

ORIGIN OF REFRACTORY AND ULTRAREFRACTORY INCLUSIONS IN CARBONACEOUS CHONDRITES

A. Krot¹, C. Ma², K. Nagashima¹, J. Beckett², S. Simon³, A. Davis⁴, M. Komatsu⁵, T. Fagan⁵, M. Ivanova⁶, A. Bischoff⁷, F. Brenker⁸. ¹University of Hawai'i, USA (sasha@higp.hawaii.edu); ²California Institute of Technology, USA; ³University of New Mexico, USA; ⁴University of Chicago, USA; ⁵Waseda University, Japan; ⁶Vernadsky Institute, Russia; ⁷Institut für Planetologie, Germany; ⁸Goethe University, Germany

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 μm 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 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 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 ^{16}O -rich ($\Delta^{17}\text{O} \sim -23 \pm 2\text{‰}$); one CH UR CAI is uniformly ^{16}O -depleted ($\Delta^{17}\text{O} \sim -10\text{‰}$). 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 ^{16}O -rich ($\Delta^{17}\text{O} \sim -23 \pm 2\text{‰}$); warkite, eringaite, kangite, Y-perovskite, davisite, and melilite are ^{16}O -depleted to various degrees ($\Delta^{17}\text{O}$ range from ~ -20 to $\sim -2\text{‰}$).

We infer that (i) vast majority of UR and less refractory CAIs formed by evaporation, condensation, aggregation, and melting processes in a solar-like ^{16}O -rich gaseous reservoir; very few CAIs formed in a ^{16}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 ^{16}O -poor aqueous fluids on the CV and CO parent asteroids. Some UR CAIs experienced incomplete melting and O-isotope exchange with ^{16}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.