RARE EARTH ELEMENT FRACTIONATION IN FINE-GRAINED INCLUSIONS FROM THE NINGQIANG AND OTHER CARBONACEOUS CHONDRITES: ORIGIN OF POSITIVE CE-EU-YB ANOMALIES.

H. Hiyagon[1], A. Yamakawa[2], M. Sasaki[1], K. Uchiyama[1], T. Ushikubo[3], Y. Lin[4] and M. Kimura[5], [1]Department of Earth & Planetary Science, Graduate School of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan, [2]Institute for Study of the Earth's Interior, Okayama University, 827 Yamada, Misasa, Tottori 682-0193, Japan, [3]Department of Geology & Geophysics, University of Wisconsin–Madison, 1215 West Dayton Street, Madison, Wisconsin 53706, USA, [4]Institute of Geology and Geophysics, Chinese Academy of Science, P.O. Box 9825, Beijing 100029, China, [5]Faculty of Science, Ibaraki University, Mito 310, Japan.

Introduction: Rare earth elements (REEs) in refractory inclusions often show strong fractionation due to variations in their condensation temperatures in the solar nebula. An example is the Group II REE pattern, in which ultrarefractory HREEs (Gd, Tb, Dy, Ho, Er and Lu) and most volatile REEs (Eu and Yb) are heavily depleted relative to LREEs and Tm. Such a pattern can be explained by condensation from the fractionated gas remaining after an earlier, HREE-rich condensate had been removed from the system at high temperatures [1, 2]. This suggests that efficient solid-gas separation processes existed in the early solar system. In our earlier work [3, 4], it was found that fine-grained inclusions from the Ningqiang meteorite (CV3 or anomalous CK, [5]) often show positive Ce±Eu+Yb anomalies with or without depletions in HREEs, and we named these patterns as Modified Group II and Modified Group I, respectively. Similar results were also obtained for fine-grained inclusions from the Y-81020 (CO3.05) and Efremovka (CV3-reduced) meteorites [6, 7]. Here we discuss the origin of such REE patterns to better understand the formation conditions of (fine-grained) refractory inclusions in the early solar nebula.

Samples and Results: Ningqiang, Y-81020 and Efremovka are primitive meteorites, in which refractory inclusions show limited amount of secondary alteration products. Ion microprobe analyses of REEs have been performed mainly for fine-grained inclusions in these meteorites, because they are considered to be condensates from the solar nebula. The analyzed phases are melilite, perovskite, diopside and spinel, though spinel contains very low REEs. Some of the preliminary results have been presented before [3, 4, 6, 7].

Positive Ce±Eu+Yb anomalies are found in 8 out of 17 inclusions from Ningqiang, 5 out of 29 inclusions from Y-81020 and 1 out of 7 inclusions from Efremovka. Many of them show depletions in HREEs, suggesting their close relation to the Group II REE pattern. We named such pattern as Modified Group II. Some of them show almost flat pattern with positive Ce±Eu+Yb anomalies, which we named as Modified Group I. Frequent occurrence of such patterns may provide important clues to the formation condition of fine-grained inclusions in the solar nebula.

Some examples of the Modified Group II patterns observed in the Ningqiang fine-grained inclusions are shown in Fig.1 (a). For comparison, typical Group II patterns observed are also shown in Fig.1 (b).

In order to understand the formation condition of the Modified Group II pattern, we have performed simple condensation calculations from the gas of solar composition at $P_{tot} = 10^{-5}$ bar and at variable temperatures. REEs are assumed to be condensed as ideal solutions into a solid phase. For simplicity, the fraction of the condensed solid was assumed to be 0.001 throughout the calculations.

Discussion: *Origin of positive Ce±Eu+Yb anomalies:* In our earlier work [3, 4], we suggested that the Modified Group II pattern was produced by a process similar to that produced the Group II pattern but at slightly lower temperatures, where not only ultra-refractory HREEs but some fractions of LREEs became condensed and removed from the system. The remaining gas would show large depletions in HREEs and some fractionation in LREEs, resulting in positive anomaly in Ce. Modified Group I pattern may be explained by mixing of a Modified Group II pattern and an unfractionated pattern; this might happen when gas-dust separation was incomplete.

A result of the condensation calculation, trying to reproduce the Modified Group II pattern, is shown in Fig.2. After removal of a solid phase at 1500K, a Modified Group II-like pattern is formed in the gas phase. There is a clear positive Ce anomaly. The problem, however, is very strong depletions (from 10^{-2} down to 10^{-4}) in HREEs including Tm. At the temperature where not only HREEs but also some fraction of LREEs are condensed and removed from the system, almost complete removal of HREEs would occur. Such high depletions of HREEs have not been observed in the fine-grained inclusions. The results (Fig.1) show that both Group II and Modified Group II have similar degree of HREE-depletions, about 10^{-1} to 10^{-2} x LREEs. This suggests that HREE-depletions seen both in Group II and Modified Group II were produced under similar conditions (at similar temperatures).

Hence, it seems more likely that positive Ce±Eu+Yb anomalies in Modified Group II formed later by addition of Ce, Eu and Yb onto HREE-depleted (Group II) inclusions. Cerium, Eu and Yb are the most volatile among REEs and they are enriched in the gas phase at relatively low temperatures. An example is shown in Fig.2. At 1400K, most of REEs except for Ce, Eu and Yb are condensed and the residual gas show large enrichments in Ce, Eu and Yb. If Group II-like inclusions once formed migrate to a Ce-Eu-Yb-rich gas region and their condensation occurs, the inclusions would have Modified Group II REE patterns. Condensation may stop at a temperature where some Eu is still in the gas phase, so that positive Eu anomaly may or may not form in the inclusions. This model requires migration of inclusions (or precursors of inclusions, possibly dust grains) from one region (Group II formation region) to another (Ce-Eu-Yb-rich gas region). Frequent occurrence of positive Ce±Eu+Yb anomalies in fine-grained inclusions suggests that such migration of solid materials was very common in their formation regions. This would provide important clues to the structure and conditions of the formation regions of (fine-grained) refractory inclusions, i.e., possibly innermost regions of the protoplanetary disk.

References: [1] Boynton, W. V. (1975) *GCA 39*, 569-584. [2] Davis A. M. and Grossman L. (1979) *GCA 43*, 1611-1632. [3] Yamakawa A. et al. (2004) *Workshop on Chondrites & the Protoplanetary Disk (Abstract)* #9038. [4] Hiyagon H. et al. (2005) *68th Ann. Meteoritical Soc. Meeting (Abstract)* #5103, [5] Lin Y. and Kimura M. (2003) *GCA 67*, 2251-2267. [6] Sasaki M. and Hiyagon H. (2006) *LPSC XXXVII (Abstract)* #2082. [7] Uchiyama K. et al. (2007) *LPSC XXXIX, (Abstract)* #1519.

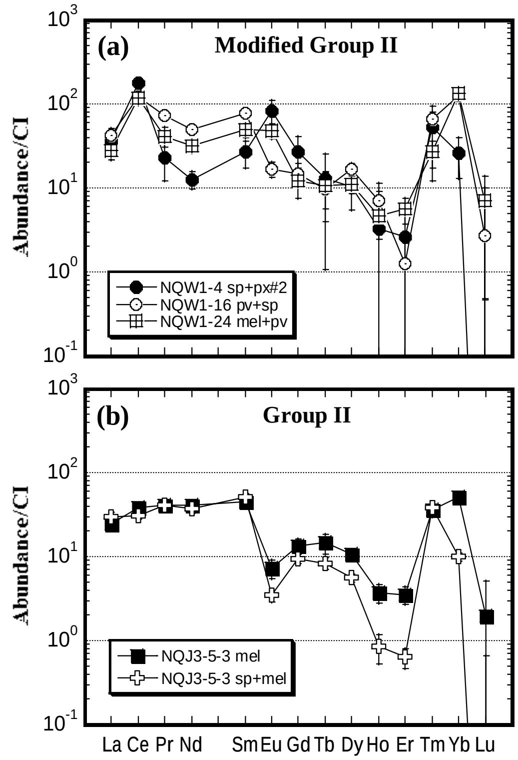

Fig.1 (a) Modified Group II and (b) Group II patterns observed in fine-grained inclusions from the Ningqiang meteorite.

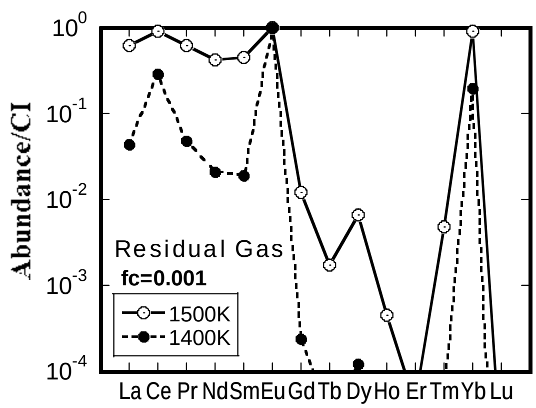

Fig.2 Calculated REE patterns in the residual gas after removal of a condensed phase at 1500K and at 1400K. Assumptions are: initial composition is solar, total pressure is 10^{-5} bar and the fraction of the condensed solid (fc) is 0.001. REEs are assumed to be dissolved in the solid phase as ideal solutions.