

## ORIGIN OF REFRACTORY AND ULTRAREFRACTORY INCLUSIONS IN CARBONACEOUS CHONDRITES

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CAIs with Group II REE patterns formed by gas-solid condensation in a disk region from which ultrarefractory (UR) REEs were removed. The carriers of UR REEs, their O-isotopic compositions and origin, condensation vs. evaporation, are not known. To address these questions, we searched for Zr- and Sc-rich CAIs (Zr and Sc are among the most refractory elements in a gas of solar composition) in multiple polished sections of CV, CO, CM, CR, and CH chondrites using element mapping in Sc and Zr x-rays. The mineralogy and petrology of ~40 UR CAIs identified were studied with SEM, EPMA and EBSD; O-isotopes were analyzed with SIMS; REE measurements are in progress. The UR CAIs studied occur as (i) isolated objects, (ii) constituents of non-igneous refractory inclusions (AOAs and FTA CAIs), and (iii) relict objects in igneous (FoB and CTA) CAIs and chondrules. They are typically <30  $\mu\text{m}$  in size and dominated by Zr, Sc, Ti, and Y-rich minerals: warkite  $\text{Ca}_2\text{Sc}_6\text{Al}_6\text{O}_{20}$ , kangite  $(\text{Sc,Ti,Al,Zr,Mg,Ca})_2\text{O}_3$ , Y-rich perovskite  $\text{Ca}(\text{Ti,Y,Sc,Zr})\text{O}_3$ , davisite  $\text{CaScAlSiO}_6$ , tazheranite  $(\text{Zr,Ti,Ca,Y})\text{O}_{1.75}$ , thortveitite  $\text{Sc}_2\text{Si}_2\text{O}_7$ , eringaite  $\text{Ca}_3(\text{Sc,Y,Ti})_2\text{Si}_3\text{O}_{12}$ , zirconolite  $\text{CaZrTi}_2\text{O}_7$ , allendeite  $\text{Sc}_4\text{Zr}_3\text{O}_{12}$ , anosovite  $(\text{Ti,Mg,Sc,Al})_3\text{O}_5$ , lakargite  $\text{CaZrO}_3$ , and panguite  $(\text{Ti,Sc,Al,Mg})_{1.8}\text{O}_3$ . Isolated UR CAIs are surrounded by Wark-Lovering rims of  $\pm$ eringaite, Sc,Al,Ti-diopside, Al-diopside, and  $\pm$ forsterite. Most UR CAIs from type 2–3.0 CCs are uniformly <sup>16</sup>O-rich ( $\Delta^{17}\text{O} \sim -23 \pm 2\%$ ); one CH UR CAI is uniformly <sup>16</sup>O-depleted ( $\Delta^{17}\text{O} \sim -10\%$ ). In contrast, nearly all UR CAIs from  $\text{CO} \geq 3.1\text{s}$  and  $\text{CV} \geq 3.1\text{s}$  are isotopically heterogeneous: spinel, hibonite, Al,Ti-diopside, forsterite, low-Ca pyroxene, and silica are <sup>16</sup>O-rich ( $\Delta^{17}\text{O} \sim -23 \pm 2\%$ ); warkite, eringaite, kangite, Y-perovskite, davisite, and melilite are <sup>16</sup>O-depleted to various degrees ( $\Delta^{17}\text{O}$  range from  $\sim -20$  to  $\sim -2\%$ ).

We infer that (i) vast majority of UR and less refractory CAIs formed by evaporation, condensation, aggregation, and melting processes in a solar-like <sup>16</sup>O-rich gaseous reservoir; very few CAIs formed in a <sup>16</sup>O-depleted gaseous reservoir. Both reservoirs coexisted in the protoplanetary disk during a CAI-forming epoch. (ii) UR CAIs from type 2–3.0 CCs retained original O-isotopic compositions, whereas those from  $\text{CO} \geq 3.1\text{s}$  and  $\text{CV} \geq 3.1\text{s}$  experienced O-isotope exchange with <sup>16</sup>O-poor aqueous fluids on the CV and CO parent asteroids. Some UR CAIs experienced incomplete melting and O-isotope exchange with <sup>16</sup>O-depleted nebular gas during chondrule formation. (iii) Zr- and Sc-rich minerals, commonly observed in UR CAIs, may represent some of the major carriers of UR REEs.