

MICRON SCALE OXYGEN ISOTOPE HETEROGENEITY IN ANORTHITE OF A FORSTERITE-BEARING TYPE B CAI E60 FROM EFREMOVKA. K. Nagashima¹, A. N. Krot¹, G. R. Huss¹, and H. Yurimoto². ¹Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA (kazu@higp.hawaii.edu). ²Department of Natural History Sciences, Hokkaido University, Hokkaido, Japan.

Introduction: Most Ca-, Al-rich inclusions (CAIs) from metamorphosed CV chondrites are isotopically heterogeneous, with melilite and anorthite being systematically ¹⁶O-depleted relative to spinel and fassaite [1]. Although there is a general agreement that this heterogeneity is due to isotopic exchange between the initially ¹⁶O-rich CAIs and ¹⁶O-poor external reservoir, the nature of this exchange and the origin of ¹⁶O-poor reservoir remain controversial. Gas-solid or gas-melt exchange in the solar nebula regions that experienced rapid fluctuations in O-isotope compositions [2] and exchange during fluid-assisted thermal metamorphism on the CV asteroidal body [3] are being discussed. Unlike CAIs from metamorphosed CVs, most CAIs from CR2 chondrites are uniformly ¹⁶O-rich and show no evidence for post-crystallization isotope exchange. O-isotope heterogeneity found only in rare igneous CAI-chondrule compound objects could be due to incomplete homogenization between ¹⁶O-enriched relict CAIs and ¹⁶O-depleted chondrule precursors, perhaps accompanied by gas-melt exchange during chondrule melting [4]. To understand the nature of O-isotope exchange in CV CAIs, we initiated O-isotope imaging analyses of a suite of CV CAIs using the UH isotope microscope system – Cameca ims-1280 SIMS combined with two-dimensional ion detector SCAPS [5, 6].

Experimental: A polished thick section of a forsterite-bearing Type B CAI, E60 from the reduced CV chondrite Efremovka was used in this study. The mineralogy and petrography of E60 were studied using a JEOL JXA-8500F field emission electron microprobe and a JEOL 5900LV scanning electron microscope at the University of Hawai'i.

The three oxygen isotopes were measured in the minerals of E60 using spot analysis as described in [4]. The analytical procedure for O-isotopography was similar to that described in [7–10]. A ~200 pA Cs⁺ primary beam in aperture illumination mode was used to achieve uniform secondary ion emission from a sample area of ~60×80 μm². The normal incident electron gun was used to compensate for sample charging. The energy band pass was set to 50 eV and a contrast aperture of 150 μm in diameter was used to improve spatial resolution of the image. The exit slit was narrow enough to eliminate the contribution of interference ions to the isotopic images. The typical mass sequence and measurement time for acquiring

secondary ion images was ²⁷Al⁺ (100s), ²⁸Si⁺ (100s), ¹⁶O⁺ (20s), ¹⁸O⁺ (1200s), and ¹⁶O⁺ (20s) for one cycle. The measurement consisted of 4 cycles in total. The digital image processing using a moving-average with 3×3 pixels was applied to secondary ion ratio image in order to reduce the statistical error. The ¹⁸O/¹⁶O isotopographs were normalized to SMOW scale using δ¹⁸O values of minerals obtained by spot analyses.

Results and Discussion: E60 is a spherical, mineralogically-zoned object with distinct core, mantle and rim. The core consists of coarse-grained fassaite and irregular shaped regions of melilite. Both minerals poikilitically enclose forsterite and small spinel grains; anorthite is rare. The mantle is composed of melilite, fassaite, spinel, and anorthite. Melilite compositions range from highly Åk-rich (~80 mol%) to Åk-poor (~20 mol%). Melilite grains contain up to ~0.2 wt% Na₂O, correlating with their Åk contents. Anorthite grains have nearly pure composition (Na₂O ~0.1 wt%); some grains have been replaced by nepheline. Fassaite in the mantle has ~2–7 wt% of TiO₂ and ~10–20 wt% of Al₂O₃, and contains fewer spinel and forsterite inclusions than that in the core. The CAI is surrounded by a Wark-Lovering rim sequence composed of the spinel, melilite, and Al-diopside layers.

Oxygen isotope compositions of primary and secondary minerals in core and mantle of E60 measured by spot analysis plot along a slope-1 line (Fig. 1). Spinel, fassaite, and forsterite are uniformly ¹⁶O-rich (Δ¹⁷O ~ -24‰). All melilite grains are ¹⁶O-depleted (Δ¹⁷O ~ -2‰), except one (Δ¹⁷O ~ -10‰). Anorthite and the nepheline replacing it are isotopically heterogeneous: Δ¹⁷O ranges from -24‰ to -4‰. Nepheline is systematically ¹⁶O depleted relative to anorthite.

Twelve regions in the mantle were mapped with isotopography. Each δ¹⁸O-isotopograph has ~5‰ (2σ) statistical uncertainty and lateral resolution of ~1 μm. Two mapped regions are shown in Figs. 2 and 3; both consist of melilite, anorthite, spinel and fassaite. In accordance with spot analysis (Fig. 1), melilite grains are uniformly ¹⁶O-poor; spinel and fassaite are ¹⁶O-rich. Anorthite grains show complex distributions of δ¹⁸O. Both ¹⁶O-rich and ¹⁶O-poor compositions are observed in anorthite next to ¹⁶O-rich spinel and ¹⁶O-poor melilite. The isotopic heterogeneity in anorthites appears to be unrelated to O-isotope compositions of adjacent minerals. Similar heterogeneity has been

previously described in a Type B CAI from Vigarano CV chondrite [10].

Figure 3 shows two $\delta^{18}\text{O}$ profiles across melilite-anorthite grain boundaries. In the profile shown in Fig. 3a, the O-isotope boundary is sharp ($\sim 1\text{--}1.5\ \mu\text{m}$) and follows the grain boundary. Since this distance is comparable to the spatial resolution of the image, the true O-isotope boundary could be shorter as observed with the higher spatial resolution $\delta^{18}\text{O}$ image [11]. In the profile shown in Fig. 3b, the O-isotope boundary is also sharp ($\sim 1\text{--}1.5\ \mu\text{m}$), but does not follow the melilite-anorthite grain boundary. Anorthite in contact with melilite is compositionally similar to ^{16}O -poor melilite; at $\sim 12\ \mu\text{m}$ from the grain boundary, anorthite abruptly becomes ^{16}O -rich. These observations suggest that solid-state diffusion was very limited. Although gas-solid isotope exchange was proposed to explain ^{16}O -rich anorthite co-existing with ^{16}O -poor melilite in the Efremovka Type B CAI, E44 [12], simple solid-state diffusion appears not to be responsible for O-isotope exchange in E60. Oxygen isotope distribution in E60 anorthite appears to support isotopic exchange of the CAI with ^{16}O -poor gas during its remelting and recrystallization [13].

References: [1] Yurimoto H. et al. 2008. In *Reviews in Mineralogy and Geochemistry* 68: 141–187. [2] Itoh S. and Yurimoto H. 2003. *Nature* 440: 728–731. [3] Krot A.N. et al. 2008. *GCA* 72:2534–2555. [4] Makide K. et al. 2009. *GCA*, 73: 5018–5050. [5] Yurimoto H. et al. 2003. *Applied Surface Science* 203-204: 793–797. [6] Nagashima K. et al. 2009. *40th LPSC* #2066. [7] Nagashima K. et al. 2004. *Nature* 428: 921–924. [8] Kunihiro T. et al. 2005. *GCA* 69: 763–773. [9] Sakamoto N. et al. 2007. *Science* 317: 231–233. [10] Nagashima K. et al. 2004. #9072, Workshop on Chondrites & Protoplanetary Disk. [11] Ito M. and Messenger S. 2008. *Applied Surface Science* 255: 1446–1450. [12] Dyl K.A. et al. 2008. *39th LPSC* #2486. [13] Yurimoto H. et al. 1998 *Science* 282: 1874–1877. [14] MacPherson G.J. et al. 2008. *39th LPSC* #2039. Supported by NASA grant NNX07AM84G to KN.

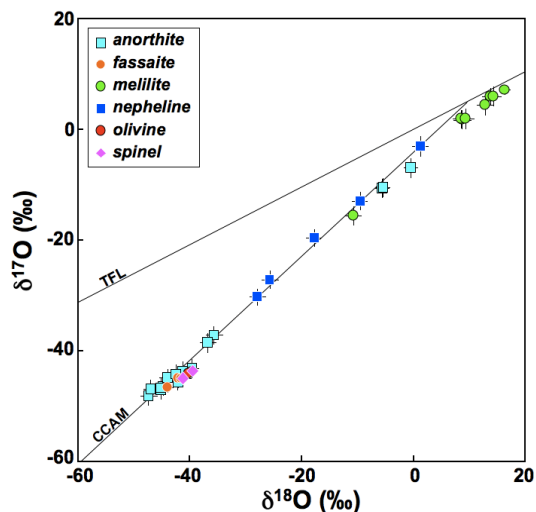


Fig. 1. Oxygen isotopic compositions of E60 minerals. Errors are 2σ . Some data are from [14].

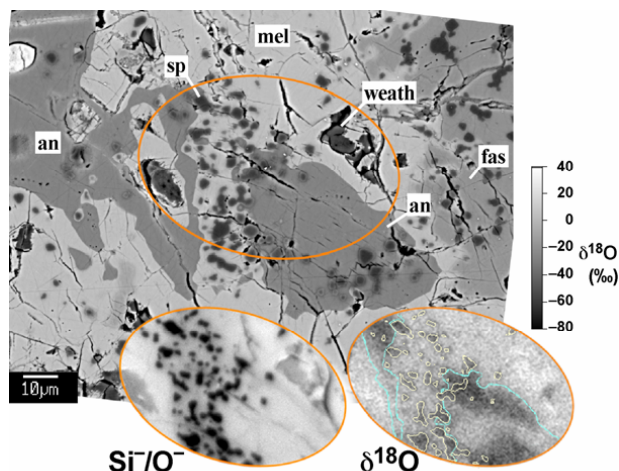


Fig. 2. BSE, $\text{Si}^{7}/\text{O}^{-}$ and $\delta^{18}\text{O}$ -isotopograph of a region consisting of anorthite (an), melilite (mel), and spinel (sp). Yellow and light-blue curves in $\delta^{18}\text{O}$ -isotopograph are outlines of spinel and anorthite, respectively. Oxygen isotopes are heterogeneously distributed in the anorthite grain. fas: fassaite, weath: weathering product.

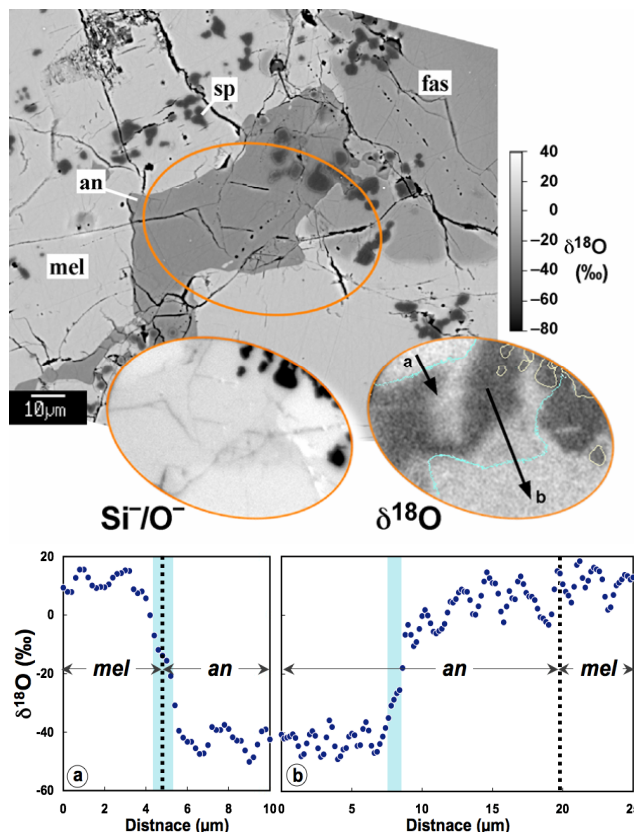


Fig. 3. BSE, $\text{Si}^{7}/\text{O}^{-}$ and $\delta^{18}\text{O}$ -isotopograph of a region composed of anorthite, melilite, fassaite and spinel. Yellow and light-blue curves in $\delta^{18}\text{O}$ -isotopograph are outlines of spinel and anorthite, respectively. Also shown are line profiles of $\delta^{18}\text{O}$ indicated by arrows in the $\delta^{18}\text{O}$ -isotopograph. Dotted lines correspond to grain boundaries between melilite and anorthite. Light-blue bands with $1\ \mu\text{m}$ width correspond to oxygen isotope boundaries. Abbreviations are the same as in Fig. 2.