

Origins of Secondary Minerals in Micrometeorites

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This study aims to understand the formation of hydrated micrometeorites through detailed descriptions of their mineralogy and measurements of their isotopic compositions. The secondary mineralogy of hydrated cometary micrometeorites may differ from hydrated asteroidal particles because the conditions of cometary alteration were likely different from asteroidal aqueous alteration. In addition, the O isotopic composition of secondary minerals in cometary particles may also be distinct and reflect the presence of spatially distinct water reservoirs in the solar nebula [1-4]. Here we present the mineralogy and oxygen isotope compositions of magnetite grains and a magnetite-dolomite assemblage that were identified in five hydrated AMMs. The purpose of these measurements is to investigate the diversity of the water reservoir from which hydrated AMMs formed and the temperature at which these minerals co-precipitated.

Secondary ion mass spectrometer (SIMS) analyses was carried out using the Cameca ims- 1280 ion microprobe. We used a ~25 pA Cs⁺ primary beam focused to ~2 μm with total impact energy of 20 keV. Masses ¹⁶O⁻, ¹⁷O⁻, and ¹⁸O⁻ were measured simultaneously in multicollection mode on a Faraday cup and two electron multipliers, respectively. We made sure we cleanly measured the desired phase by later imaging of the analyzed grains by scanning electron microscopy (SEM). We corrected ¹⁶OH interference contribution onto ¹⁷O (< 0.5‰). Detailed SEM studies were performed on five polished sections using a FEI Quanta 3D field emission gun (FEG) SEM/FIB operating at 30 kV. Eight transmission electron microscopy (TEM) sections of a selected region containing magnetite with different morphologies were prepared using the FIB technique with a FEI Quanta 3D Dualbeam® FIB. Bright- and dark-field TEM images and quantitative EDS X-ray analyses were carried out at 200 kV on a JEOL 2010F FEG TEM/Scanning TEM (STEM).

Five unmelted AMMs (99-12-45, 94-4B-21, 03-26-59, 03-36-46, and 07-13-01) were analyzed in this study. The first 2 samples were collected from blue ice fields at Cap-Prudhomme [5] and the last 3 from the pristine CONCORDIA snow in 2002 and 2006 [6]. Sample 07-13-01 is a fragment of a larger micrometeorite. The rest are whole particles collected from ice or snow. The AMMs vary in size from 25 x 50 μm (particle 07-13-01) to 100 x 200 μm (particle 94-4B-21). SEM imaging of the five polished sections analyzed in this study show the presence of magnetite embedded in a fine-grained, fibrous material. An enstatite (En₈₈) of ~15 μm in length was identified in sample 07-13-01. Magnetite was identified in all particles and has four different morphologies (plaquettes, framboidal, spherulite, anhedral) up to 7 μm in size. Additionally, we identified a magnetite-dolomite assemblage in 03-36-46. The TEM study shows that the magnetite is associated with phyllosilicates in three of the samples analyzed, except 07-13-01. Sample 07-13-01 was heated during atmospheric entry as evidenced by the presence of vesicles, which are commonly formed upon melt devolatilization during atmospheric entry.

Other signs of heating during atmospheric entry are observed in the sample 94-4B-21, which shows the presence of a continuous <1 μm -thick magnetite rim in one of the FIB sections. The $\Delta^{17}\text{O}$ values of magnetites in the AMMs range from 1.3‰ to 4.2‰. The magnetite $\delta^{18}\text{O}$ values span a range of $\sim 30\%$, much larger than those of analytical artifact [7]. Generally, the magnetites measured show a large range within individual AMMs. For example, the magnetite measured in sample 94-4B-21 spans the largest range in $\delta^{18}\text{O}$: -9.8‰ to +17.4‰. We measured the magnetite-dolomite assemblage to be different by $18\pm 3\%$ (2σ) in $\delta^{18}\text{O}$.

The oxygen isotopic compositions and the morphologies of the magnetites analyzed in this study show that they were formed by precipitation processes from a gel-like phase during aqueous alteration of their parent planetesimals [8]. Their O isotopic compositions indicate that the water reservoir from which hydrated AMMs formed is intermediary between CCs and OCs, and that the particles were not modified during atmospheric entry heating [9]. The $\delta^{18}\text{O}$ values of magnetites in AMM 94-4B-21 show a $\sim 27\%$ mass-dependent spread in a single $100 \times 200 \mu\text{m}$ particle. This spread is 4 times larger than that for $\delta^{18}\text{O}$ values of several magnetites measured in a thin section of the CR chondrite Renazzo [2] that is in turn orders of magnitude larger in size. It has been suggested that the mass-dependent spread in O isotopes measured in CR indicates changes in fluid temperature and/or composition during magnetite formation [2]. For the case of the AMMs, the large heterogeneity of the oxygen isotopic compositions could indicate that there was a localized control on the fluid composition.

If we assume that the magnetite and dolomite formed in equilibrium, the relative equilibrium O-isotope fractionation between dolomite and magnetite can be used to extract the temperature at which these minerals co-precipitated [e.g. 2]. The $\delta^{18}\text{O}$ difference between carbonate and magnetite in the magnetite-dolomite assemblage in 03-36-46 is 18‰, corresponding to the precipitation temperature between 160 and 280°C (100-200°C warmer than the equilibration temperature of a calcite-magnetite assemblage from the CR2 chondrite, Al Rais [2]).

Our measurements indicate that the parent-bodies of hydrated AMMs sampled a different water reservoir than the parent bodies of OCs and CCs. Recently, similar results were obtained by the IR and Raman measurements of hydrated AMMs, indicating that the AMMs sampled parent bodies different from CR and CM chondrites [10].

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