed throughout the melt inclusion phases, with Zr and Y found primarily in the glassy phase (Fig. 4).

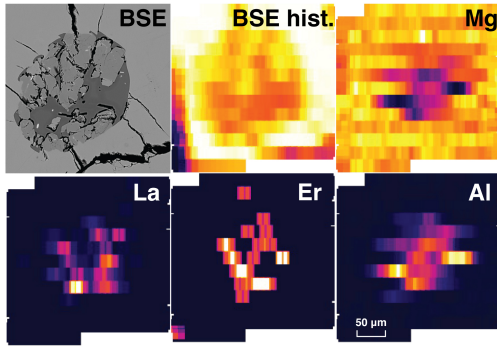


Fig. 3: Element mapping of melt inclusion in NWA 2737. BSE hist. = histogram made from grey ranges in BSE image. Erbium was the heaviest REE resolvable with the LA-ICP-MS settings used.

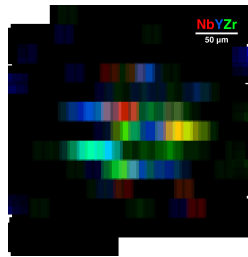


Fig. 4: LA-ICP-MS Nb, Y, and Zr RGB mapping of the melt inclusion in NWA 2737.

**Discussion:** Parallel REE abundances across all melt inclusions indicates that the parental melts for the suite likely originate from a single source (Fig. 1). However, inconsistencies between individual ratioed trace elements (Fig. 2) may be due to a number of effects: chemical heterogeneities in the inclusions (Fig. 3,4), reequilibration of the host mineral in a new magma, or unique parental melt compositions resulting from different degrees of source partial melting [7,8].

Melt inclusions in the nakhlites and chassignites differ in terms of their crystallinity and thus, of their composition. Melt inclusions that are polycrystalline (including both glass and mineral phases) can be highly chemically heterogeneous, and thus affect bulk chemical analyses, especially in 2D thin sections (Fig. 3). Mixing different phases in a single laser beam may introduce error due to differential matrix-dependent fractionation [e.g., 9]. Melt inclusions hosted in some nakhlite olivine and all melt inclusions in chassignites are polycrystalline and results from *in situ* trace element analyses may be scattered as a result (Fig. 2).

Analyzed nakhlite pyroxene and some olivine host less complex melt inclusions comprised primarily of glass. Single-phase melt inclusions may be matrix-matched against a calibrant on LA-ICP-MS to avoid matrix error (e.g., glass with glass) [9]. Trace elements may not be homogeneously distributed throughout the melt inclusion glass, however, and there may be some biases in analyzing melt inclusions in a non-representative thin section. If the glassy melt inclusion is homogenized by the laser, and if its contents are representative of the bulk entrapped melt inclusion,

trace elements may still be affected by post-entrapment reequilibration of their hosts [7]. For instance, although all REE are incompatible in olivine, the heavy REE have higher partition coefficients ( $K_D$ ) than light REE, and are more rapidly affected by diffusion across a reequilibrated olivine grain [7]. Such an effect may result in different REE distributions throughout a melt inclusion, as seen in the glassy phase of Fig. 3.

Ratioing elements with similar partitioning (such as Nb, Zr, and Y in olivine,  $K_D = 0.01$ ) may reveal chemical trends in parental magmas despite reequilibration. In Hawaiian basalts, variability between bulk rock and melt inclusions in Nb/Y and Zr/Y ratios is shown to represent different degrees of partial melting from a single source [8]. The same may be true in nakhlite-hosted and glassy olivine melt inclusions, which plot closely and between the bulk nakhlite and depleted shergottite fields (Fig. 2). These entrapped melts may be unique from the bulk nakhlite magma, indicating that nakhlite olivine is generated from a different degree of partial melting from the bulk nakhlite source and is then stored and later entrained in the bulk magma as an antecryst. Pyroxene-hosted melt inclusions, however, may have undergone significant reequilibration, as Zr (0.123), Y (0.467), and Nb (0.06) have  $K_D$  values that are an order of magnitude different in clinopyroxene, resulting in scatter (Fig. 2). Reequilibration itself, especially combined with evidence of multiple parental melts in a suite, is evidence of long-term magma generation and storage.

We find that the effects of diffusional equilibration or addition of melted host phases on nakhlite and chassignite olivine (and possibly pyroxene) are possibly too significant for melt inclusions to obtain a single parental melt composition [7,10]. Additionally, ppm-scale heterogeneities in melt inclusions may introduce error to analyses. However, we conclude that nakhlite olivine-hosted melt inclusion trace elements that are equally affected by diffusion in olivine (Nb, Y, Zr) fall in a narrow range away from bulk nakhlite compositions, and thus nakhlite olivine may host a different parental melt composition than the rest of the bulk rock in keeping with findings from major element analyses [11].

**References:** [1] Udry, A., and Day, J. M. D. (2018) *GCA*, 238, 292–315. [2] Stockstill, K. R., et al. (2005) *Meteoritics & Planet. Sci.*, 48, 2371–2405. [3] Goodrich, C. A., et al. (2013) *Meteoritics & Planet. Sci.*, 48, 819–853. [4] Paton, C., et al. (2011) *JAAS*, 26, 2508–2518. [5] McDonough and Sun (1995) *Chem. Geo.*, 120, 223–253. [6] Day, J. M. D. et al., (2018) *Nat. Comm.*, 9, 4799. [7] Cottrell, E., et al., (2002) *Geochem. Geophys. Geosyst.* 3(5), 1–26. [8] Wallace, P. J., et al. (2021) *Annu. Rev. Earth Planet. Sci.*, 49, 465–494. [9] Zhang, S., et al. (2015) *JAAS*, 31, 358–382. [10] Gaetani, G. A., and Watson, E. B. (2000) *EPSL*, 183m 27–41. [11] Ostwald, A. M., et al (2021) *LPSC LII*, abstract #1079.  $K_D$  values from kdd.earthref.org (accessed 13 Nov 21).