Hf-W chronology of large igneous inclusions from ordinary chondrites

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INTRODUCTION

Large (multi-mm to cm) igneous-textured inclusions poor in metal and sulfide represent a distinct lithology unique to ordinary chondrites, whose origins may hold important clues for melting processes in the early solar system. Here we report the first Hf-W ages for a suite that has also been studied for major and trace element compositions [1,2], oxygen-isotope compositions [3], and I-Xe systematics [4].

Samples

Inclusions from H, L, and LL chondrites of 3 different chemical types [1] and varying degrees of Fe-Mg equilibration were studied.

Table 1

Inclusions studied by Hf-W

Inclusion	Chemical type*	Fe-Mg uniform?§	Host
Lut-I1	*Vfr*	No	Lut 005 (LL3)
4859-I18	*Unfr*	Yes	NWA 4859 (LL5)
869-I1	*Unfr+K*	No	NWA 869 (L3-6)
8645-I1	*Unfr*	Yes	NWA 8645 (L5)
7871-I1	*Unfr*	Yes	NWA 7871 (L6)
Dim-I1	*Unfr+K*	No	Dimmitt (H3)
4686-I1	*Unfr*	No	NWA 4686 (H4)
8231-I1	*Unfr+K*	No	NWA 8231 (H4-6)

*chemical types:
Vfr = vapor-fractionated, lithophile element abundances correlated with 50% condensation temperatures (Tc,50 values), evidence for evaporative melting
Unfr = unfractionated lithophile abundances similar to ordinary chondrites, could have formed by melting of such material
Unfr+K = generally chondritic but K-enriched, best explained as chondritic impact melts [1,3]
§ Fe-Mg equilibration (standard deviation Fa and Fs < 1 mol%) in olivine and low-Ca pyroxene, yes or no.

Methods

- **Aliquots of inclusions (~90-1200 mg, judged 100% pure by binocular observation) were separated from host chondrites by a combination of breaking, cutting, and abrading.**
- **For Hf-W analysis, inclusions were digested in HF-HNO_3.**
- **10% aliquots were taken to determine Hf & W concentrations by isotope dilution.**
- **For unspiked samples, W was separated by anion exchange chromatography [5] and W isotope compositions were measured on a Neptune *Plus* MC-ICPMS at Münster.**
- **Results are reported as $\varepsilon^{182}W$ values as parts-per-10000 deviation from the $^{182}W/^{184}W$ measured for terrestrial standards.**
- **Model ages relative to CAI formation time [6] (Δt_{CAI}) were determined assuming evolution in a chondritic chemical system.**

Results I

- **Different inclusions have diverse Hf/W and $\varepsilon^{182}W$ values (Table 1, Fig. 1).**
- **Four inclusions (Lut-I1, 7871-I1, 4859-I18, 8645-I1) plot along a ~2 Ma isochron that also passes through bulk chondritic composition (Fig. 1).**
- **Other inclusions (Dim-I1, 869-I1, 4686-I1, 8231-I1) lie variably below this isochron suggesting a variety of younger ages.**

Results II

- **Hf-W Δt_{CAI} model ages vary from ~2 Ma to >50 Ma (Fig. 2, Table 2).**
- **A lower limit model age of Δt_{CAI} > 50 Ma is assigned to 4686-I1 and 8231-I1 as these inclusions have essentially no radiogenic ^{182}W despite high Hf/W.**
- **For 8645-I1, which has a nearly chondritic composition, the model age calculation is less useful than the observation that this inclusion could lie on an isochron with three other inclusions (Fig. 1).**
- **Two age groups are identified, an old-age and a young-age group.**

Old age group (Lut-I1, 7871-I1, 4859-I18, 8645-I1) has Δt_{CAI} ~ 2 Ma.

Young age group (4686-I1, Dim-I1, 869-I1, 8231-I1) has Δt_{CAI} ~7 to >50 Ma.

Discussion: old-age group

- **Four inclusions could have formed about the same time as chondrules (Δt_{CAI} ~2 Ma based on Al-Mg data for chondrules from primitive ordinary chondrites [7]) (Fig. 2).**
- **This includes the *Vfr* Lut-I1 droplet (Fig. 3a) in an LL3 host, as well as three *Unfr* inclusions (7871-I1, 8645-I1, 4859-I1—Fig 3b) in type 5 or 6 hosts, with the latter having texturally-blurred inclusion-host contacts and uniform Fe-Mg compositions in ferromagnesian silicates (Table 1).**
- **The *Vfr* inclusion is best regarded as an unusually large chondrule (megachondrule), and the *Unfr* inclusions can be interpreted as large-volume melts of chondritic material that formed prior to thermal metamorphism in the host meteorites.**
- **Consistent with the latter possibility, the *Unfr* inclusions have Δt_{CAI} model ages (<3.0 Ma) that are older than those found for metal-silicate isochrons in H5-H6 chondrites (~6-10 Ma) [5].**
- **The preservation of old ages for these *Unfr* inclusions implies that they did not all equilibrate with their host chondrites. However, equilibration cannot be ruled out for 8645-I1 given its quasi-chondritic composition.**
- **A second aliquot analyzed for 4859-I18 gives a Δt_{CAI} model age of ~7 Ma, which can be interpreted as reflecting internal re-equilibration during metamorphism.**

Fig. 1

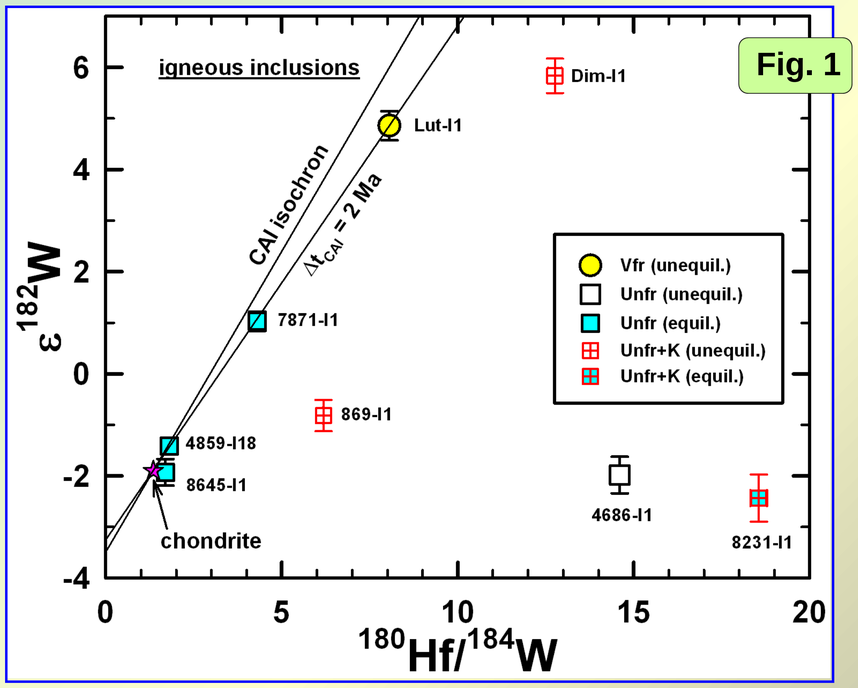


Fig. 2

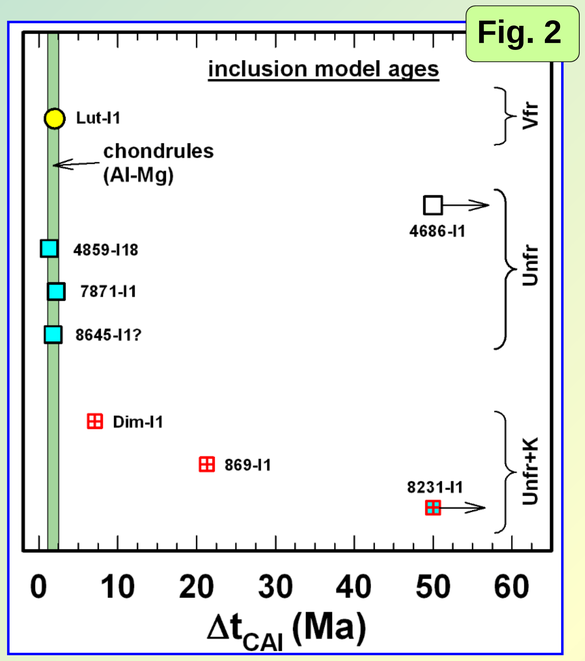
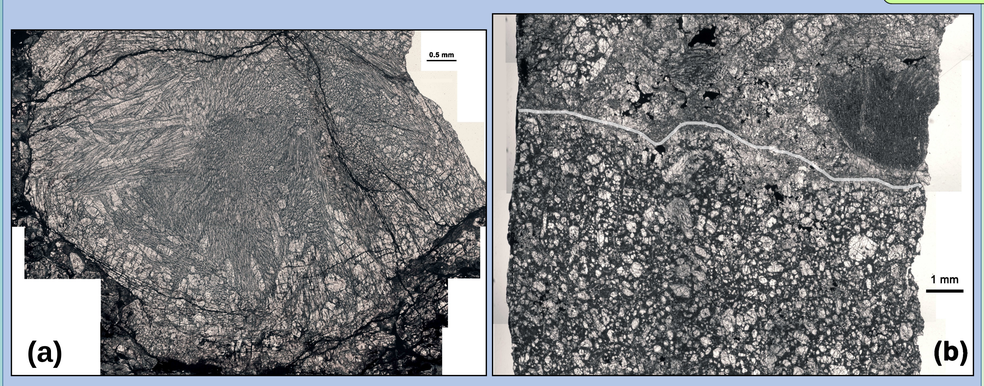


Fig. 3



Images of inclusions.

(a) Plane-polarized light image mosaic of Lut-I1, a brecciated droplet showing radiating and concentric pyroxene-olivine texture suggestive of inward growth from the inclusion edge. Scalebar = 0.5 mm.
(b) Plane-polarized light image mosaic of 4859-I18 (bottom of image), a holocrystalline olivine microporphyry with an indistinct contact with the host (white line marks contact). Scalebar = 1 mm.
(c) Plane-polarized light image mosaic of 4686-I1, an olivine microporphry with a glassy mesostasis and a distinct contact with the host. Scalebar = 0.5 mm.
(d) Cross-polarized light image mosaic of 8231-I1, a holocrystalline inclusion with poikilitic texture composed of orthopyroxene oikocrysts (larger visible crystals) enclosing olivine chadocrysts and a mesostasis of olivine, pyroxene, plagioclase, and troilite. Scalebar = 0.5 mm.

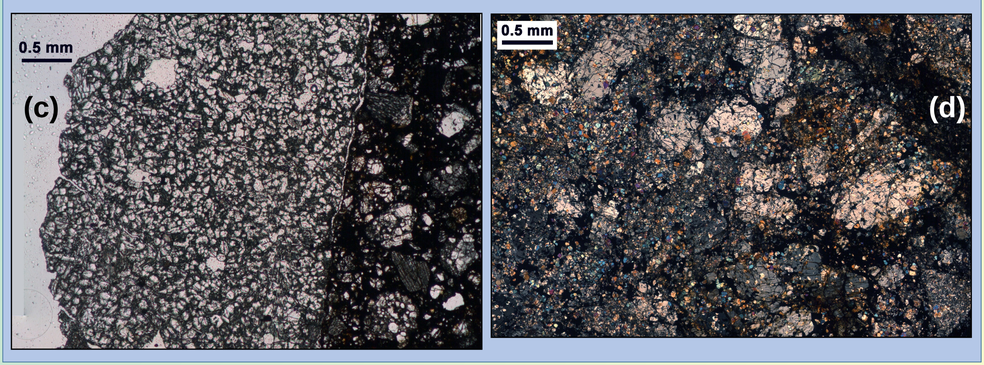


Table 2

Hf-W Results and Model Ages

Inclusion	$^{180}Hf/^{184}W$ (±2σ)	$\varepsilon^{182}W$ (6/4) (±2σ)	Δt_{CAI} (Ma)*
Lut-I1	8.055 ± 0.054	4.86 ± 0.28	2.0
4859-I18	1.807 ± 0.005	-1.41 ± 0.10	1.3
869-I1	6.181 ± 0.017	-0.82 ± 0.31	21.3
8645-I1	1.690 ± 0.006	-1.93 ± 0.26	~2?
7871-I1	4.301 ± 0.012	1.03 ± 0.19	2.2
Dim-I1	12.759 ± 0.197	5.83 ± 0.34	7.1
4686-I1	14.602 ± 0.047	-1.98 ± 0.36	>50
8231-I1	18.554 ± 0.235	-2.44 ± 0.46	>50

* Model age relative to CAIs [6], assuming evolution in a chondritic system with $^{180}Hf/^{184}Hf$ = 1.35 and $\varepsilon^{182}W$ = -1.9. Model age for 8645-I1 uncertain owing to near-chondritic composition, but consistent with a ~2 Ma isochron (Fig. 1).

Discussion: young-age group

- **Four inclusions formed distinctly later than chondrules (Fig. 2).**
- **They likely formed by impact-melting.**
- **They include all three of the *Unfr+K* inclusions analyzed (Dim-I1, 869-I1, 8231-I1) that are best explained as impact melts, as well as an *Unfr* inclusion (4686-I1).**
- **Three of the inclusions (869-I1, Dim-I1, 4686-I1—Fig. 3c) contain mesostasis glass and unequilibrated olivine, implying rapid cooling in a cool portion of their parent bodies. These petrographic-mineral chemistry indicators for fast cooling are consistent with Δt_{CAI} model ages for 869-I1 (~21 Ma) and 4686-I1 (>50 Ma) that are much later than the time of peak thermal metamorphism (~6-10 Ma) [5].**
- **8231-I1 (Fig. 3d) (Δt_{CAI} model age > 50 Ma) is holocrystalline and has chemically uniform olivine and pyroxene. It may have cooled slowly in a larger batch of melt, possibly in an intracrater melt pool.**

SUMMARY

1) **Large igneous inclusions have a variety of model Hf-W ages.**
2) **Older inclusions could have formed as large-volume melts potentially by the same process that formed chondrules about the same time. Lut-I1 almost certainly formed as an unusually large chondrule (megachondrule), given its droplet form and vapor-fractionated composition. The other old inclusions (4859-I18, 7871-I1, 8645-I1) formed at about the same time as Lut-I1 and typical ferromagnesian chondrules prior to thermal metamorphism.**
3) **Younger inclusions formed later than chondrules, by impact melting. Such melting affected various chondritic lithologies, including H3 (Dim-I1), H4 (4686-I1), H4-6 (8231-I1) and L3-6 (869-I1).**

References: [1] Armstrong K. and Ruzicka A.M. (2015) *LPS XXXXVI*, Abstract #1571. [2] Ruzicka A. et al. (2017) *LPS XXXXVIII*, Abstract #2477. [3] Ruzicka A. et al. (2017) *LPS XXXXVII*, Abstract #2230. [4] Crowther S.A. et al. (2017) *Meteoritics & Planetary Sci.*, Abstract #6284. [5] Kleine et al. (2008) *EPSL* 270, 106-118. [6] Kruijer T.S. et al. (2014) *EPSL* 403, 317-327. [7] Kita N. et al. (2000) *GCA* 64, 3913-3922. **Acknowledgments:** NASA grant support for this work (grant NNH12ZDA001N) is gratefully acknowledged.

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