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

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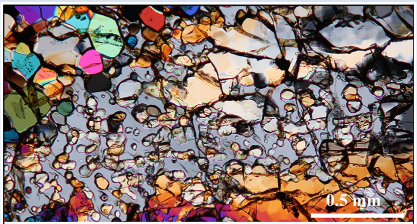
Abstract



Tafassites: carbonaceous primitive achondrites

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 $1.1^{+0.3}_{-0.4}$ 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. Given their carbonaceous-like affinity, Tafassites therefore constitute the first early accreted chondritic meteorite group from an outer region of the protoplanetary disc, presumably close to the further CR feeding zone. Our findings support that planetary formation in the outer protoplanetary disc evolved nearly coevally with the inner part of the disc, with limited admixing of inward material during planetesimal formation over 4 million years after CAIs.

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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 Mojzsis, 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 ^{26}Al (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 aqueous 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 grouplets 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 grouplets is however not known with respect to CR chondrites.

Tafassasset is an unusual primitive achondrite. It contains predominantly FeO-rich olivine (Fa_{29}), pyroxene (Fs_{26}) 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 merrillites (Fig. S-7) to obtain their ^{207}Pb–^{206}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 grouplets, 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, $Fa_{27–38}$, Fe/Mn atomic ratios ranging from 60 to 94, 40–80 vol. %; Fig. S-2), orthopyroxene (Opx, $Fs_{23–31}$, Fe/Mn 38–67, 10–40 vol. % for two pyroxenes), minor clinopyroxene (Cpx; Fig. S-6), and intermediate plagioclase (Plg, $An_{28–56}Ab_{43–68}Or_{1–5}$, <1 to >10 vol. %, variable abundance and composition reflecting partial melting and melt extraction), together with abundant Fe-Ni metal, troilite (Tro), Al-rich chromite (Chr, ~$Mg_{0.2}Fe_{0.8}Al_{0.4}Cr_{1.5}Ti_{0.1}O_{4.0}$, 7–23 vol. % for all opaques) and trace merrillite (Mer; Fig. S-7, Tables S-1 to S-3).

Tafassites show further prograde textural equilibration from:

(1) Subsolidus 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 fO_2 (ΔIW = −1.4 ± 0.1), along with unique Δ^{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 grouplets (Schrader *et al.*, 2011; Gardner-Vandy *et al.*, 2012; Hibiya *et al.*, 2019). Figure 1a shows that Tafassites plot tightly on a mass-dependent fractionation line (slope ~0.51) while CR chondrites fall on a mass-independent mixing line (slope ~0.71). The homogeneous Δ^{17}O anomaly in Tafassites (−1.67 ± 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 Δ^{17}O values that are distinct from other known groups of primitive achondrites.

NWA 011 and NWA 6704 grouplet meteorites have also been linked with Tafassasset and CR chondrites based on oxygen isotope signatures. NWA 011 grouplet has Δ^{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 (~An_{85}) are difficult to reconcile petrogenetically with Tafassites. NWA 6704 grouplet comprises a unique Fe-rich and pyroxenitic lithology with its own oxygen mass-dependent fractionation line different from Tafassites and CR with Δ^{17}O = −1.06 ± 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 ~720 K; Cherniak *et al.*, 1991) of 4559.5 ± 5.8 Ma (n = 10, all uncertainties reported as ± 2 s.e.) for NWA 7317 T6; 4560.4 ± 5.7 Ma (n = 21) for NWA 11561 T7; 4557.8 ± 3.4 Ma (n = 16) for NWA 12455 T7 depleted and slightly younger 4548.0 ± 15.9 Ma (n = 7) for Tafassasset T7 (Fig. 2). These ages are consistently younger than Hf–W (2.9 ± 0.9 Myr after CAI, T_c ~1200 K) and Mn–Cr ages (4.9 ± 0.3 Myr after CAI, T_c ~950 ± 100 K) (Breton *et al.*, 2015; Göpel *et al.*, 2015) reported for Tafassasset, suggesting rapid cooling to <720 K at a rate of ~100 K/Myr within 9.0 ± 5.0 Myr after CAIs. Thermal numerical modelling indicates that the Tafassite parent body (TPB) accreted within $1.1^{+0.3}_{-0.4}$ 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

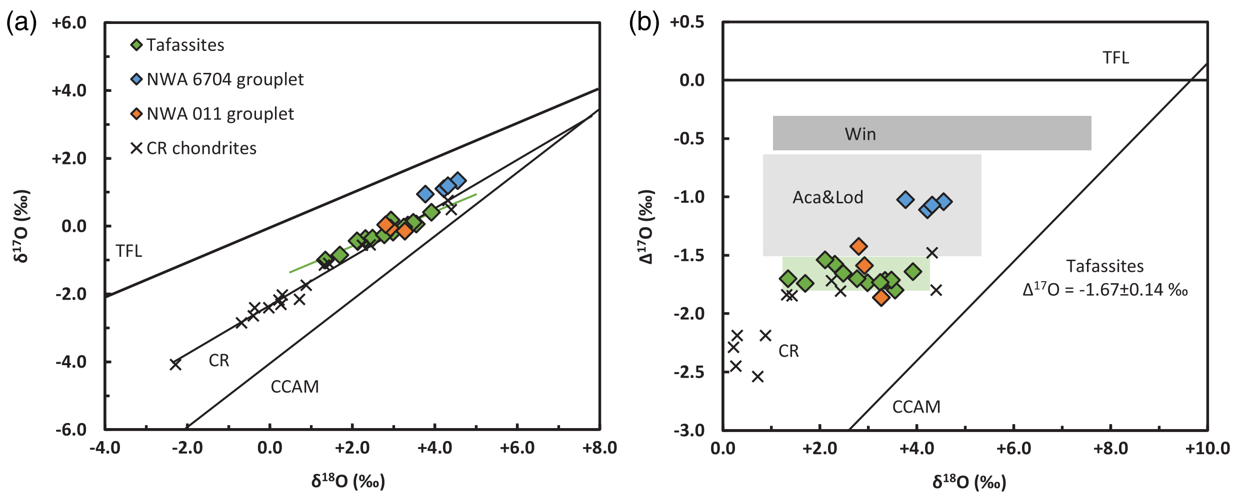

Figure 1 Oxygen isotope compositions of Tafassites. **(a)** Tafassites define a mass-dependent fractionation line (slope ~0.51), distinctive from the mass-independent CR mixing line (slope ~0.71). **(b)** Tafassites show a homogeneous and unique $\Delta^{17}O$ anomaly (−1.67 ± 0.14 ‰, 2 s.d.) distinct 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 ($1.1^{+0.3}_{-0.4}$ *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 unreconcilable with late CR chondrite PB formation based on Al–Mg chondrule ages therefore placing a minimum age for its accretion (> $4.0^{+0.5}_{-0.3}$ 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.

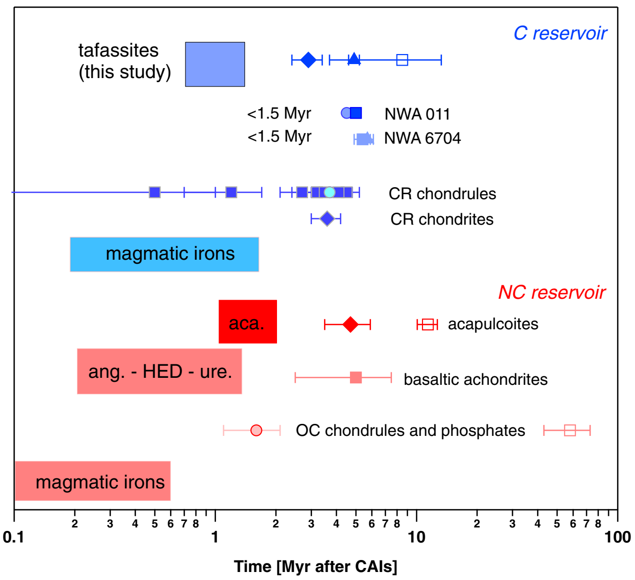

Figure 2 Comparative chronology from CAI formation (U corrected Pb–Pb average age of 4567.73 ± 0.81 Ma; Sanborn *et al.*, 2019) of selected meteorite groups (data points) and modelled timing of accretion of their parent bodies (boxes) in the carbonaceous (C, blue) and non-carbonaceous (NC, red) reservoirs. Parent body accretion ages are from this study for Tafassites, and taken from Kruijer *et al.* (2020) and Neumann *et al.* (2018) for other relevant groups. The Tafassite Hf–W, Mn–Cr (Breton *et al.*, 2015; Göpel *et al.*, 2015) and average Pb–Pb phosphate ages of 4558.4 ± 5.0 Myr (2 s.e.) (open square, this study) are comparable to Mn–Cr, Al–Mg and Pb–Pb isochron ages measured for the NWA 011 (Bouvier *et al.*, 2011) and NWA 6704 (Amelin *et al.*, 2019; Sanborn *et al.*, 2019) grouplets. Tafassasset Hf–W age is however older than most CR2 individual chondrule ages obtained by Al–Mg (Schrader *et al.*, 2017) and Pb–Pb (Amelin *et al.*, 2002; Bollard *et al*, 2017), and Hf–W average age obtained in CR chondrites (Budde *et al.*, 2018) after CAIs. Symbols: circle = Al–Mg; full diamond = Hf–W; triangle = Mn–Cr; square = phosphate Pb–Pb; full square = Pb–Pb.

Isotopic Anomalies

Tafassasset belongs to the carbonaceous reservoir (Fig. S-13) based on reported mass-independent isotopic anomalies for several elements (Table S-6) *i.e.* ε^{50}Ti = 2.07 ± 0.14, ε^{54}Cr = 1.44 ± 0.08 (Sanborn *et al.*, 2019), ε^{94}Mo = 1.54 ± 0.40 (Burkhardt *et al.*, 2011) and $\varepsilon^{100}Ru_{metal}$ = −1.15 ± 0.04 (Fischer-Gödde *et al.*, 2015). Other Tafassites also show similar compositions with ε^{54}Cr (1.31 to 1.50) and ε^{50}Ti (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. Tafassites show rather homogeneous ε^{54}Cr and Δ^{17}O but somewhat more heterogeneous ε^{50}Ti anomalies presumably due to limited number of measurements and/or slower diffusion rate of Ti^{4+} over Cr^{3+} and O^{2-}, 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 Tafassites that constitute a unique group of carbonaceous primitive achondrites. The parent body of Tafassites 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).

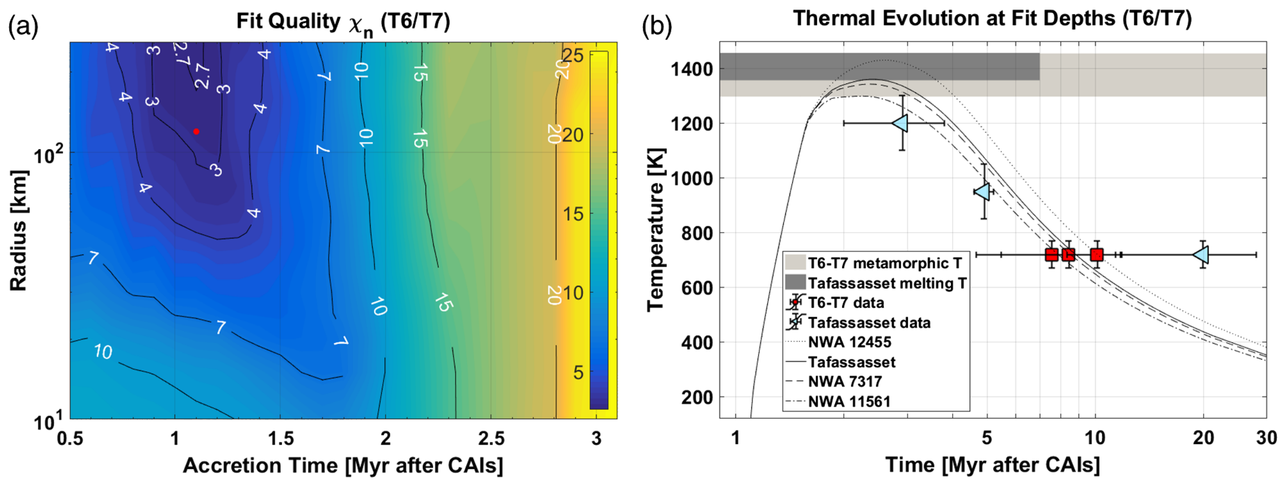

Figure 3 Thermal evolution model of the Tafassite parent body. **(a)** Fit quality χ_n as a function of the planetesimal accretion time t_0 and radius R. Tafassite parent body is best fitted to have an accretion time $t_0 = 1.1^{+0.3}_{-0.4}$ Myr and radius R >50 km. **(b)** Modelled thermal history curves based on Tafassasset Hf–W and Mn–Cr ages, and Tafassasset and T6–T7 Tafassite Pb–Pb Ca phosphate chronological records. The thermal history is shown for an object with R = 120 km and t_0 = 1.1 Myr marked in **(a)** with a red dot, and is representative for bodies with an acceptable fit quality of $\chi_n \leq 4$. The fit depths for NWA 12455, Tafassasset, NWA 7317 and NWA 11561 are ~4.1 km, ~3.3 km, ~3.1 km and ~2.6 km, respectively.

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 ($1.1^{+0.3}_{-0.4}$ Myr, likely comparable to NWA 011 and NWA 6704 grouplets) is similar to C magmatic irons and pallasites ($0.9^{+0.4}_{-0.2}$ Myr; Kruijer *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, ^{54}Cr and ^{50}Ti isotopic anomalies for Tafassites and CR chondrites ($1.1^{+0.3}_{-0.4}$ *vs.* > $4.0^{+0.5}_{-0.3}$ 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 thermal modelling. NM, WS, TL carried out the SIMS analyses, assisted by AB and MT. AN and NM carried out 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 the data included in this manuscript.

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Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2234.

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