Early condensation history from two ultrarefractory inclusions

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Carbonaceous chondrites rarely contain ultrarefractory (UR) inclusions, which are characterized by the occurrence of minerals composed of ultrarefractory elements such as Zr, Sc, and Re. They are an important material in meteorites, because such inclusions were formed at the earliest stage of the solar nebula. We have already reported two UR inclusions from Murchison (CM) [1] and Y-793261 (CR) [2]. Here we compare these inclusions with the other URs, and discuss their distinct formation processes.

An inclusion, Romulus in Murchison, contains UR minerals, such as Zr-Sc-bearing pyroxene, Zr-Sc-Y-oxide, and Ru-Re-Os-Ir-metal, with spinel. This mineral assemblage is surrounded by forsterite. No perovskite, hibonite, or melilite are encountered in this inclusion.

Y-793261 contains an amoeboid olivine aggregate, AOA 4, which mainly consists of forsterite (70 vol.%), with 10% enstatite, 18 % refractory to UR minerals (spinel, Zr-Sc-bearing pyroxene, and Zr-oxide), and 2.5% silica mineral. Enstatite occurs within forsterite and in the peripheral parts of this AOA. We also noticed thin enstatite veinlet, 2-5 μm in width, occurs just between silica and forsterite.

The occurrence of UR minerals within forsterite is a distinct feature of Romulus and AOA 4 among known URs. No occurrences of hibonite, melilite, and perovskite, are distinguished from the other UR inclusions. Because of no textural evidence for melting, the constituent minerals in Romulus and AOA 4 reflect condensation sequence ranging from 1800 to 1400K. However, these mineral assemblages are not complete condensation sequence products, because perovskite and some others are not encountered in these URs.

Some enstatite grains in AOA 4 were formed by the reaction between forsterite and gaseous SiO and/or direct condensation [3]. However, from the occurrence of enstatite veinlet between forsterite and silica, we propose that such enstatite was also formed through the reaction between forsterite and silica under subsolidus conditions.

[1] Ushikubo *et al.* (2004) *MAPS* **39**, A107. [2] Komatsu *et al.* (2018) *PNAS* **115**, 7497-7502. [3] Krot *et al.* (2004) *GCA* **68,** 1923-1941.