

A rare earth and trace element study of refractory inclusions in Ningqiang meteorite by SIMS

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Ca-, Al-rich inclusions (CAIs) are known as the oldest solid materials in the solar system (4567 Ma; Amelin et al., 2002) and may retain important information about the high temperature processes occurred in the early stage of the solar system.

Rare earth element (REE) and trace element (TE: Sc, V, Y, Zr, Nb, Ba and Hf) abundances in 19 refractory inclusions from Ningqiang carbonaceous chondrite were analyzed by secondary ion mass spectrometry (SIMS) with CAMECA ims-6f at the University of Tokyo.

The relationship between bulk chemical compositions and REE and TE abundances had been poorly constrained for CAIs and amoeboid olivine aggregates (AOAs). The bulk chemical compositions of refractory inclusions and AOAs in Ningqiang carbonaceous chondrite vary along the condensation trajectory on the anorthite-gehlenite-forsterite plane (Lin and Kimura, 2003). The purpose of this study is, first, to investigate a possible correlation between the bulk chemical compositions and REE abundances, and then to estimate the formation processes and environments for CAIs in Ningqiang meteorite by condensation calculations.

Four characteristic REE abundance patterns were observed as follows: (1) Flat with/without Eu anomalies, (2) Group II, (3) modified Group II (with Ce+Eu+Yb excesses) and (4) flat REE pattern having Ce+Eu+Yb excesses.

The bulk chemical composition and REE distributions do not show clear correlation. Since the condensation temperature of each REE is higher than those of major elements such as Mg and Si, we consider that REE patterns had already been established when these elements were condensed.

An interesting observation is that seven inclusions have positive Ce+(Eu)+Yb anomalies (groups (3) and (4)). They are newly classified REE groups and formation processes of such REE patterns have not been studied in detail, though similar patterns have been found in the previous studies. Therefore, condensation calculations of REE were performed to reproduce the analytical results for better understanding of the formation processes of CAIs.

Formation processes for the observed REE patterns were proposed as follows. (1) Group II inclusions were condensed after the separation of HREE-rich component in the cooling hot gas at a very high temperature. (2) Modified Group II inclusions were formed by condensation from the gas after separation of a solid component containing HREE and partially condensed LREE (except for Ce and Eu) at a slightly lower temperature under relatively oxidizing conditions (where Ce became relatively volatile). (3) Flat pattern with positive Ce+Eu+Yb anomalies were produced by a similar process as for modified Group II, except that the gas/dust separation was incomplete. Hence, various degree of dust/gas separation was suggested for the formation processes of these groups.

This model is successful in explaining the observed REE patterns rather consistently with simple assumptions. However, a problem exists in explaining the Tm abundance. The abundance of Tm is comparable to those of light REE (e.g., La) for modified group II. This can be reproduced under reducing conditions, where Tm becomes as volatile as LREE (e.g., La). On the other hand, the positive Ce+(Eu)+Yb anomaly can be reproduced under relatively oxidizing conditions, where Ce becomes as volatile as Eu and Yb. Hence, it is difficult to satisfy these two requirements in the present model. This problem might indicate either (1) there is a large error in the thermodynamic data for Tm, or (2) the Group II inclusions were moved into relatively oxidizing environment and additional condensation of Ce + Eu + Yb-rich gas occurred. The latter process may be possible, but it requires an efficient transportation process of inclusions from one region to another, where condensation of Ce+Eu+Yb occurred under an oxidizing condition, and high abundances of Ce+Eu+Yb in the gas phase in the latter environment.