OXYGEN ISOTOPE EXCHANGE RECORDED WITHIN ANORTHITE SINGLE CRYSTAL IN VIGARANO CAI: EVIDENCE FOR REMELTING BY HIGH TEMPERATURE PROCESS IN THE SOLAR NEBULA. K. Nagashima, M. Yoshitake, and H. Yurimoto, Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Ookayama 2-12-1, Meguro, Tokyo 152-8551, Japan. (kazu@geo.titech.ac.jp)

Introduction: It is believed that Ca-Al-rich inclusions (CAIs) have been formed initially in a 16O-rich solar nebula followed by processing in a 16O-poor solar nebula based on the O isotopic distribution among the CAI minerals [1]. The clear evidence for O isotope exchange from 16O-poor to 16O-rich composition in the CAI was reported [2]. They proposed remelting and recrystallization during short-term heating events in 16O-poor nebula as the O isotope exchange mechanism. Recently, anorthite grains with an intracrystalline O isotopic zoning in the CAI of Vigarano chondrite were found [3-5], while the determination of isotope exchange mechanism was not conclusive because the spatial resolution was not enough. In this study, high precision isotope imaging analyses with micro-scale resolution (isotopography [6-8]) are applied to obtain O isotope distribution in the Vigarano CAI. This would allow depicting the isotopic exchange mechanism in the CAI.

Experimental: The sample used in this study is a coarse-grained type B2 CAI (TTV1-01 [3]) found in a thick section from Vigarano CV3 chondrite. Petrologic and mineralogical studies by scanning electron microscope (JEOL JSM-5310LV) equipped with energy dispersive X-ray spectroscopy (Oxford LINK ISIS) were made before and after the isotopography.

Isotopographs were obtained by the TiTech isotope microscope (Cameca ims 1270 + SCAPS [6]). The analytical techniques for isotopographs generally followed those described in [7, 8]. The size of an ion image corresponds to 70 x 70 µm on the sample. The typical mass sequence for acquiring secondary ion images was 27Al-, 28Si-, 16O-, 18O-, and 16O- for one cycle.

The digital image processing using the blind deconvolution algorithm and a moving-average with 3 x 3 pixels were applied to simple secondary ion ratio image in order to reduce defocusing of the images and to reduce the statistical error, respectively. The 18O/16O isotopographs were normalized to SMOW scale using δ18OSMOW values for minerals obtained by spot analyses.

Results: Two δ18O isotopographs of each area containing anorthite #B and #C grain [5] were obtained. BSE image of the area containing anorthite #B grain is shown in Fig. 1. Anorthite #B is a blocky-shaped grain with the size of ~50 µm. The chemical composition is nearly pure CaAl2Si2O8 for both anorthite grains. The #B grain contains spinel grains and is adjacent to aluminowakelite-rich melilite (Åk69) and fassaite containing 16.9 wt% Al2O3 and 2.2 wt% TiO2.

The isotopograph of δ18O of the area containing #B are shown in Fig. 1 with the backscattered electron image of the same area. Yellow curves in the isotopographs are outline of anorthite #B grain. The δ18O isotopograph clearly shows that oxygen isotopes are heterogeneously distributed among minerals. Spinel and fassaite are enriched in 16O (δ18O ~ -40 ‰ and -40 ~ -30 ‰, respectively). Melilite is depleted in 16O (δ18O = 5 ~ 10 ‰). Alteration products and some locations of crack show 16O depletions. In these minerals, oxygen isotopes are homogeneously distributed within each mineral within analytical error. On the other hand, anorthite #B shows extreme O isotopic heterogeneity (~-40 % to ~5 %) within the grain. Oxygen isotopic compositions in #B grain are 16O-rich (δ18O ~ -40 ‰) in the center and 16O-poor (δ18O ~ -5 ‰) near the edge of the grain consistent with [5].

Fig. 1. Corresponding images of backscattered electrons and oxygen isotope ratio (δ18O) of an area containing anorthite #B. Yellow curves indicate outline of anorthite #B grain. The arrow at grain boundary between melilite and anorthite in upper-left region of the images shows location of traverse shown in Fig. 2. Craters of SIMS analyses are observed in the backscattered electron image. Abbreviations: sp = spinel, mel = melilite, an = anorthite, fas = fassaite, and alt = alteration products.
Figure 2 shows compositional (^{27}Al/^{16}O) and \(\delta^{18}O\) profiles perpendicular to the grain boundary between \#B and melilite indicated by the arrow in Fig. 1. From \(\delta^{18}O\) profile, O isotopic composition of \#B near the edge (~4 \(\mu m\) from the grain boundary) is constant (\(\delta^{18}O \sim 5\)‰) against the distance, and same as that of melilite within analytical error. At ~4 \(\mu m\) from the grain boundary, O isotopic composition abruptly changes toward to ^{16}O-rich composition. Then, O isotopic composition becomes constant value with ^{16}O-rich composition (\(\delta^{18}O \sim -4\)‰) in the center of \#B (>~8 \(\mu m\) from the grain boundary).

Discussion: The CAI, TTV1-01, have crystallized from a liquid droplet because of an intergrown texture of coarse-grained crystals and rounded outer-shape [5]. The ^{16}O-rich spinel, which is the first major liquidus mineral [9], indicates the liquid droplet was initially enriched in ^{16}O. On the other hand, melilite and part of anorthite \#B are ^{16}O-poor. Two kinds of mechanisms of O isotope exchange can be considered to form such ^{16}O-poor minerals: solid-state diffusion or melting and recrystallization in ^{16}O-poor environment. If O isotope exchange is due to solid-state diffusion, O isotopic compositions should change gradually inside the grain from the grain boundary. The \(\delta^{18}O\) profile rules out solid-state diffusion as a mechanism to generate O isotopic zoning in \#B. On the other hand, the melting and recrystallization in ^{16}O-poor environment adapt to the profile showing abrupt change with a sharp boundary of O isotopic distribution in a single crystal [2, 10]. Therefore, the ^{16}O-poor anorthite results from O isotope exchange during melting and recrystallization caused by a reheating event in ^{16}O-poor environment. The slope across ^{16}O-poor/^{16}O-rich boundary in Fig. 2 results from defocusing effect of ion optics plus O diffusion of heating event. If we assume this slope is due to the diffusion contribution, we estimate maximum reheating duration using the diffusion coefficient for O in anorthite [11]. Applying the crystallization temperature of anorthite of 1260°C [9], maximum reheating duration of the slope is calculated to be ~5 days. Such short reheating duration is consistent with the case of [10]. These results indicate that the heterogeneous O isotopic distribution of the CAI resulted from short-term heating events in the solar nebula. A possible candidate for the astrophysical setting to form the CAI might be the inner edge of the solar nebula around the protosun [12].


Fig. 2. Compositional (^{27}Al/^{16}O) and \(\delta^{18}O\) profiles indicated by the arrow in the isotopographs in Fig. 1. Distance is measured from grain boundary between melilite and anorthite \#B grains determined by ^{27}Al/^{16}O profile. Each plots is averaged over ~\pm0.5 \(\mu m\) width from the arrow along a direction parallel to the grain boundary (i.e. the direction perpendicular to the arrow) in order to reduce statistical errors. Red curve indicates a diffusion curve fitting the plot assuming the one-dimensional diffusive pair. The parameters of the curve are fitted to 2(Dt)^{1/2} = 1.5 \(\mu m\), \(\delta^{18}O\) of overgrown anorthite = 5‰, and initial anorthite (not melted) = -40 ‰, where D and t are oxygen self diffusion coefficient and annealing time, respectively.