**INTRODUCTION**

Large igneous-textured inclusions poor in metal and sulfide occur in ~4% of ordinary chondrites 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 they were produced by igneous differentiation [4]. Here we expand the geochemical database to 41 inclusions, and report on the oxygen isotope composition of 12. This represents the largest data set yet obtained for the bulk chemistry and oxygen isotope composition of these inclusions. Our results suggest an important role for shock melting for many inclusions but indicate somewhat different origins and processes operated.

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### Bulk chemistry (Fig. 1, 2)

Compositions reconstructed from modal and phase compositions (SEM and EMPA data).

- Data confirm earlier work [4] that inclusions comprise a few basic chemical groups, none of which correspond to igneous differentiation, unlike other inclusions that could have formed by differentiation [5].

**Chemical types:**
- Unfr+K (13 examples), generally unfractuated lithophile abundances, similar to ordinary chondrites (Fig. 1a).
- Igneous-fractionated (Unfr) (18 examples), shows evidence of a vapor-fractionation process; lithophile element abundances correlate with volatility (Fig. 1c) but overall compositions are not far removed from ordinary chondrites (Fig. 2). Includes different subtypes (alkali-depleted, refractory-element enriched, enriched in elements of intermediate volatility (Si, Mg), Mg).
- Generally unfractuated, but K-enriched (Unfr+K) (n=4).
- Compositions are similar to some impact melts compositions, as for Chico [6]. Fig. 1b shows the average silicate portion of two L melt rocks (NWA 6454 and NWA 6375) and two L melt breccias (NWA 5964, NWA 6380) determined in the same way as for inclusions.

- Fastastic-rich (Ftr) (n=4), enriched in both alkali elements as well as Al, Ti, Ca and plotting with elevated normative feldspar (Fig. 2).

Examples of each group can be found in more-or-less metamorphosed chondrites, although Unfr+K is more prevalent in type 5 & 6 hosts (9 of 13 examples) and Vfr in type 3 & 4 chondrites (17 of 18). Average ordinary chondrite data from Jaroszewicz [8].

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### Petrography (Fig. 3)

- All inclusions are depleted in metal-sulfide compared to hosts suggesting loss of metal and sulfide during melting.
- Five Unfr inclusions are located near coarse metal-sulfide nodules that could have separated from the inclusions during in situ melting (Fig. 3a).
- Both Unfr and Unfr+K inclusions show evidence for brecciation while partly molten. Evidence consists of obviously brecciated olivine microphenocrysts (arrows, Fig. 3b), or brecciated regions of olivine + mesostasis embedded in inclusion matrixes that is not brecciated. This suggests deformation accompanied by melting. Inclusion 869-I1 in NWA 869 (Fig. 3b) texture resembles impact melt rock identified elsewhere in the meteorite [7].
- Six of 18 Vfr inclusions are droplets, the highest proportion among inclusion types, and could be termed megachondrules (Fig. 3c). These inclusions evidently formed as dispersed melts in a space environment. Both droplets and non-droplets have similar compositions, suggesting a similar origin for all Vfr inclusions.
- Inclusions formed both before and after (possibly during) metamorphism, based on whether they have equilibrated Fe-Mg composition in relation to their hosts. Inclusion 8645-I1 was clearly metamorphosed in situ, as olivine composition both within and outside the inclusion are similar (similar colors in the false color map in Fig. 3d) and the inclusion boundary is blunted (boundary highlighted in Fig. 3d).

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### Conclusions

1) Inclusions formed by nearly complete melting of chondritic material accompanied by metal and sulfide loss and generally modest chemical fractionation.

2) Both Unfr and Unfr+K inclusions probably formed by shock melting of chondritic precursors, sometimes in situ, sometimes involving brecciation, sometimes involving enrichment of K.

3) Oxygen isotope compositions of inclusions do not always reflect that of their hosts, suggesting large-scale transport processes and preservation of primitive signatures even through metamorphism.

4) Vfr inclusions probably formed as dispersed melt droplets in a space environment that facilitated vaporization.

5) Why all Vfr inclusions have low $\delta^{17}O$ is not clear, but suggests a distinctive process or provenance, possibly exchange with nebular gas of distinctive composition.

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### References


Acknowledgment: NASA grant support for this work is gratefully acknowledged.

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### Oxygen isotope compositions (Fig. 4)

Fig. 4. Oxygen isotopic compositions of inclusions compared to type 4-6 H, L, LL chondrites [10], analyzed by laser fluorination [9]. System precision (2σ) for $\delta^{17}O$, $\delta^{18}O$ and $\Delta^{17}O$ is ±0.05‰, ±0.09‰, and ±0.02‰, respectively.

- Inclusions span a range in $\delta^{18}O$ (5.1-4.6‰) and $\delta^{16}O$ (3.8-8.3‰), broader than but overlapping the H-L-L fields [10] (Fig. 4).

- Inclusions span a range in $\Delta^{17}O$ (0.1-1.4‰) and $\delta^{17}O$ (0.8-3.4‰), broader than but overlapping the H-L-L fields [10] (Fig. 4).

- There is only partial correspondence between inclusion-host O-isotope composition and Fe-Mg equilibration state. For example, inclusion 8645-I1 (host NWA 6454) has L-like sialic compositions and was clearly metamorphosed in situ (Fig. 3d) but has $\Delta^{17}O$ values far from L, at the upper end of LL fields (Fig. 4a). Conceivably, this inclusion preserved an L-like O-isotope signature that was preserved even during Fe-Mg metamorphic equilibration.

- Similarly, inclusion 7871-I1 has L-like Fe-Mg sialic compositions but fits better within the H-group oxygen field (Fig. 4a).

- Most inclusions with unfractuated 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. 4a).

Fig. 3. (a) BSE image montage of 7871-I1, located adjacent to coarse metal-sulfide.

(b) BSE image of 869-I1, arrows show a melt droplet that has obviously displaced olivine but apparently not the mesostasis (messo), suggesting brecciation while partly molten.

(c) False color EDS maps of droplet 8645-I1 in Richfield (c) and inclusion 8645-I1 in NWA 8645 (d). Olivine is light green, low-Ca pyroxene (lpx) is olivine green to brown depending on Fe-Mg, diopside high-Ca pyroxene is red-orange, troilite yellow-green, metal blue. The similar green colors for olivine inside and outside of inclusion 8645-I1 indicates similar composition, verified with point analyses.

References:


Acknowledgment: NASA grant support for this work is gratefully acknowledged.