Mineralogy and oxygen isotopes of ultrarefractory inclusions

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Fine-grained CAIs with Group II rare earth element (REE) patterns condensed from a gaseous reservoir from which the ultrarefractory (UR) REEs were removed. The carriers of UR REEs are poorly known. Here we report on the mineralogy, petrology and O-isotope compositions of ~20 CAIs, presumably UR (REEs have not been measured yet), from the CO, CV, CH, CR, and CM carbonaceous chondrites (CCs). The UR CAIs studied are dominated by Zr, Sc, Ti, and Y-rich oxides (allendeite, kangite, lakargite, panguite, Y-perovskite, tazheranite, warkite, zirconolite) and silicates (davisite, eringaite, thortveitite) and often contain platinum group element nuggets; most are surrounded by Wark-Lovering rims of Sc-pyroxene, ±eringaite, Al,Ti-diopside, and ±forsterite. UR CAIs occur as (*i*) individual objects, (*ii*) constituents of amoeboid olivine aggregates and Fluffy Type A CAIs, and (*iii*) relict objects in forsterite-bearing Type B CAIs and chondrules. UR CAIs from the least metamorphosed CCs studied [Murchison (CM2), Y-793261 (CR2), Acfer 182 (CH3.0), and DOM 08006 (CO3.0)], are uniformly ^{16}O-rich (Δ^{17}O ~ –24±2‰). In contrast, most UR CAIs from CCs of petrologic type ≥3.1 (CVs: Kaba, Vigarano, Efremovka, and NWA 3118, and COs: DOM 08004, Moss, and Ornans) are isotopically heterogeneous: spinel, hibonite and forsterite are ^{16}O-rich (Δ^{17}O ~ –24‰), whereas warkite, eringaite, kangite, Y-perovskite, and davisite are ^{16}O-depleted to various degrees (Δ^{17}O range from ~ –20 to ~ –2‰). We infer that (*i*) Zr, Sc, Ti, and Y-rich minerals in UR CAIs may represent one of the major carriers of UR REEs. (*ii*) UR CAIs formed in an ^{16}O-rich gaseous reservoir; some subsequently experienced melting during CAI- and chondrule-forming events. (*iii*) UR CAIs from CCs of petrologic type 2–3.0 largely retained their original O-isotope compositions, whereas those from CCs of higher petrologic type that experienced fluid-assisted thermal metamorphism, recorded mineralogically-controlled O-isotope exchange most with an ^{16}O-depleted fluid phase on the host chondrite parent asteroids. Some UR CAIs from CCs experienced O-isotope exchange during chondrule melting.