

TRACE ELEMENT COMPOSITIONS BEARING ON THE ORIGINS OF LARGE IGNEOUS INCLUSIONS IN ORDINARY CHONDRITES. A. M. Ruzicka¹, K.L. Schepker¹, Yunbin Guan², ¹Cascadia Meteorite Laboratory, Department of Geology, Portland State University, Portland, OR, U.S.A. (ruzicka@pdx.edu), ²Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, U.S.A.

Introduction: Large (multi-mm to cm) igneous-textured inclusions poor in metal and sulfide occur in ~4% of ordinary chondrites [1] and have an uncertain origin. Most have major-element compositions and oxygen isotopic compositions broadly similar to ordinary chondrites and chondrules, and fall into two main chemical types, relatively unfractionated (*Unfr*), and vapor fractionated (*Vfr*); these appear to have formed by melting of chondritic material with (*Vfr*) or without (*Unfr*) chemical exchange with nebular gas [2,3]. Other inclusions have distinctly different compositions and could have been produced dominantly by igneous differentiation [4]. We obtained SIMS data for 37 elements in 9 inclusions, using the Cameca 7f-Geo ion microprobe at Caltech, using an energy filtering technique [5]. Here results are discussed for four representative inclusions of the dominant *Unfr* and *Vfr* types. Our results suggest complex, multistage processing.

Context: Based on reconstructions of bulk major element compositions using SEM and EMPA data, inclusion 7871-I1 (from host NWA 7871, L6) and 8645-I1 (NWA 8645, L5) were judged to be relatively unfractionated in lithophile major element abundances, whereas Tdk-I2 (Tamdakht, H5) and droplet Par-I2 (Parnallee LL3.6) were judged to be vapor-fractionated with depletions in volatile elements [2,3]. Both 7871-I1 and 8645-I1 are texturally integrated with their hosts, implying *in situ* metamorphism. 8645-I1 has L-chondrite-like Fe/Mg silicate compositions but distinctly different oxygen isotope compositions more consistent with the LL group, suggesting metamorphic Fe-Mg exchange *in situ* but derivation from an LL-like parent body [3]. 7871-I1 has L-like Fe/Mg silicate compositions but oxygen-isotope compositions that fit better with the H-group [3].

SIMS Results and Discussion: Phase compositions determined by SIMS were used for modal reconstructions of bulk compositions supplemented with SEM and EMPA data. The new data confirm with additional elements the relatively unfractionated compositions for 7871-I1 and 8645-I1 typical for the *Unfr* group, and the stronger depletions of alkali elements for Par-I2 and Tdk-I2 typical for the *Vfr* group (Fig. 1).

Figure 2 shows selected REE analyses of phases in the inclusions. All these analyses imply non-igneous features. Olivine in 7871-I1 has nearly uniform REE abundances at ~0.3-0.5 x CI (Fig. 2), likely caused by

metamorphic re-equilibration. Olivine in 8645-I1 has a very different “W-shaped” pattern with huge positive Eu anomaly (Eu/Sm x CI ~32) (Fig. 2). No inclusions in olivine that could account for such a huge positive Eu anomaly are seen. The REE abundances of olivine, orthopyroxene, and feldspar in this inclusion are all remarkably similar, implying all were equilibrated to roughly the same composition. W-shaped REE patterns in chondrites can be explained by sequestration of REE into merrillite [6]; the data for 8645-I1 imply metamorphic exchange with phosphate which occurs in this inclusion and in 7871-I1. However, phosphate only accounts for ~0.15% of the total area in 8645-I1, suggesting the possibility of open-system exchange between the inclusion and surrounding chondritic host. Notably, far more phosphate (~1.1%) occurs in 7871-I1, which does not show the distinctive W patterns.

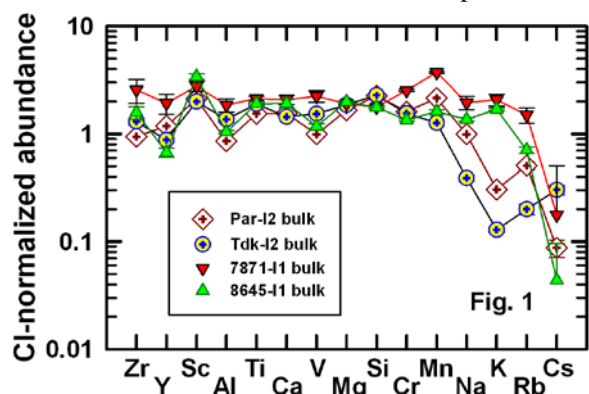


Figure 1. CI-chondrite-normalized abundances in four inclusions, elements arranged left to right in order of increasing volatility. Errors are based on uncertainties in modes and SIMS counting errors.

The bulk REE abundances in 8645-I1 show a W pattern with somewhat flattened “wings” (Fig. 3). Evidently REE exchange with phosphate occurred on a scale at least as large as the inclusion (cm scale). Both this and the small amounts of phosphate present in the inclusion could be explained by melting of a phosphate-poor portion of a metamorphosed chondritic protolith. Thus, two metamorphic events with an interim melting and transport period may have occurred for 8645-I1: early metamorphism and subsequent melting of the LL-chondrite-like protolith implied by oxygen isotopic and SIMS data, transport to the L chondrite protolith, and later metamorphism of this protolith im-

plied by L-chondrite-like Fe/Mg and textural integration with the host.

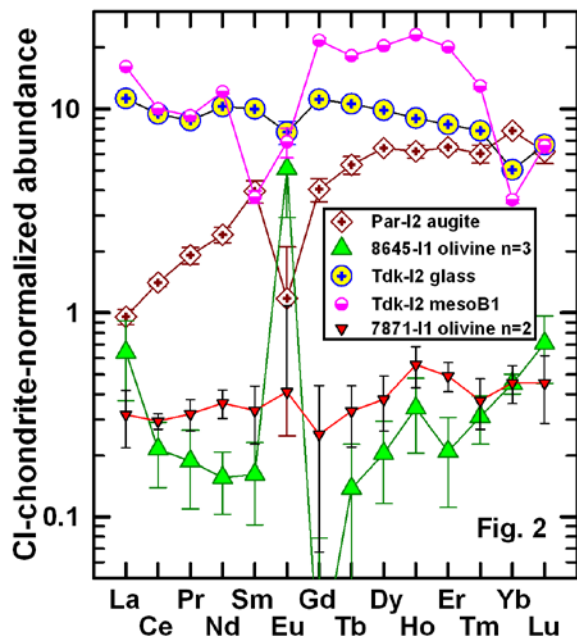


Figure 2. CI-chondrite-normalized REE abundances of selected phase analyses. Errors are based on SIMS counting errors or standard deviations of average compositions, whichever is larger.

In the *Vfr* inclusion Par-I2, augite with an otherwise typical igneous REE pattern has a small but distinct Yb anomaly (Fig. 2), suggesting exchange with a vapor enriched in this relatively volatile REE. More precisely, augite probably crystallized from melt that was exchanging with a Yb-rich vapor at high temperature. Despite such evidence for high-temperature processing, the bulk REE pattern for Par-I2 is nearly chondritic (Fig. 3), which seems inconsistent with a high temperature origin for the inclusion overall. Ultramafic minerals (olivine and low-Ca pyroxene) in Par-I2 show overlapping LREE-depleted compositions with no evidence for an Yb anomaly, and no evidence for systematic igneous fractionation between magnesian and ferroan low-Ca pyroxene, or between olivine and pyroxene. The lack of Yb anomaly in these phases implies that exchange with a Yb-rich vapor did not occur at the time of their formation. Further, the lack of evidence for systematic igneous fractionation implies disequilibrium, either during the initial formation of these minerals or in subsequent heating events. The data for Par-I2 can be explained by two melting episodes: an early event that created the mafic minerals, and a later, brief but intense melting event that partially melted the inclusion and resulted in exchange between gas and melt.

In Tdk-I2, interstitial feldspathic phases show a variety of REE patterns, including glass with negative Eu

and Yb anomalies (Group III pattern), and some portions of mesostases with super-refractory patterns characterized by irregular REE with mostly high HREE and low Eu, Yb and Sm (Fig. 2). These data unambiguously indicate high-temperature processing and exchange with vapor during intense evaporative melting. However, the bulk REE pattern for Tdk-I2 is close to chondritic (~ 0.7 - $1.5 \times CI$) (Fig. 3), which indicates that the inclusion is not very refractory overall. Olivine in the inclusion has an irregular, non-igneous REE pattern. Although pyroxene shows evidence for fractional crystallization, there is also evidence for a disturbance that modified the pyroxene composition, creating somewhat offset patterns between HREE and LREE. The data for Tdk-I2 can be reconciled with two melting events: one to produce the chief mafic minerals at a comparatively lower temperature, and a later, brief but intense heating episode at higher temperature that resulted in partial melting, evaporation to create a refractory mesostasis, and chemical disturbance of the ultramafic residua.

References: [1] Bridges J.C. and Hutchison R. (1997) *MAPS* 32, 389-394. [2] Armstrong K. (2014) Chemical and petrographic survey of large, igneous-textured inclusions in ordinary chondrites, MS Thesis, Portland State Univ. [3] Ruzicka A.M. et al. (2016) 47th LPS, Abstract #2230. [4] Ruzicka A. et al. (2012) *MAPS* 47, 1809-1829. [5] Zinner E. and Crozaz G. (1986) *Int. J. Mass Spectrom. Ion Proc.* 69, 17-38. [6] Ruzicka A. et al. (2005) *MAPS* 40, 261-295.

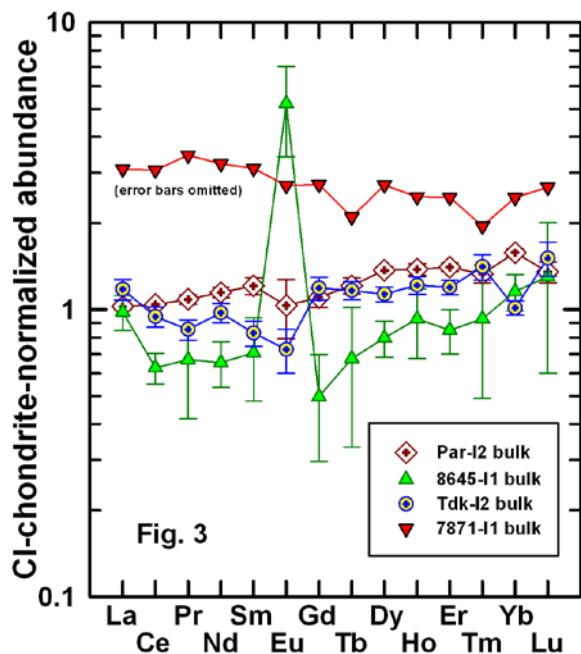


Figure 3. CI-chondrite-normalized REE abundances of four inclusions. Errors are based on SIMS counting errors and errors in modal compositions.