Early formation of primitive achondrites in an outer region of the protoplanetary disc

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Abstract

We compare 13 Tafassasset-related meteorites and propose that they form the first meteorite group of carbonaceous primitive achondrites. We name this new group the Tafassites, which form a continuum from equilibrated petrological type 6 chondrites (termed T6) to partially molten type 7 primitive achondrites (T7) and bear carbonaceous meteorite-like (C) mass-independent isotopic signatures. We use SIMS Pb–Pb Ca phosphate ages to model the Tafassite parent body (TPB) accretion at 1.1⁺²⁻¹ Myr before rapid cooling to below ~720 K within ~9.0 ± 5.0 Myr after CAI formation, respectively. This scenario is consistent with other primitive achondrites but incompatible with a commonly assumed CR chondrite parent body, which was constrained by Al–Mg, Hf–W, and Pb–Pb chondrule ages up to >3.7 Myr after CAIs.

Introduction

Mass-independent nucleosynthetic anomalies in meteorites have revealed a fundamental isotopic dichotomy between s-process-rich (slow neutron capture) non-carbonaceous meteorites (NC) and s-process-depleted carbonaceous meteorites (C), accreted within the inner and outer parts of the protoplanetary disc, respectively (Warren, 2011; Burkhardt et al., 2019; Kruijer et al., 2020). Presolar stardust grains, as carriers of nucleosynthetic signatures, are thought to have been heterogeneously distributed very early into protoplanetary disc. The two NC and C reservoirs evolved as spatially separate and isotopically distinct entities, potentially as a result of the early formation of Jupiter (Kruijer et al., 2020) or a pressure maximum in the disc (Brasser and Mojsis, 2020). Later inward migration of Jupiter could have scattered NC and C planetesimals, leading to the eventual formation of the asteroid belt (Kruijer et al., 2020).

So far, all NC parent bodies appear to have accreted relatively early (<0.5 to ~2 Myr after calcium aluminium-rich inclusions; CAIs), while still abundant short-lived ⁶⁰⁷Al (half-life of ~0.7 Myr) was the dominant heat source to drive planetesimal differentiation. In contrast, carbonaceous chondrites are proposed to have accreted later (~2 to >4 Myr after CAIs) based on chondrule formation ages and common aequous alteration processes instead of thermal metamorphism (Budde et al., 2018; Kruijer et al., 2020). Molybdenum nucleosynthetic isotopic anomalies have related a number of magmatic iron meteorite groups to carbonaceous meteorites (Budde et al., 2019; Burkhardt et al., 2019). Their Hf–W compositions constrain their accretion ages to ~1–2 Myr after CAIs, therefore representing the earliest evidence of planetary formation in the C region, but slightly later than their NC counterparts (Kruijer et al., 2020). Only three stony meteorite groups have so far been argued to be C-related based on O, Cr and Ti nucleosynthetic anomalies. These include Tafassasset (Göpel et al., 2015) and several related meteorites referred to as highly equilibrated CR chondrites (Sanborn et al., 2019), NWA 011-related ungrouped basaltic achondrites (Yamaguchi et al., 2002), and NWA 6704-related ungrouped pyroxenitic achondrites (Hibiya et al., 2019; Sanborn et al., 2019; Table S-6 and references therein). The parent body formation and evolution history for these meteorite groups is however not known with respect to CR chondrites.

Tafassasset is an unusual primitive achondrite. It contains predominantly FeO-rich olivine (Fa₂₉), pyroxene (Fs₂₀) and intermediate plagioclase in coexistence with abundant Fe-Ni metal. Tafassasset was initially suggested to be an equilibrated CR achondrite based on its oxygen isotopic composition. Tafassasset was later re-classified as an ungrouped primitive

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achondrite based on distinct oxygen fugacity and bulk elemental composition, incompatible with a partially molten CR precursor (Gardner-Vandy et al., 2012; Göpel et al., 2015).

The high FeO contents in silicates in coexistence with abundant Fe-Ni metal (bulk Fe content 23–40 wt. %) distinguishes Tafassasset from any known groups of primitive achondrites (Figs. S-2 to S-4).

### Samples and Methods

Based on their reported mineralogical and oxygen isotopic compositions, here we demonstrate that a group of 13 Tafassasset-related meteorites can be established, for which we recommend the name ‘Tafassites’. The members with corresponding thermal metamorphic types are NWA 7317, NWA 6921 and NWA 2994 as type 6 chondrites (T6); Tafassasset, NWA 11561, NWA 5131, NWA 12869 and NWA 11112 as type 7 primitive achondrites (T7); and NWA 12455, NWA 6901, NWA 3250, NWA 8548 and NWA 3100 as primitive achondrites with melt depletion (T7 depleted or T7 dep.) (Tables S-1, S-2). Together, these meteorites constitute the first and so far unique group of carbonaceous primitive achondrites.

The petrology, geochronology and thermal evolution of four Tafassites (NWA 7317 T6, Tafassasset T7, NWA 11561 T7, and NWA 12455 T7 dep.) were characterised in detail by optical microscopy, scanning electron microscopy, energy dispersive spectroscopy elemental mapping and electron microprobe analysis. We further analysed the Pb isotopic compositions of merrillite (Fig. S-7) to obtain their $^{206}\text{Pb}$-$^{207}\text{Pb}$ ages. Our Pb-Pb phosphate ages along with published Mn–Cr and Hf–W ages on Tafassasset (Breton et al., 2015; Göpel et al., 2015) were fitted using a 1 D thermal model to constrain the thermal history of the Tafassite parent body. Further Tafassite classification criteria and comparison against primitive achondrites, CR chondrites, NWA 011 and NWA 6704 group, including ours and published data, and our analytical and numerical model designs are detailed in the Supplementary Information.

### Petrology of Tafassites

Tafassites are equilibrated meteorites composed of abundant Fe-rich olivine (Ol, $\text{Fa}_{52-58}$; Fe/Mn atomic ratios ranging from 60 to 94; 40–80 vol. %; Fig. S-2), orthopyroxene (Opx, $\text{Fs}_{23-35}$; Fe/Mn 38–67; 10–40 vol. % for two pyroxenes), minor clinopyroxene (Cpx; Fig. S-6), and intermediate plagioclase (Fig. $\text{An}_{28-43}\text{Ab}_{56-48}\text{Or}_{5-8}$; <1 to >10 vol. %, variable abundance and composition reflecting partial melting and melt extraction), together with abundant Fe-Ni metal, troilite (Troc), Al-rich chromite (Chr, $\sim\text{Mg}_{2}\text{Fe}_{0.42}\text{Al}_{0.06}\text{Cr}_{0.37}\text{Ti}_{0.06}\text{O}_{4}$; 7–23 vol. % for all opaques) and trace merrillite (Merr; Fig. S-7, Tables S-1 to S-3).

Tafassites show further prograde textural equilibration from:

1. (Sub)solidus heated poikiloblastic type 6 chondrites (abbreviated as T6, e.g. NWA 7317 T6, metamorphosed at T $<1313$ K with exsolved metal-sulfide nodules and rare relict chondrules; Figs. S-1, S-8);

2. Supersolidus heated poikilitic type 7 primitive achondrites (T7, e.g. Tafassasset T7, NWA 11561 T7, partially molten at T $>1353$ K with interstitial and heterogeneous plagioclase and inverted pigeonite exsolution of mm-sized pyroxene oikocrysts; Figs. S-1, S-6, S-9, S-10);

3. Supersolidus heated protogranular type 7 primitive achondrites with variable degrees of opaque and silicate melt depletion (T7 dep., e.g. NWA 12455 T7 depleted, with curved grain boundaries, thin opaque veins; Figs. S-1, S-11).

The higher FeO contents in silicate, metal content, calculated $\Delta$O$_2$ ($\Delta$IW = $-1.4 \pm 0.1$), along with unique $\Delta^{17}$O values, distinguish Tafassites from other primitive achondrites (Figs. 1, S-2, S-4, S-5 and Tables S-3, S-4). Bulk chemical analyses on Tafassasset show from nearly chondritic to depleted trace element patterns, consistent with variable melt extraction (Gardner-Vandy et al., 2012; Göpel et al., 2015).

### Mass-dependent and Mass-independent O Isotopic Compositions

Despite commonly argued similarities, a re-evaluation of published O isotopic data (Table S-4) reveals clear compositional differences between Tafassites, CR chondrites, and NWA 011 and NWA 6704 group (Schrader et al., 2011; Gardner-Vandy et al., 2012; Hibia et al., 2019). Figure 1a shows that Tafassites plot tightly on a mass-dependent fractionation line (slope $\sim0.51$) while CR chondrites fall on a mass-independent mixing line (slope $\sim0.71$). The homogeneous $\Delta^{17}$O anomaly in Tafassites ($-1.67 \pm 0.14 \%$; 2 s.d; Fig. 1, Table S-4) barely overlaps with highly heterogeneous CR2 ($-1.5$ to $-2.5\%$; Schrader et al., 2011). These O isotopic compositions strongly suggest that Tafassites originated from a common and fairly equilibrated parent body, previously unrecognised and different from the CR chondrite parent body (PB). In this case, the oxygen isotope similarity to CR chondrites, likely reflects similar accreting materials in lieu of a common parent body. Tafassites also have $\Delta^{17}$O values that are distinct from other known groups of primitive achondrites.

NWA 011 and NWA 6704 group meteorites have also been linked with Tafassasset and CR chondrites based on oxygen isotope signatures. NWA 011 group has $\Delta^{17}$O values ranging from $-1.43$ to $-1.86 \%$ overlapping with Tafassites (Yamaguchi et al., 2002; Fig. 1b). However, the higher FeO abundance in silicates (Fig. S-2), distinct Fe/Mn ratio in orthopyroxene (Fig. S-3) and calcic plagioclase composition ($\sim\text{An}_{85}$) are difficult to reconcile petrogenetically with Tafassites. NWA 6704 group comprises a unique Fe-rich and pyroxenitic lithology with its own oxygen mass-dependent fractionation line different from Tafassites and CR with $\Delta^{17}$O $= -1.06 \pm 0.06 \%$ (Fig. 1b and Table S-14).

### Thermal History of the Tafassite Parent Body

Merrillite Pb–Pb chronology (Fig. S-12 and Table S-5) provides retrograde metamorphic ages ($T_c$ $\sim 720$ K; Chemiak et al., 1991) of $4559.5 \pm 5.8$ Ma ($n = 10$, all uncertainties reported as $\pm 2$ s.e.) for NWA 7317 T6; $4560.4 \pm 5.7$ Ma ($n = 21$) for NWA 11561 T7; $4557.8 \pm 3.4$ Ma ($n = 16$) for NWA 12455 T7 depleted and slightly younger $4548.0 \pm 15.9$ Ma ($n = 7$) for Tafassasset T7 (Fig. 2). These ages are consistently younger than Hf–W ($2.9 \pm 0.9$ Myr after CAI, $T_c \sim 1200$ K) and Mn–Cr ages ($4.9 \pm 0.3$ Myr after CAI, $T_c \sim 950 \pm 100$ K) (Breton et al., 2015; Göpel et al., 2015) reported for Tafassasset, suggesting rapid cooling to $<720$ K at a rate of $\sim 100$ K/Myr within $9.0 \pm 5.0$ Myr after CAIs. Thermal numerical modelling indicates that the Tafassite parent body (TPB) accreted within $1.1^{+0.2}_{-0.2}$ Myr after CAI into a $>50$ km radius planetesimal (Fig. 3), before experiencing severe but rapid thermal annealing. Our Pb–Pb ages and thermal history model result in identical
Figure 1  Oxygen isotope compositions of Tafassites. (a) Tafassites define a mass-dependent fractionation line (slope ~0.71), distinctive from the mass-independent CR mixing line (slope ~0.51), distinct from acapulcoite-lodranite (Aca&Lod), winonaite (Win) and CR chondrite meteorites (Schrader et al., 2011). Data are compiled in Table S-4, and carbonaceous chondrite anhydrous mixing (CCAM) and terrestrial fractionation lines (TFL) are shown for reference.

accretion age estimation (1.1±0.3 vs. <1 Myr) compared to Breton et al. (2015), but predict larger PB size (>50 km vs. <25 km) and shallow burial depth (all ≤4 km). Though sharing a thermal history similar to primitive achondrites, the early accretion of TPB is completely unconstrained by late CR chondrite PB formation based on Al–Mg chondrule ages therefore placing a minimum age for its accretion (> 4.0±0.5 Myr; Schrader et al., 2017). Our results support the formation of a partially differentiated TPB with highly equilibrated T6 chondrites and partially molten T7 primitive achondrites at a shallow depth. The TPB may also be fully differentiated within its interior.

Isotopic Anomalies

Tafassisset belongs to the carbonaceous reservoir (Fig. S-13) based on reported mass-independent isotopic anomalies for several elements (Table S-6) i.e. ε50Ti = 2.07 ± 0.14, ε54Cr = 1.44 ± 0.08 (Sanborn et al., 2019), ε94Mo = 1.54 ± 0.40 (Burkhardt et al., 2011) and ε180Rnmetal = −1.15 ± 0.04 (Fischer-Gödde et al., 2015). Other Tafassisset also show similar compositions with ε54Cr (1.31 to 1.50) and ε50Ti (1.91 to 2.90), distinct from any known groups of primitive achondrites (all NC-like; Kruijer et al., 2020) but similar to carbonaceous (in particular CR) chondrites. Tafassisset show rather homogeneous ε54Cr and Δ17O but somewhat more heterogeneous ε50Ti anomalies presumably due to limited number of measurements and/or slower diffusion rate of Ti4+ over Cr3+ and O2−, also consistent with their partially differentiated nature.

Based on chemical and isotopic signatures, we rule out a common parent body hypothesis for all CR chondrite and achondrite-related meteorites, and Tafassisset that constitute a unique group of carbonaceous primitive achondrites. The parent body of Tafassisset accreted early, ~1.1 Myr after CAIs, in an outer region of the disc, close to where the parent body of CR chondrites will form, at least ~3 Myr later. Similarly, the NWA 011 and NWA 6704 achondrite grouplets form two groups of carbonaceous achondrites for which the time of accretion is currently not as well constrained, but suggested to be within 1.5 Myr after CAIs (Sanborn et al., 2019). Their respective parent bodies likely accreted in close regions of the outer protoplanetary disc (Figs. 1, S-2, S-4, S-13).
The Protoplanetary Disc Farther Out is Just as Diverse

We show Tafassites as the first known group of carbonaceous primitive achondrites, which expands the diversity of meteorite parent bodies, providing essential clues about planetesimal formation and protoplanetary disc evolution beyond the snow line. We identified at least four parent bodies for Tafassites, NWA 011 grouplet, NWA 6704 grouplet, and CR chondrites. The PB accretion age of Tafassites (1.1±0.4 Myr, likely comparable to NWA 011 and NWA 6704 grouplets) is similar to C magmatic irons and pallasites (0.9±0.3 Myr; Kralier et al., 2020) and provides evidence for early accretion of rocky planetesimals beyond the snow line and with coeval planetesimal formation between the inner and outer disc (Fig. 2). The divergent PB accretion ages and O, 54Cr and 50Ti isotopic anomalies for Tafassites and CR chondrites (1.1±0.3 Myr; Schrader et al., 2017) indicate a prolonged and multi-epoch of planetesimal formation in the Tafassite-feeding zone (related to the metal-rich carbonaceous chondrites CR, CH and CB) associated with limited radial mixing of building materials throughout planetesimal formation period.

Author Contributions

AB and NM designed the study, and characterised the samples. WN and MT carried out the SIMS analyses, assisted by AB and MT. AN and NM conducted the thermodynamic calculations. HK discussed the implications of the findings to our current understanding of planetesimal formation. All co-authors contributed to writing the manuscript and discussion. NM and WN contributed equally to this work.

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Additional Information

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