

OXYGEN ISOTOPE SYSTEMATICS IN A COMPOUND AMOEBOID OLIVINE AGGREGATE – CHONDRULE OBJECT FROM ACER 094 METEORITE: IMPLICATIONS TO O-ISOTOPE EXCHANGE BETWEEN MELT AND GAS DURING CHONDRULE FORMATION. K. Nagashima¹, G. Libourel², and A. N. Krot¹, ¹HIGP, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA. kazu@higp.hawaii.edu, ²Observatoire de la Côte d'Azur, 06304 Nice, France.

Introduction: There has been a debate about whether chondrules behaved as closed or open systems during their formation. If chondrules formed in the protoplanetary disk by melting of solid precursors in closed systems, the observed range in chondrule bulk chemistry and modal mineralogy was entirely inherited from solid precursors [e.g., 1]. Alternatively, gas-melt interaction, including condensation of SiO from gas into chondrule melt, could have played a major role in evolution of mineralogy, chemical and isotopic compositions of chondrules [e.g., 2]. The uniform O-isotope compositions, in terms of $\Delta^{17}\text{O}$, among single chondrules from the least metamorphosed chondrites, except for relict grains, could be due to precursors dominating O-isotope composition of chondrule melt and/or very efficient O-isotope exchange between the melt and the surrounding gas [e.g., 3]. However, majority of chondrule precursors could have been ^{16}O -poor, comparable to those of chondrules, and therefore it could be difficult to see whether O-isotope exchange was efficient. We located a compound object consisting of an amoeboid olivine aggregate (AOA) and a type I chondrule in the Acfer 094 ungrouped 3.0 carbonaceous chondrite. Since AOAs have exclusively ^{16}O -rich composition ($\Delta^{17}\text{O} < -20\text{‰}$ [4]) distinctly different from those of most chondrules ($\Delta^{17}\text{O} > -10\text{‰}$ [5]), the object can be used to constrain O-isotope exchange during chondrule formation.

Methods: We used the FEG-EPMA (JEOL JXA-8500F) at U. of Hawai'i (UH), the FEG-SEM (JEOL JSM-7000F) with Gatan MonoCL4 cathodoluminescence (CL) detector at CRHEA, France [5], and the UH Cameca ims-1280 SIMS with SCAPS detector [6].

Results and Discussion: The compound AOA/chondrule object (A/Ch#1) from Acfer 094 has an igneous texture and consists predominantly of olivine, anorthite, low-Ca pyroxene; high-Ca pyroxene and Al-Mg spinel are minor. Forsteritic olivine (Fo₉₉) is within the compositional range of olivines in AOAs from Acfer 094 [4]. Anorthite (An₉₉) occupies interstitial regions between olivine grains and often encloses small (<10 μm) spinel grains. The spinel grains contain relatively high Fe and Cr contents (FeO ~0.6–1.0 wt%; Cr₂O₃ ~0.8–3.0 wt%), significantly higher than those in the Acfer 094 AOAs [e.g., 4]. Ferromagnesian low-Ca pyroxene (Fs₁₋₃Wo₅₋₈) occurs mostly in the peripheral region of the object.

CL images (Fig. 1d) reveal concentric zoning patterns in many olivine grains and at least 3 domains (CL-dark-core, CL-bright-mantle, and CL-dark-rim) can be identified. The CL patterns in olivines are correlated with distributions of Al and Ti obtained using high-resolution x-ray mapping. These elements are slightly enriched in CL-bright-mantle regions (Al₂O₃ ~0.06 wt%; TiO₂ ~0.1 wt%). Other elements, including Mg, Fe, Ca, Cr, and Mn, are rather homogeneously distributed in olivine grains, and no discernable differences are identified. Thus it appears Al and Ti contents are responsible for different CL emissivity in the olivine grains. These distributions imply sluggish diffusion of Al³⁺ and Ti^{3+&4+} in olivine compared to that of divalent cations.

Oxygen isotopes in olivine are heterogeneously distributed with sharp isotopic boundaries (Fig. 1e), and are correlated with the CL patterns. The CL-dark-core and CL-bright-mantle have similarly ^{16}O -enriched composition, while the CL-dark-rim has ^{16}O -poor composition. Figure 1f shows 3O-isotope compositions of olivine, spinel and low-Ca pyroxene measured with ~1 μm SIMS spots. The measured locations in two olivine grains are indicated with colored circles (Figs. 1d,e). The CL-dark-core and CL-bright-mantle in olivines and spinel are similarly ^{16}O -rich ($\Delta^{17}\text{O} \sim -23\text{‰}$), while CL-dark-rim in olivine has ^{16}O -poor compositions with a small spread along the CCAM/PCM lines ($\Delta^{17}\text{O} \sim -11\text{‰}$ to -7‰). Low-Ca pyroxene is even more ^{16}O -depleted ($\Delta^{17}\text{O} \sim -4\text{‰}$).

The ^{16}O -rich compositions in spinel and core and mantle of olivine grains are consistent with those in typical AOAs, confirming the object contains AOA materials. On the other hand, the ^{16}O -poor compositions of olivine rim and low-Ca pyroxene are consistent with those in type I chondrules from Acfer 094 ($\Delta^{17}\text{O} \sim -11\text{‰}$ to -1‰ [7]). These observations suggest original AOA materials experienced partial melting and transformation into the AOA/chondrule compound object during chondrule formation. This transformation was accompanied by condensation of gaseous SiO into AOA melt and O-isotopic exchange between this initially ^{16}O -rich melt and ^{16}O -poor gas. The CL-dark-core and CL-bright-mantle in olivine are relicts that avoided melting during this process. The more ^{16}O -poor composition in low-Ca pyroxene than CL-dark-rim in olivine and the small O-isotope spread in the latter could be due to progressive O-isotope exchange between melt

and gas during crystallization of olivine, and nearly complete equilibration between them by the time pyroxene crystallized. If we assume $\Delta^{17}\text{O} \sim -4\%$ of low-Ca pyroxene represents that of the gas, and $\Delta^{17}\text{O} \sim -23\%$ of spinel and ^{16}O -rich olivine represents composition of the melt prior to O-isotope exchange, then based on the O-isotope spread in CL-dark-rim olivine, we calculate $\sim 60\text{--}85\%$ of oxygen was introduced from the gas to produce the compositions in the rim, suggesting efficient O-isotope exchange between melt and gas.

The same O-isotope composition but different minor element compositions of olivine in CL-dark-core and CL-bright-mantle could have resulted from partial melting of AOA precursors in a ^{16}O -rich gaseous reser-

voir, prior to chondrule formation. If this is the case, the CL-dark-core is relict and CL-bright-mantle crystallized onto the core from relatively Al and Ti enriched AOA melt, possibly due to melting of some CAI materials together. Thus the object has experienced at least two partial melting events in the ^{16}O -rich and ^{16}O -poor gaseous reservoirs.

References: [1] Jones R.H. (2005) In *Chondrites and Protoplanetary Disk*. 251-286. [2] Libourel G. et al. (2006) *EPSL*, 251, 232-240. [3] Tenner T.J. et al. (2018) In *Chondrules-Records of Records of Protoplanetary Disk Processes*. 196-246. [4] Krot A.N. et al. (2004) *Chemie der Erde*, 64, 185-239. [5] Libourel G. and Portail M. (2018) *Science Advances*, 4, eaar3321. [6] Nagashima K. et al. (2015) *GCA*, 151, 49-67. [7] Ushikubo T. et al. (2012) *GCA*, 90, 242-264. Supported by NASA EW Grant NNX15AH44H.

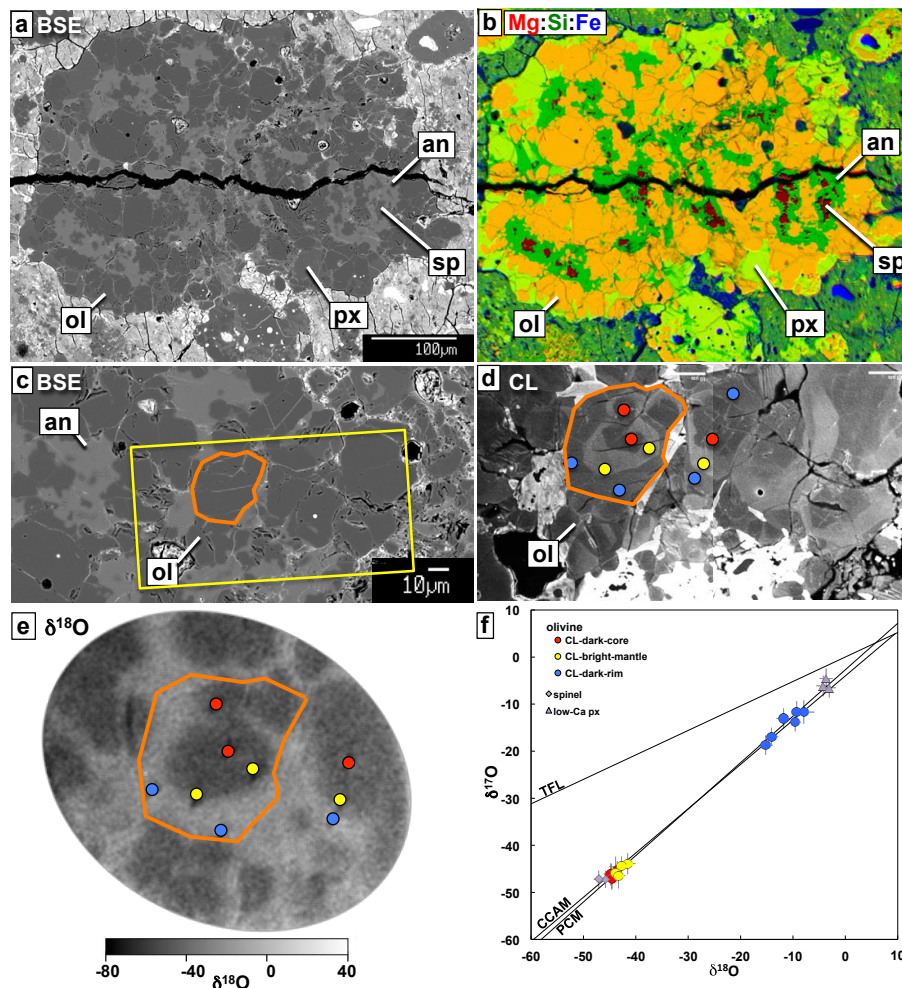


Fig. 1. A compound AOA/chondrule object from Acfer 094. (a) BSE and (b) combined X-ray map (Mg in red, Si in green, Fe in blue) of the object. A region outlined by a yellow box in (c) is shown as a cathodoluminescence (CL) image in (d). The brightest CL regions correspond to anorthite. Olivine grains show concentric zoning patterns and at least 3 CL domains (dark-core, bright-mantle, and dark-rim) are identified. One of olivine grains is outlined by orange line in (c, d). (e) $\delta^{18}\text{O}$ isotope map. Dark gray areas correspond to ^{16}O -rich compositions, while bright gray regions are ^{16}O -poor. The olivine grain outlined in (c, d) is also outlined and clearly shows internal O-isotope heterogeneity. (f) 3-O-isotope compositions measured with $\sim 1\text{ }\mu\text{m}$ spot. Small circles with blue, yellow and red in (d, e) are locations from which O-isotope compositions of olivines were obtained. The O-isotope compositions from CL-dark-core and CL-bright-mantle in olivines are similarly ^{16}O -rich as spinel, while CL-dark-rim in olivines have ^{16}O -poor compositions. Low-Ca pyroxene has most ^{16}O -depleted composition. an: anorthite, ol: olivine, px: low-Ca pyroxene, sp: spinel. PCM: primordial carbonaceous minerals line [7].