Antarctic micrometeorites as a resource to complement the current Solar System inventory: the case of ^{16}O-poor cumulate porphyritic cosmic spherules

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Introduction

Micrometeorites, dust-sized extraterrestrial particles (< 2mm) surviving atmospheric entry, constitute the primary component of extraterrestrial matter reaching Earth's surface. They are categorized based on the extent of heating during atmospheric entry [1]. Cosmic spherules (CSs), which represent the melted form of micrometeorites, make up approximately 70% of all micrometeorites. Extensive melting during atmospheric entry erases primary characteristics of CS precursors (i.e., mineralogy and petrology), complicating their parentage identification through comparison with meteorites.

Recent research has highlighted the efficiency of oxygen isotope ratios in determining the nature of the parent bodies of CSs, as well-characterized chondrite groups exhibit distinct δ^{18}O and δ^{17}O values [2, 3]. Three factors influence the oxygen isotopic composition of CSs during atmospheric entry: 1/ the precursor's oxygen isotopic composition, 2/ mass-dependent fractionation resulting from particle melting and evaporation, shifting values toward higher δ^{18}O, and 3/ mixing with atmospheric oxygen, pulling values toward stratospheric levels. The precise contribution of these processes to the final oxygen isotopic composition of CSs requires further refinement. Although most CSs originate from known chondrite groups, roughly 10% are depleted in δ^{16}O and have relatively high Δ^{17}O values inconsistent with established chondritic materials. These ^{16}O-poor particles are classified into the isotopic Group 4, alongside Group 1 CSs related to CV/CO/CM chondrites, Group 2 CSs associated with to CR chondrites, and Group 3 CSs linked to ordinary chondrites [2]. Although Group 4 CSs could potentially stem from intensely aqueously altered ^{16}O-poor unmelted micrometeorites [4], these micrometeorites could also represent ^{16}O-poor nebular material from an as-yet-unidentified reservoir.

The key to unraveling the parent body of Group 4 CSs may reside in a specific subset of porphyritic olivine (Po) CSs. Approximately 14% of Po CSs, known as Cumulate Porphyritic Olivine (CumPo) CSs, exhibit textures indicating the settling of olivine crystals during atmospheric deceleration [5]. This unusual texture suggests that these particles entered Earth's atmosphere at a velocity of approximately 16 km s^{-1}, corresponding to orbital eccentricities exceeding 0.3, higher than most asteroidal dust bands. Planetary or secular perturbations of dust orbits within the recent geological past (<800 kyr) may account for the increased eccentricity of dust particles and the formation of CumPo CSs. Nevertheless, the possibility that these particles originated from a parent asteroid not represented in current meteorite collections cannot be ruled out.

Experimental

We selected 5 CSs from the Sør Rondane Mts. micrometeorite collection and 1 CS from the Larkman Nunatak collection that exhibited textural characteristics and oxygen isotope values consistent with ^{16}O-poor CumPo particles. These samples were previously sectioned and examined using a scanning electron microscope. The major element composition of individual mineral phases within the CumPo CSs was determined using a JEOL JXA-8200 electron microprobe analyzer at the Japanese National Institute of Polar Research. To determine their triple-O isotope composition, spot analyses were performed on each particle utilizing a Cameca IMS 1270 SIMS instrument at the Centre de Recherches Pétrographiques et Géochimiques (CRPG) in Nancy, France. Additional oxygen isotope data for relict and neoformed olivine crystals were obtained using a Cameca 50L NanoSIMS at the Open University.

Results and Discussion

The ^{16}O-poor CumPo CSs studied here exhibit petrological and geochemical properties at odds with conventional Po CSs. A notable difference is the absence of magnetite in the glassy mesostatis, which is a frequent accessory phase in S-type CSs, including the Po CSs [1]. Upon melting of the particles, magnetite rapidly forms by the oxidation of Fe^{2+} of the silicate melt, even at the relatively low oxygen fugacity in the mesosphere [6]. The complete absence of magnetite in the ^{16}O-poor CumPo CSs characterized here suggests reducing conditions, as also confirmed by S-bearing metal in several of the sectioned CSs. In addition, the nickel (Ni) content of neoformed olivine affirms reducing conditions as increasing oxidizing conditions favours the insertion of Ni in the lattice of olivine [7]. Here, the olivine compositions of the ^{16}O-poor CumPo CSs particles are systematically Ni-poor (NiO < 0.5 wt%), supporting reducing conditions during atmospheric entry.

Surprisingly, sulphur (S) concentrations of the ^{16}O-poor CumPo are consistently above detection limit, whereas S is typically severely depleted in CSs due to intense degassing of volatiles [6, 8]. Such high S content in combination with the occurrence of S-bearing metal points to reducing conditions due to a high initial carbon content in the precursor material, although chemical data of CSs cannot provide a definite initial S content due to evaporative chemical fractionation by atmospheric entry heating. Furthermore, the overabundance of S can explain the absence of magnetite, as S atoms readily react with atmospheric oxygen to form sulphur dioxide, similarly to the pyrolysis of carbon leading to the formation of carbon dioxide. Thus, the lack of magnetite may result from the C- and S-rich nature of the ^{16}O-poor CumPo CS precursor.

Most SIMS triple-O data narrowly plot in the Group 4 region defined by [2], although several particles exhibit at least one outlier below the terrestrial fractionation line (TFL) in a region commonly associated with CM or CY chondrites. Similarly, the NanoSIMS data for the ^{16}O-poor CumPo CSs exhibit values consistent with the Group 4 range, except for two particles that exhibit data points overlapping with CY or CO/CM values. Isotopic fractionation cannot account for isotopic shifts from negative to positive $\Delta^{17}O$ values, since fractionation effects during atmospheric entry either shift primary values towards higher $\delta^{18}O$ along the TFL due to preferential evaporation of lighter $\delta^{16}O$ and towards atmospheric oxygen values due to mixing [2]. A single large relict olivine crystal in particle WN-790 analyzed using NanoSIMS exhibits the lowest $\delta^{17}O$ and $\delta^{18}O$ values of all olivine crystals measured, plotting along the CM-line and consistent with olivine in chondrules of CM chondrites [9]. All other relict analyses broadly plot between this extreme value and ^{16}O-poor values, suggesting mixing between these two components.

Migration of relict olivine to the periphery of the melt during deceleration and/or spinning of CumPo CSs results in the observed textures of the particles [5]. We therefore suggest that the precursors of ^{16}O-poor CumPo CSs consisted of Fe-poor olivine grains with O values typical of primitive carbonaceous chondrites and a ^{16}O-poor fine-grained hydrous matrix. During recrystallization following atmospheric passage, these isotopic signatures largely re-equilibrated yielding signature consistent with those of Group 4 CSs. Three ^{16}O-poor unmelted micrometeorites have previously been identified in the Transantarctic Mountain collection and proposed to represent precursors of ^{16}O-poor CSs, accounting for the <10‰ difference in $\delta^{18}O$ values, which is consistent with mass-dependent fractionation during the formation of CSs [10, 11]. Suttle et al. [11] suggested that these ^{16}O-poor unmelted micrometeorites could originate from two potential sources: 1/ an extension of the yet to be defined CM-CO-CY clan, as evidenced by them prolonging the CM-line, and which consists of material that formed in the same region of the solar nebula, although with variable water/rock ratios attesting to different alteration histories, or alternatively 2/ an extension of the CY chondrite group. CY chondrites are unusually rich in sulphide (~10 to 30 vol%; [12]), which is consistent with the abnormally high S content determined for the ^{16}O-poor CumPo particles. Combined, these observations suggest that ^{16}O-poor CumPo CSs, and possibly ^{16}O-poor CSs in general, are likely linked to CM-CO-CY chondrites and may represent the extension of a new chondrite clan.

References

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