Combined chemical-oxygen isotope study of large igneous inclusions in ordinary chondrites

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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 objects. Our results suggest an important role for shock melting for many inclusions but indicate somewhat different origins and processes operated.

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:

- Unfractionated (Unfr) (n=13 examples), generally unfractionated lithophile abundances, similar to ordinary chondrites (Fig. 1a, 2).
- Vapor-fractionated (Vfr) (n=18), show evidence of a vapor-fractionation process; lithophile element abundances correlate with volatility (Fig. 1c) but overall compositions are not far removed from ordinary chondrite (Fig. 2). Includes different subtypes (alkali-depleted, refractory-element enriched, enriched in elements of intermediate volatility (Si, Mg).
- Generally unfractionated, but K-enriched (Unfr+K) (n=4). Compositions are similar to some impact melt compositions, such as for Chico [6]. Fig. 1b shows the average silicate portion of two L melt rocks (NWA 6454 and NWA 6575) and two L melt breccias (NWA 5964, NWA 6580), determined in the same way as for inclusions.
- Feldspar-rich (FldR) (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* 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 Jarosewich [8].

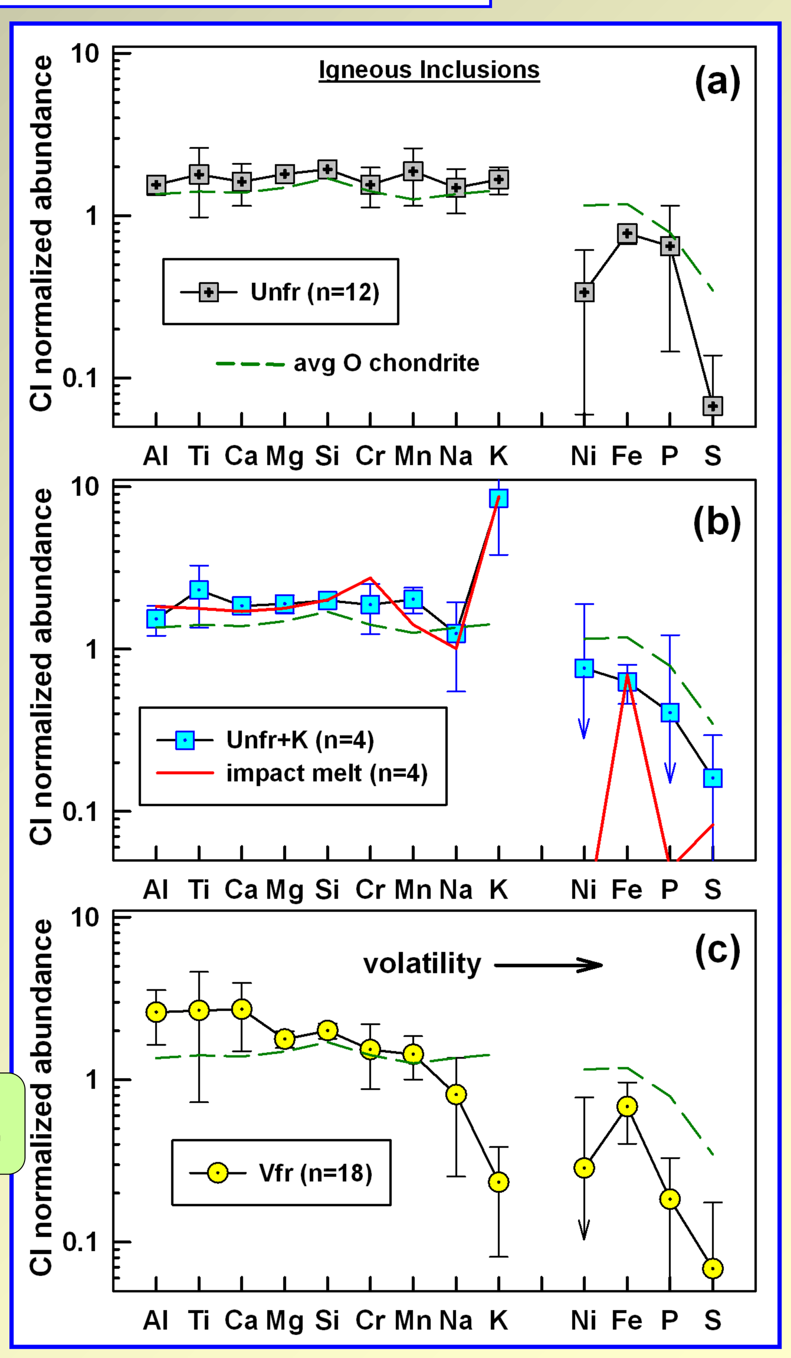

Fig. 1

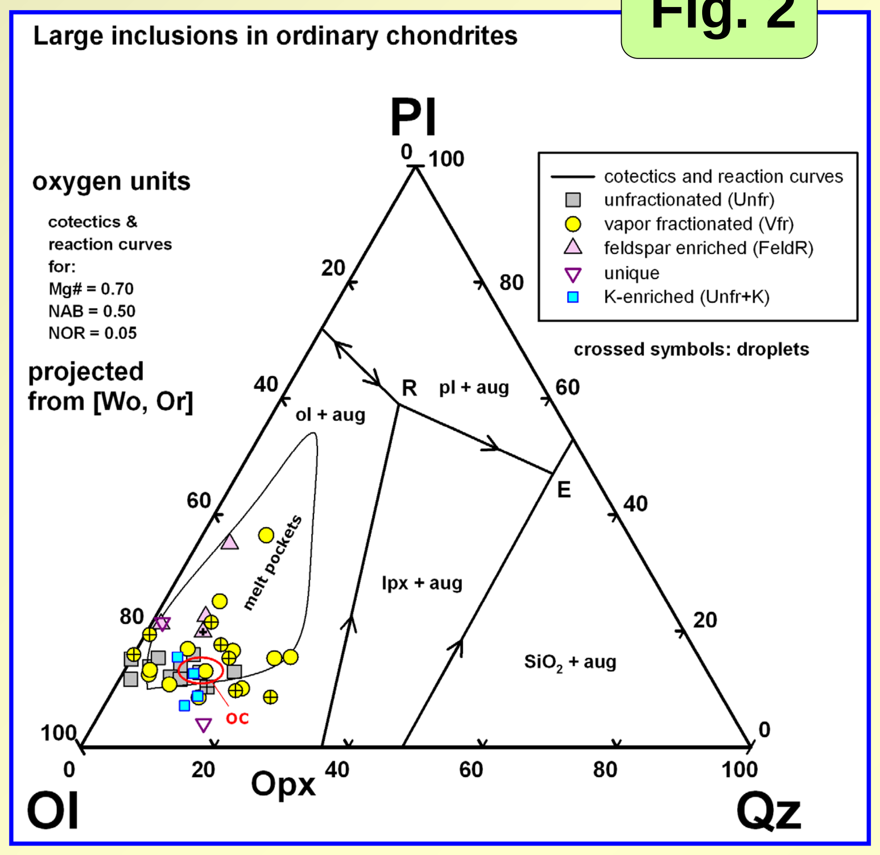

Fig. 2

Fig. 2 Compositions projected on pseudoternary liquidus diagram olivine (Ol) – quartz (Qz) – plagioclase (Pl)

- Bulk compositions cluster around ordinary chondrite (OC); all inclusions have olivine on liquidus.
- No evidence these inclusions originated by igneous differentiation; instead, their compositions suggest nearly complete melting of chondritic material, with mostly modest chemical fractionation.

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 mesostasis that is not brecciated. This suggests deformation accompanied by melting. Inclusion 869-I1 in NWA 869 (Fig. 3b) texturally 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 clearly was 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 as the inclusion boundary is blurred (boundary highlighted in Fig. 3d).

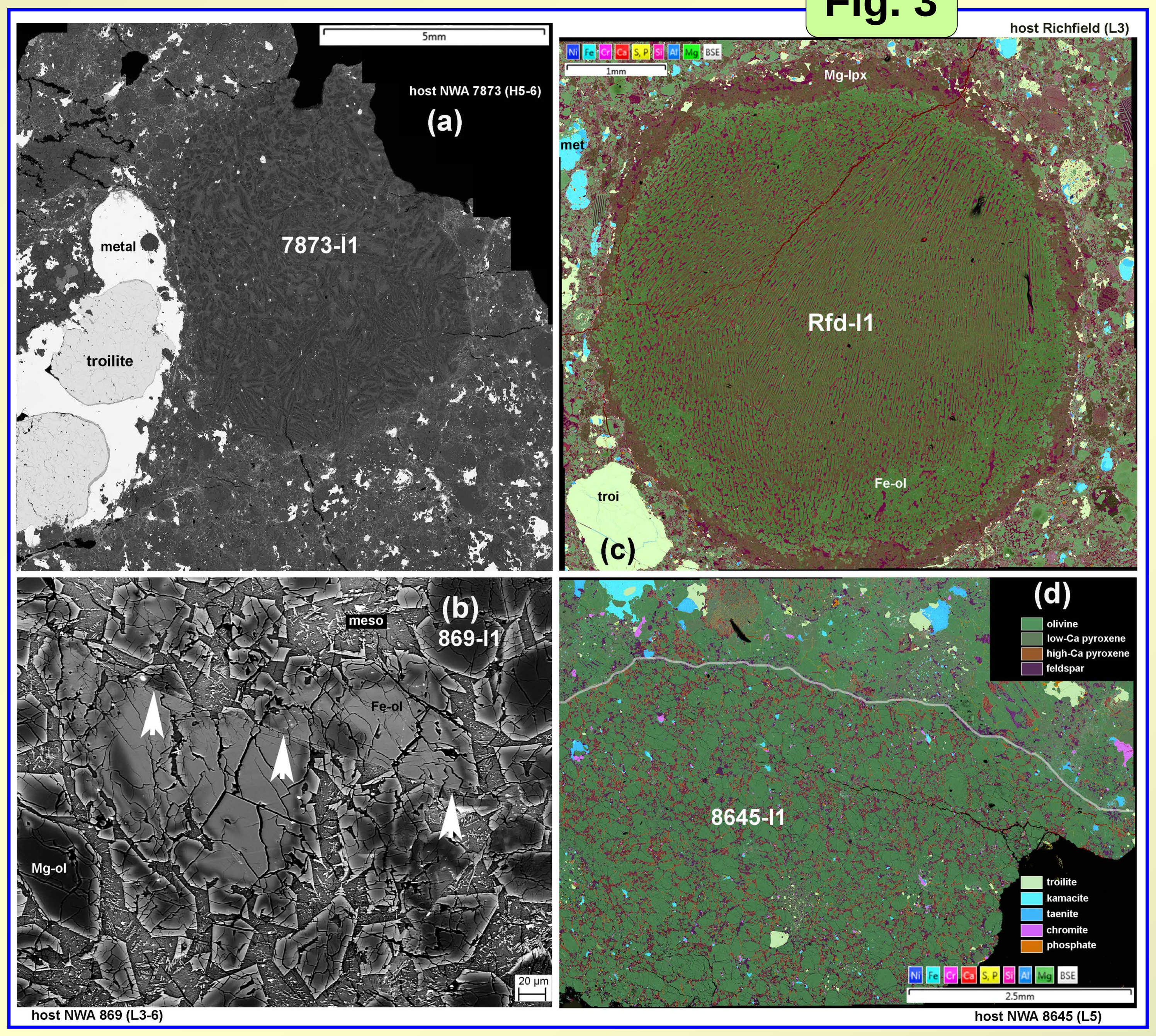

Fig. 3

Fig. 3

(a) BSE image montage of 7873-I1, located adjacent to coarse metal-sulfide.

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

(c, d) False color EDS maps of droplet Rfd-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, diopsidic high-Ca pyroxene is red-orange, troilite yellow-green, metal blue. The similar green colors for olivine inside and outside inclusion 8645-I1 indicates similar composition, verified with point analyses.

CONCLUSIONS

1) Inclusions formed by nearly complete melting of chondritic material accompanied by metal and sulfide loss and generally modest chemical fractionations.
2) Both *Unfr* and *Unfr+K* inclusions probably formed by shock melting of chondritic precursors, sometimes in situ, sometimes involving brecciation during melting, 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 evaporation.
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.

References: [1] Bridges J.C. and Hutchison R. (1997) *MAPS* 32, 389-393. [2] Ruzicka A. et al. (1998) *GCA* 62, 1419-1442. [3] Ruzicka A. et al. (2000) *Antarctic Meteorite Res.,* 13, 19-38. [4] Armstrong K. and Ruzicka A.M. (2015) *46th LPS*, Abstract #1572. [5] Ruzicka A. et al. (2012) *MAPS* 47, 1809-1829. [6] Norman M.D. and Mittlefehldt D.W. (2002) *MAPS* 37, 329-344. [7] Metzler K. et al. (2011) *MAPS* 46, 652-680. [8] Jarosewich E. (1990) *Meteoritics* 25, 323-337. [9] Miller M.F. et al. (1999) *Rapid Comm. Mass Spectrm.* 13, 1211-1217. [10] Clayton R.N. et al. (1991) *GCA* 55, 2317-2377. [11] Jamsja N. and Ruzicka A. (2010) *MAPS* 45, 828-849.

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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 at Open University [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 $\Delta^{17}O$ (~0.1-1.4‰) and $\delta^{18}O$ (3.8-7.8 ‰), broader than but overlapping the H-L-LL fields [10] (Fig. 4)
- There is only partial correspondence between inclusion and host O-isotope composition and Fe-Mg equilibration state. For example, inclusion 8645-I1 (host NWA 8645) has L-like silicate compositions and was clearly metamorphosed in situ (Fig. 3d) but has $\Delta^{17}O$ values far from L, at the upper end of LL (Fig. 4a). Conceivably, this inclusion preserved an LL-like O-isotope signature that was preserved even during Fe-Mg metamorphic equilibration.
- Similarly, inclusion 7871-I1 has L-like Fe-Mg silicate compositions but fits better within the H-group oxygen field (Fig. 4a).
- 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. 4a).

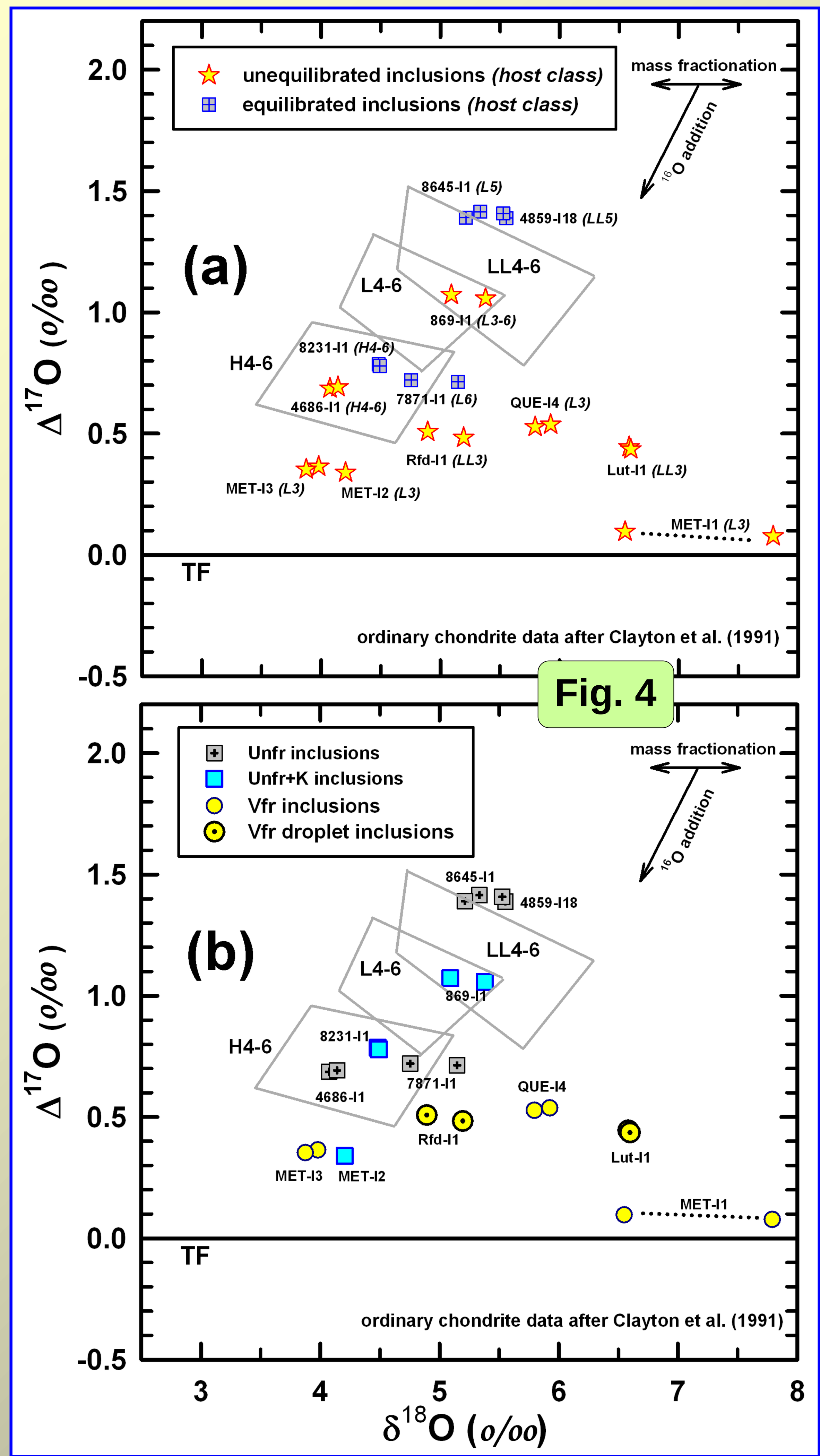

Fig. 4

Fig. 4., continued.

- *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 idea inclusions 869-I1 (Fig. 3b) and 8231-I1 are shock melts of L and H chondrite, respectively (Fig. 4b). Inclusion 4859-I18 could be a shock melt of LL chondrite, consistent with previous interpretations of igneous material in NWA 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 (Fig. 4). MET-I2 has a low $\Delta^{17}O$ value (Fig. 4b) and could have formed by impact melting of a separate, low- $\Delta^{17}O$ body (other than H, L, or LL).
- All *Vfr* inclusions analyzed to date have low $\Delta^{17}O$ values, outside the main H-L-LL fields (Fig. 4b). Although the O isotope compositions of chondrules are more diverse than type 4-6 H-L-LL [10], there are not many with the low $\Delta^{17}O$ values we found for *Vfr* inclusions.

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