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Formation of spinel-, hibonite-rich inclusions found in CM2 carbonaceous chondrites

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ABSTRACT

We report petrography, mineral chemistry, bulk chemistry, and bulk isotopic compositions of a suite of 40 spinel-rich inclusions from the Murchison (CM2) carbonaceous chondrite. Seven types of inclusions have been identified based on mineral assemblage: spinel-hibonite-perovskite; spinel-perovskite-pyroxene; spinel-perovskite-melilite; spinel-hibonite-perovskite-melilite; spinel-hibonite; spinel-pyroxene; and spinel-melilite-anorthite. Hibonite-bearing inclusions have Ti-poor spinel compared to the hibonite-free ones, and spinel-hibonite-perovskite inclusions have the highest average bulk TiO_2 contents (7.8 wt%). The bulk CaO/Al_2O_3 ratios of the inclusions range from 0.005 to 0.21, well below the solar value of 0.79. Hibonite-, spinel-rich inclusions consist of phases that are not predicted by condensation calculations to coexist; in the equilibrium sequence, hibonite is followed by melilite, which is followed by spinel. Therefore, hibonite-melilite or melilite-spinel inclusions should be dominant instead. One explanation for the "missing melilite" is that it condensed as expected, but was lost due to evaporation of Mg and Ca during heating and melting of spherule precursors. If this theory were correct, melilite-poor spherules would have isotopically heavy Mg and Ca, assuming Rayleigh fractionation accompanied evaporation. Except for one inclusion with $F_{Mg} = 4.3 \pm 2.6‰$/amu and another with isotopically light Ca ($F_{Ca} = -3.4 \pm 2.0‰$/amu), however, all the inclusions we analyzed have normal isotopic compositions within their 2σ uncertainties. Thus, we found no evidence for significant mass-dependent fractionation. Conditions necessary for non-Rayleigh evaporation are unlikely if not unrealistic, and our preferred explanation for the general lack of melilite among hibonite-, spinel-bearing inclusions is kinetic inhibition of melilite condensation relative to spinel. Because of similarities between the crystal structures of hibonite and spinel, it should be easier for spinel than for melilite to form from hibonite.

Keywords: Spinel, refractory inclusions, melilite, hibonite, carbonaceous chondrites, mass fractionation