COMBINED CHEMICAL-OXYGEN ISOTOPE STUDY OF LARGE IGNEOUS INCLUSIONS IN ORDINARY CHONDRITES.

A. M. Ruzicka[1], K. L. Schepker[1], R.C. Greenwood[2], and I.A. Franchi[2]. [1]Cascadia Meteorite Laboratory, Portland State University, Dept. of Geology, 1721 SW Broadway, Portland, OR 97201 U.S.A. (ruzickaa@pdx.edu), [2]PSSRI, Open University, Walton Hall, Milton Keynes MK7 6AA, UK.

Introduction: Large igneous-textured inclusions poor in metal and sulfide occur in ~4% of ordinary chondrites [1] but are otherwise diverse, suggesting various formation mechanisms [2,3]. Recent work on the petrology of 29 inclusions suggested that they can be subdivided into different bulk chemical groups, with no evidence that any were produced by igneous differentiation [4]. This is in contrast to other inclusions that could have formed by differentiation [5]. Here we expand the geochemical database to 41 inclusions and report on the oxygen isotopic compositions of 12. Our results have important implications for the origins of such inclusions.

Chemical groups: Bulk chemical compositions of inclusions reconstructed from modal and phase composition data (SEM + EMPA) confirm earlier work [4] that inclusions comprise a few basic chemical groups, none of which correspond to that expected for igneous differentiation. The groups include: vapor-fractionated (*Vfr*, n=18 examples), unfractionated (*Unfr*, n=13), K-enriched but otherwise unfractionated (*Unfr+K*, n=4), feldspar-rich (*FldR*, n=4), and unique (n=2). Examples of each group can be found in both less and more metamorphosed chondrites, although *Unfr* is more prevalent in type 5 and 6 (9 of 13 examples) and *Vfr* in type 3 and 4 chondrites (17 of 18).

The unfractionated *(Unfr)* group has lithophile element abundances similar to ordinary chondrites and depletions in Ni, Fe and S (Fig. 1a). This composition is best explained by the melting of chondrite accompanied by metal and sulfide loss. Five such inclusions are located near coarse metal-sulfide nodules that could have separated from the inclusions during in situ melting. *Unfr* inclusions sometimes show evidence for brecciation while partly molten, consisting of obviously brecciated olivine microphenocrysts or brecciated regions of olivine + mesostasis embedded in inclusion mesostasis that is not brecciated. Some or all *Unfr* inclusions could have formed by shock melting of chondrites.

The *Unfr+K* group (inclusions 869-I1, 8231-I1, MET-I2, Dim-I1) is chemically and texturally similar to *Unfr* but distinguished by variable and sometimes large enrichments in K (3.5-14.5 x CI chondrite) (Fig. 1b). This composition resembles the silicate portion of impact melt in some ordinary chondrite melt rocks and melt breccias, which also are enriched in K (2.3-12.7 x CI) (Fig. 1b). K-enriched impact melt was previously noted for Chico [6]; inclusion 869-I1 in Northwest Africa 869 texturally resembles impact melt rock identified elsewhere in the meteorite [7]. Although the reason for K enrichment in these melts is uncertain, inclusions in the *Unfr+K* group probably formed by impact melting.

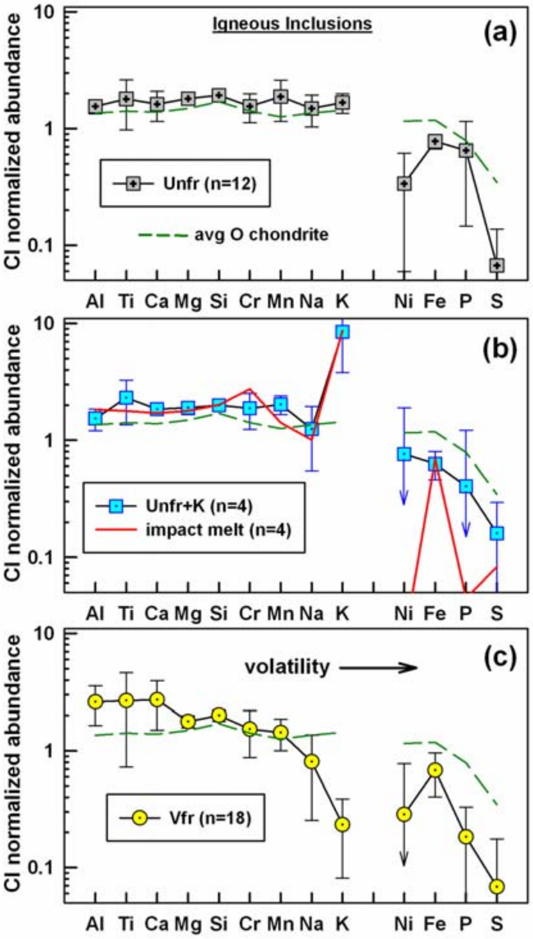

Fig. 1. CI-normalized abundances (mean and ±1σ) of 3 inclusion types compared to mean O chondrite composition [8]; impact melt composition in (b) is based on the average of 2 L melt rocks and 2 L melt breccias.

Inclusions in the *Vfr* group show evidence for a vapor-fractionation process, as lithophile element abundances trend with volatility (Fig. 1c). Six of the 18 inclusions are droplets and could be called megachondrules, but both the droplets and nondroplets have similar compositions. Compared to other inclusion melts, *Vfr* melts were evidently more exposed to a space environment (to facilitate evaporation or condensation) and/or were more thoroughly heated (to facilitate evaporation). These inclusions could have formed as dispersed melts analogous to chondrules.

Oxygen isotope composition: 1.2-10.2 mg samples of inclusions were mechanically separated and 1-2 mg subsamples were analyzed by laser fluorination at Open University [9] with system precision (2σ) for $\delta^{17}O$, $\delta^{18}O$ and $\Delta^{17}O$ of ±0.05 ‰, ±0.09 ‰, and ±0.02 ‰, respectively. Results are shown compared to type 4-6 H-L-LL chondrites [10] in Fig. 2. Inclusions span a range in $\Delta^{17}O$ (~0.1 to 1.4 ‰) and $\delta^{18}O$ (3.8-7.8 ‰) values, broader than but overlapping the H-L-LL fields.

There is only a partial correspondence between inclusion and host oxygen isotope composition and Fe-Mg equilibration state (Fig. 2a). Inclusions with equilibrated Fe-Mg tend to lie close to the H-L-LL fields, but not always within the appropriate host composition. For example, 8645-I1 (host Northwest Africa 8645, L5) has L-like silicate compositions but $\Delta^{17}O$ values far from L, at the upper end of LL (Fig. 2a). Conceivably 8645-I1 was metamorphosed in situ and equilibrated in Fe-Mg, but preserved an oxygen composition different than the host reflecting a different formation reservoir. Inclusion 7871-I1 has L-like silicate compositions but fits better with the H-group oxygen field. Finally, most inclusions with unequilibrated Fe-Mg have L and LL hosts and lie well outside of the L and LL fields, with $\Delta^{17}O$ values between H chondrites and the terrestrial fractionation (TF) line (Fig. 2a).

The relationship between inclusion chemical group and oxygen isotope composition is shown in Fig. 2b. *Unfr* and *Unfr+K* inclusions mostly have O-isotopic compositions that resemble H-L-LL chondrites, consistent with them being impact melts of such chondrites. Specifically, the oxygen data support the interpretation that inclusions 869-I1 and 8231-I1 are shock melts of L and H chondrite, respectively; and that inclusion 4859-I18 is a shock melt of LL chondrite (consistent with previous interpretations of igneous material in Northwest Africa 4859 [11]). Inclusions 8645-I1 and 7871-I1 could be shock melts of LL and H chondrites, respectively, though both were incorporated in L chondrite. Inclusion MET-I2 has a low $\Delta^{17}O$ value (Fig. 2b), and could have formed by impact melting of a separate, low-$\Delta^{17}O$ parent body. Lastly, the *Vfr* inclusions all have generally low $\Delta^{17}O$ values outside the main H-L-LL fields (Fig. 2b). Potentially all are megachondrules. Although the oxygen isotopic compositions of chondrules from ordinary chondrites are more diverse than type 4-6 H-L-LL [10], there are not many with the low $\Delta^{17}O$ values we have found for *Vfr* inclusions. Why all such inclusions (so far) have low $\Delta^{17}O$ is not clear, but suggests a distinctive process or provenance, possibly exchange with nebular gas of distinct O-isotope composition.

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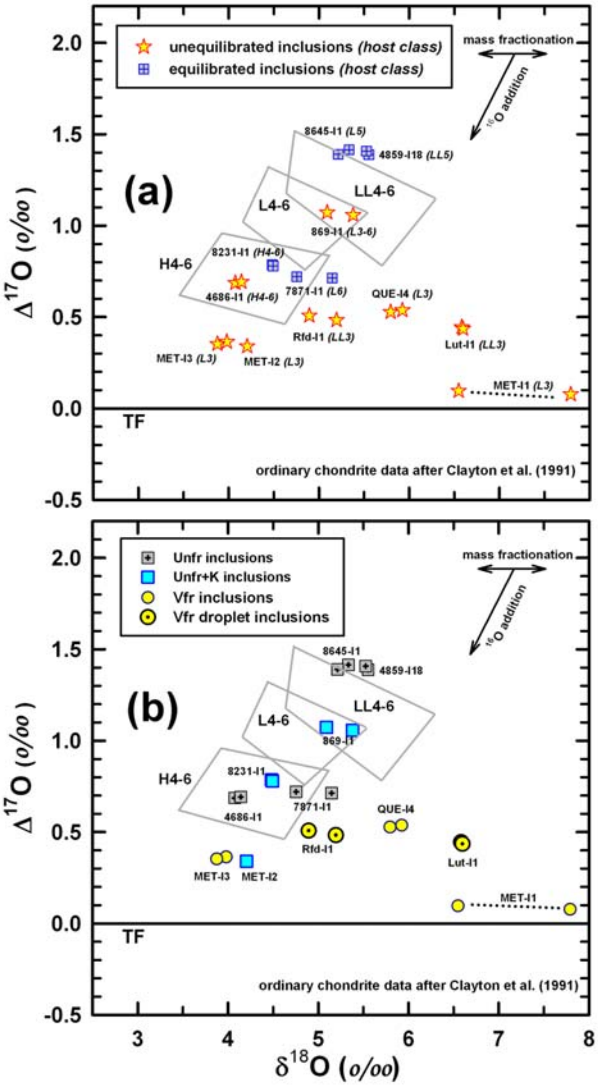

Fig. 2 Oxygen isotopic compositions of inclusions compared to type 4-6 H, L, LL chondrites [10].