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Oxygen isotopic distribution in an amoeboid olivine aggregate from the Allende CV chondrite: Primary and secondary processes

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Abstract—The oxygen isotopic distribution in an amoeboid olivine aggregate (AOA), TTA1-02, from the Allende CV3 chondrite has been determined by secondary ion mass spectrometry. The irregular shaped TTA1-02 (5×3mm) consists mostly of olivine grains of ca. 5 μm in diameter. Olivine grains of Mg-rich (Fo₉₅) and Fe-rich (Fo₆₀) composition are in direct contact with each other, with a sharp compositional boundary. Oxygen isotopic compositions of Fe-rich olivine grains are ¹⁶O-poor ($\Delta^{17}\text{O} \cong -5\text{‰}$), whereas Mg-rich olivine is ¹⁶O-rich ($\Delta^{17}\text{O} \cong -25\text{‰}$). Several Al-rich inclusions (<ca. 500 μm in diameter) are enclosed by olivine grains in the AOA. Oxygen isotopic compositions of spinel and fassaite in Al-rich inclusions are ¹⁶O-rich ($\Delta^{17}\text{O} \cong -20\text{‰}$), whereas those of anorthite, nepheline and phyllosilicate are ¹⁶O-poor ($\Delta^{17}\text{O} \cong -5\text{‰}$). We propose the following sequence of events during the formation of AOAs in the Allende meteorite: 1) Formation of Al-rich inclusions with ¹⁶O-rich oxygen isotopic composition; 2) Accretion of Mg-rich olivine grains with ¹⁶O-rich oxygen isotopic composition around Al-rich inclusions; 3) Accretion into parent body; and 4) Aqueous alteration in the parent body, which led to crystallization of ¹⁶O-poor minerals, Fe-rich olivine, anorthite, nepheline, and phyllosilicate. This is reflecting reactions among primary ¹⁶O-rich AOA minerals and aqueous fluid having ¹⁶O-poor oxygen isotopic composition. Fe-rich olivine grains precipitated from aqueous fluids, which partially dissolved pre-existing Mg-rich olivine grains. Sintering and Mg-Fe diffusion occurred during thermal metamorphism. Anorthite, nepheline and phyllosilicate in Al-rich inclusions replaced primary anorthite or melilite during the aqueous alteration stage. Copyright © 2003 Elsevier Science Ltd

1. INTRODUCTION

Amoeboid olivine aggregates (AOAs) consist predominantly of olivine grains and have irregular shapes. Based on textures, Grossman and Steele (1976) suggested that AOAs were primary solid condensates from the solar nebula that retained information about the environment of the early solar nebula. Moreover, because olivine is the most abundant mineral in the chondritic meteorites, AOAs are one of the most appropriate samples to understand the evolution of solid material in the early solar system.

Oxygen isotopic studies are useful to understand the formation processes of solid materials. Clayton et al. (1977) performed the first oxygen isotopic studies for AOAs. They obtained oxygen isotopic compositions for milligram amounts of separated materials from AOAs. They reported oxygen isotopic compositions of olivine from the Allende CV chondrite with values of $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ as low as -30‰ (Clayton, 1993). Hiyagon and Hashimoto (1998, 1999) reported oxygen isotopic compositions of olivine grains in AOAs from the Yamato-86009 CV3, Yamato-82050 CO3 and ALH-77307 CO3 chondrites. The values of $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ of olivine grains were as low as -50‰ . These values are similar to those of typical spinel grains in CAIs in carbonaceous chondrites (Clayton, 1993). These results of oxygen isotopic studies for olivine indicated that oxygen isotopic anomalies were preserved not only in refractory phases but also in the major silicate phases of

the solar system. However, the origins of AOAs are still controversial.

In this study, we have measured the distribution of oxygen isotopes in a large amoeboid olivine aggregate (TTA1-02) from the Allende meteorite to clarify the formation mechanism of AOAs. Preliminary results were reported by Imai and Yurimoto (2001).

2. EXPERIMENTAL PROCEDURE

An AOA designated TTA1-02 from the Allende meteorite was the focus of this study. The sample surface was coated with a 20 nm carbon film for electron microprobe analysis. Quantitative analysis of each mineral in the AOA was performed by a scanning electron microscope (JEOL JSM-5310LV), equipped with an energy dispersive X-ray spectrometer (Oxford LINK ISIS) at Tokyo Institute of Technology (TiTech). Accelerating voltage, beam currents and the analysis area were set to 15 kV, 1 nA and ca. 1 μm, respectively. The X-ray data were corrected by the ZAF method, which is installed in the EDS system (Link ISIS Operator's Guide, 1997).

After the EDS analyses, the carbon film was removed and the surface was covered with a 30 nm thick gold coating. In-situ oxygen isotope analyses were performed using the TiTech CAMECA ims 1270 SIMS instrument. The primary ion beam was mass filtered positive ¹³³Cs⁺ ions accelerated to 20 keV and the beam spot size was 5 to 10 μm in diameter. The typical primary current was 2 pA and was adjusted to obtain a count rate of negative ¹⁶O ions of $\sim 4 \times 10^5 \text{ s}^{-1}$ for each measurement. A normal-incident electron gun was utilized for charge compensation of the analysis area. Negative secondary ions of

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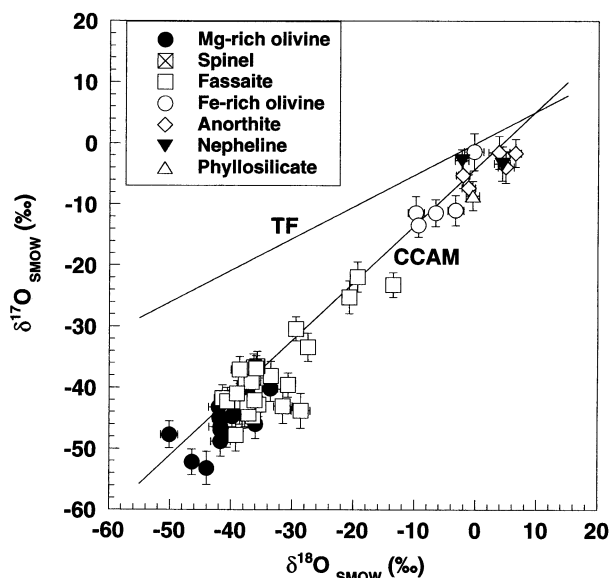


Fig. 1. Oxygen isotopic compositions of minerals in TTA1-02. TF and CCAM represent the terrestrial fractionation line and carbonaceous chondrite anhydrous mineral line, respectively. ^{16}O -rich phases are Mg-rich olivine, spinel and fassaite. ^{16}O -poor phases are Fe-rich olivine, anorthite, nepheline and phyllosilicate.

the ^{16}O -tail, ^{16}O , ^{17}O , ^{16}OH and ^{18}O were analyzed by automatic peak jumping at a mass resolution power of ca. 6000, sufficient to completely eliminate the hydride interference at mass 17. Secondary ions were detected by an electron multiplier operated in a pulse counting mode. The secondary ion intensities were corrected for dead time of the detection system (21, or 28 or, 43 ns depending on the analytical session). Matrix effects among the analyzed minerals were not considered because the effects were less than the analytical error (Ito, 1999). A Russian spinel standard, SPU (Yurimoto et al., 1994), was used for correcting of instrumental mass fractionation. We use only SPU as a standard for each sample mineral. Ito (1999) estimated that accuracy for this analysis method is $\pm$ ca. 5‰ (σ). Errors given in the tables and plotted in reply to Figure 1 show the precision (not accuracy) of the analyses only.

After the SIMS analysis, additional SEM-EDS imaging and analyses were conducted to obtain detailed petrographic characterization and to check beam overlap among different minerals of SIMS analysis. During the additional SEM-EDS study, the thin gold film was removed but remained in some areas, such as voids and cracks. Some residues of the gold thin film were observed in backscattered electron images (Figs. 2 to 7) shown in this paper.

3. RESULTS

3.1. Mineralogy and Petrology

Amoeboid olivine aggregate TTA1-02 is irregular in shape and ca. 5×3 mm in size (Fig. 2). TTA1-02 consists mainly of olivine grains. Assemblages of Al-rich minerals, which were called "Al-rich inclusions" by Hashimoto and Grossman (1987), were observed within olivine clusters. These textures of

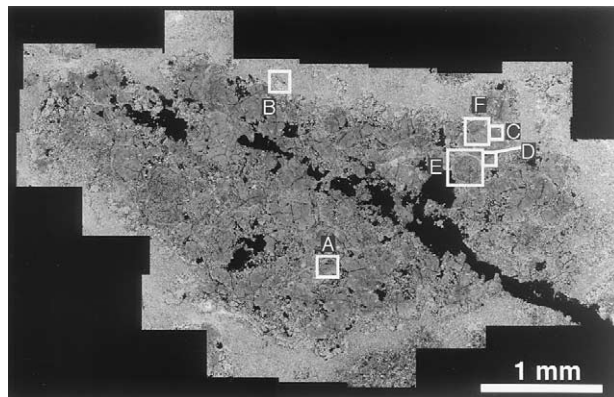


Fig. 2. Backscattered electron image of TTA1-02 AOA from the Allende CV chondrite. Fe-rich olivine clusters surround TTA1-02 (see text). Detailed images of areas A and B are shown in Figure 3 and area C and D are shown in Figure 4 and Figure 7, respectively. Al-rich inclusions of areas a and b are shown in Figures 5 and 6, respectively.

AOAs have been described by Grossman and Steele (1976), Hashimoto and Grossman (1987) and Komatsu et al. (2001).

Olivine occurs in clusters of fine equigranular grains as shown in Figures 3a and 3b. The olivine clusters consist of Mg-rich and Fe-rich olivine. Fe-rich olivine is commonly located along interstitial margins between Mg-rich olivine grains. Many small cavities exist among Fe-rich olivine grains. These cavities are consistently round in shape. If the cavities were made by gouging during sample preparation, we would expect the shape to be (at least partly) angular or irregular in thin section. If small round crystals did break off during sectioning, at least small amounts of crystal remnants should be observed in the cavities. However, we could not find such crystals. Thus the cavities are not artifacts of sample preparation. The mean

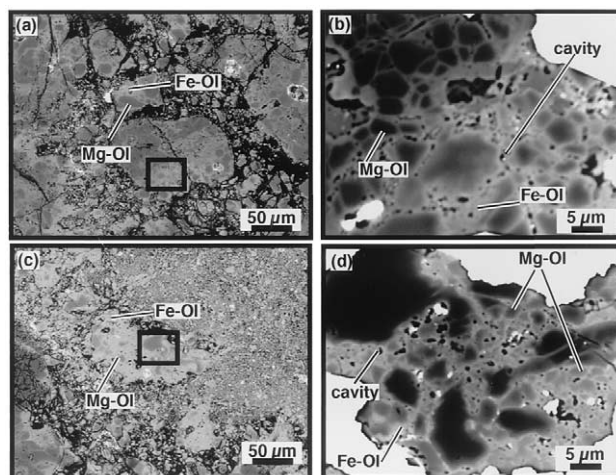


Fig. 3. Backscattered electron images of olivine clusters in TTA1-02. Black to medium gray areas correspond to Mg-rich olivine (Mg-Ol). Fe-rich (Fe-Ol) olivine appears light gray. (a) Olivine cluster inside TTA1-02, located at area A in Figure 2. (b) An enlarged picture of black square area in (a). (c) Olivine cluster at the rim of TTA1-02, located at area B in Figure 3. (d) An enlarged picture of black square area in (c). The brightest areas including some of the cavities are such covered by the thin Au thin film cover for SIMS analyses.

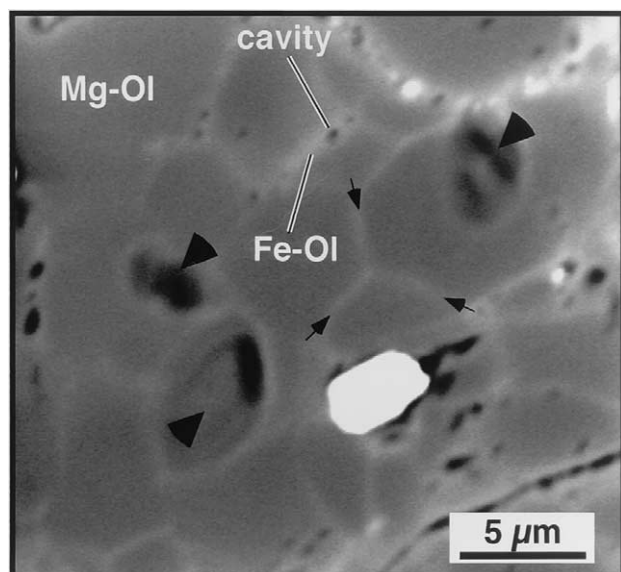


Fig. 4. Backscattered electron image of triple junction of olivine grains in TTA1-02, located at area C in Figure 1. Dark gray areas correspond to Mg-rich olivine grains (Mg-Ol). Mg-rich olivine grains formed triple junction (thin arrows). Fe-rich olivine grains (Fe-Ol), which seem to be brighter than Mg-rich olivine grains, and cavities intervene among Mg-rich olivine grains. The brightest areas including some of the cavities are such covered by the thin Au film cover for SIMS analyses. Three craters, which are pointed by thick black arrows, were produced by SIMS analyses.

size of Mg-rich olivine grains is ca. $5\mu\text{m}$. The largest Mg-rich olivine grain is estimated as ca. $15\mu\text{m}$. Generally, clusters that have low modal ratio of Mg-rich to Fe-rich olivine are abundant at the rim of TTA1-02 (Figs. 2 and 3). However, the ratio varies even within the olivine clusters (Fig. 3b). For example, the modal ratio of Mg-rich to Fe-rich olivines is high in upper left of Figure 3b, but low in lower left of Figure 3b. As the ratio of Mg-rich to Fe-rich olivine decreases, the number of cavities tends to increase (Figs. 3b and 3d). Therefore, the cavity density is higher at the rim of the AOA.

Some olivine grains around Al-rich inclusions have triple junctions with 120° grain boundaries (Fig. 4). Fe-rich olivine sometimes forms vein-filling cracks (upper right area in Fig. 5). Hedenbergite often exists in the periphery of olivine grains, which enclose Al-rich inclusions. Troilite and metal are rare.

Al-rich inclusions in TTA1-02 are characterized by a core-rim layered structure (Fig. 5). The core consists of fine grains of spinel + fassaite $\pm$ perovskite $\pm$ anorthite + nepheline $\pm$ phyllosilicate. The rim consists of fassaite. All phases except spinel and perovskite have cavities indicating that the crystal sizes of each phase are micron to submicron. Some Al-rich inclusions show a spherical shape (Fig. 5) and others, which enclose Mg-rich olivine clusters, have an irregular one (Fig. 6)

3.2. Mineral Chemistry

Representative compositions of olivine grains are shown in Table 1. Mg-rich olivine grains that coexist with small amounts of Fe-rich olivine grains and cavities have compositions of Fo_{90} to 99 . Each compositional gradient layer of Fe between

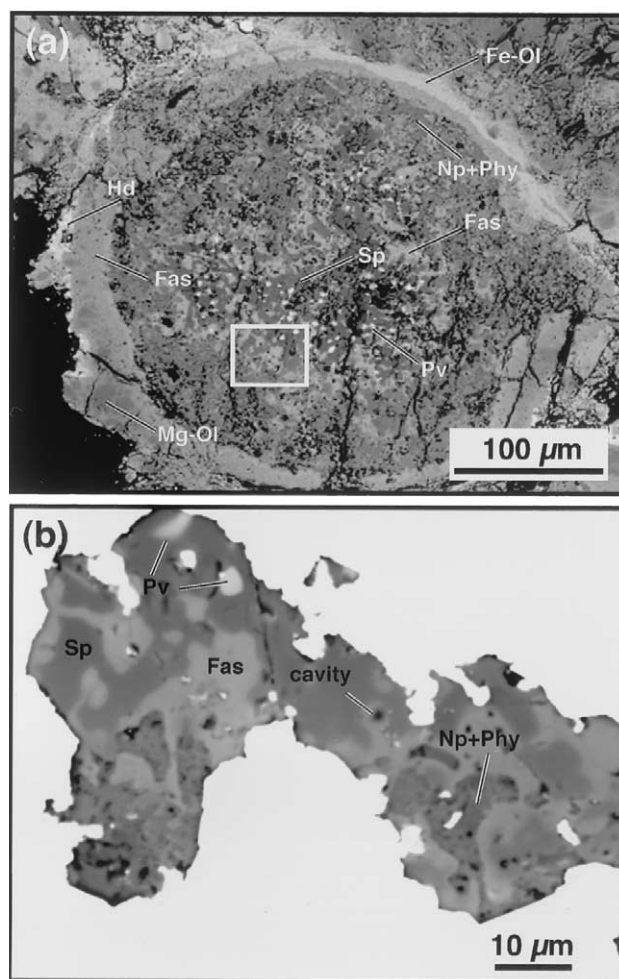


Fig. 5. Backscattered electron image of Al-rich inclusion#1 in TTA1-02 from Allende meteorite. This inclusion is located at a in Figure 1. Al-rich inclusion#1 shows a spherical shape and a core-rim layered structure. (b) An enlarged picture of white square area in (a). The core consists of fine grains of spinel, perovskite, fassaite, nepheline and phyllosilicate. All phases except spinel and perovskite contain cavities. The brightest areas including some of the cavities are such covered by the thin Au film cover for SIMS analyses. Abbreviations: Sp = spinel; Pv = perovskite; Fas = fassaite; Np = nepheline; Phy = phyllosilicate; Hd = hedenbergite. Other abbreviations as used previously.

Mg-rich and Fe-rich olivine is less than $2\mu\text{m}$ (Fig. 7) In contrast, Mg-rich olivine grains that coexist with abundant Fe-rich olivine grains and cavities have moderate Fo contents ranging between 70 and 90. The smallest Mg-rich olivine grains have the lowest Fo contents. The Fe-rich olivine ranges in composition between Fo_{60} and Fo_{70} . The diffusion profiles are easily observed in those small Mg-rich olivine grains (Figs. 3b and 3d).

Spinel in the Al-rich inclusions is almost pure MgAl_2O_4 (Table 1). Spinel grains that coexist with secondary phases near the rim of Al-rich inclusions have high FeO contents ($<12\text{wt.}\%$). Fassaite (Table 2) shows compositional variations in Al_2O_3 (3 to $30\text{wt.}\%$) and in TiO_2 ($<16\text{wt.}\%$). The Ti and Al contents of fassaite in the core of Al-rich inclusions are higher than those in the rim. The compositions of perovskite, anorthite

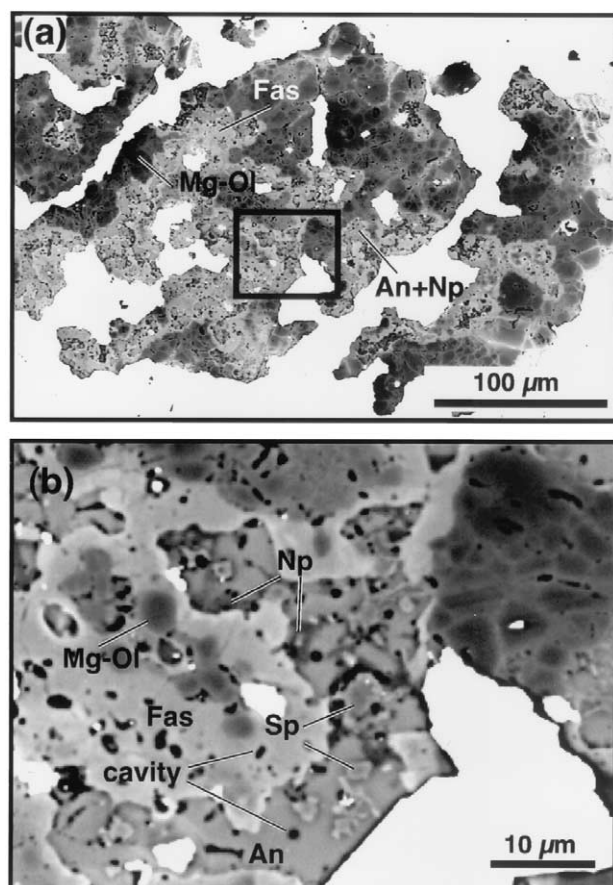


Fig. 6. Backscattered electron image of Al-rich inclusion#4 in TTA1-02 from Allende meteorite. This inclusion is located at b in Figure 2. Al-rich inclusion #4 shows irregular shape and encloses Mg-rich olivine clusters. The diameter is ca. 400 μm . (b) An enlarged picture of the black square area in (a). Assemblages of spinel, anorthite and nepheline are surrounded by fassaite. All phases except spinel contain cavities. The brightest areas including some of the cavities are such covered by the thin Au film cover for SIMS analyses. Abbreviations as used previously.

and hedenbergite are nearly pure CaTiO_3 , $\text{CaAl}_2\text{Si}_2\text{O}_8$ and $\text{CaFeSi}_2\text{O}_6$ (Table 2). Nepheline (Table 3) shows variations in Na_2O (12 to 17wt.%), MgO (<2wt.%), K_2O (<2wt.%), CaO (2 to 6wt.%) and FeO (<1wt.%), similar to values previously reported for nepheline in AOAs (Grossman and Steele, 1976). Compositions of phyllosilicate grains (Table 3) show variations in Na_2O (1 to 4wt.%), MgO (1 to 2wt.%), K_2O (1 to 2wt.%), CaO (3 to 4wt.%) and FeO (0.5 to 1wt.%).

3.3. Oxygen Isotopic Compositions

Oxygen isotopic compositions in minerals of TTA1-02 are listed in Tables 4, 5, and 6 and are plotted in Figure 1. Oxygen isotopic compositions of minerals are heterogeneously distributed along the carbonaceous chondrite anhydrous mineral (CCAM) line. Although some analyses show small deviations from the CCAM line, we cannot rule out that the deviations are artifacts because the accuracy (note: what is shown is the precision; cf. experimental section) of the data is estimated as $\pm$ ca. 5‰ (σ).

Table 1. Composition of olivine (ol) and spinel (sp) in TTA1-02 AOA

	ol#1	ol#3	ol#9	sp#1	sp#5
SiO_2	35.8	38.7	42.6	n. d.	n. d.
Al_2O_3	n. d. ^a	n. d.	n. d.	73.6	69.2
FeO	33.4	24.0	0.7	n. d.	12.2
MgO	29.7	36.5	55.2	28.2	19.2
total	98.9	99.2	98.5	101.8	100.6
Number of cations per formula unit					
Si	1.00	1.02	1.01	n. d.	n. d.
Al	n. d.	n. d.	n. d.	2.02	2.02
Fe	0.78	0.53	0.01	n. d.	0.25
Mg	1.23	1.43	1.96	0.98	0.71
O	4.00	4.00	4.00	4.00	4.00
cation sum	3.01	2.98	2.98	3.00	2.98
Fo ^b	61	73	99	–	–

^a not detected.

^b $100 \times \text{Mg}/(\text{Mg} + \text{Fe})[\text{mol}\%]$.

Olivine has a bimodal distribution in Figure 1, i.e., one group is ^{16}O -poor with Fe-rich olivine composition and the other group is ^{16}O -rich with Mg-rich olivine composition. Figure 7 shows the analytical locations of Ol#17 in Mg-rich olivine and Ol#41 in Fe-rich olivine. The $\Delta^{17}\text{O}$ values of Ol#17 and Ol#41 are -28‰ and -6.3‰ , respectively. Mg-rich and Fe-rich olivine grains, which have sharp compositional change of Fe, have different oxygen isotopic compositions from each other. Mean $\Delta^{17}\text{O}$ values of Fe-rich and Mg-rich olivines are ca. -5‰ and -25‰ , respectively.

Typical fassaite oxygen isotopic compositions are $\Delta^{17}\text{O} =$ ca. -20‰ (Table 5; Fig. 1), but fassaite having intermediate values between the ^{16}O -rich and ^{16}O -poor components occurs in rims of one Al-rich inclusion. Detailed SEM observations show that intermediate values are not due to beam overlap with other phases. Fassaite having intermediate values are adjacent to Na-rich phases in Al-rich inclusions. The heterogeneous ^{16}O -rich distribution corresponding to alteration phases indicates partial O isotopic exchange in fassaite occurred during alteration processes.

The oxygen isotopic composition of spinel is $\Delta^{17}\text{O} =$ ca. -20‰ (Table 6). This is similar to that of typical spinel in CAIs (e.g., Clayton, 1993). The mean $\Delta^{17}\text{O}$ values of anorthite, nepheline and phyllosilicate are ca. -5.0‰ , -5.0‰ , -10‰ , respectively (Table 6; Fig. 1).

4. DISCUSSION

TTA1-02 shows an irregular shape. It consists mainly of small olivine grains ($\sim 5 \mu\text{m}$) containing several Al-rich inclusions. The texture indicates that TTA1-02 aggregated as olivine grains formed around preexisting Al-rich inclusions in the solar nebula. The olivine aggregate portion did not experience total melting. However, incomplete melting as suggested by Wasson and Rubin (1997) and Komatsu et al. (2001) may have occurred during formation of the AOA because of the relatively compact texture (Fig. 4). In the following sections we discuss the formation of olivine grains and Al-rich inclusions. As TTA1-02 is a typical AOA from the CV chondrite on the basis of mineral-

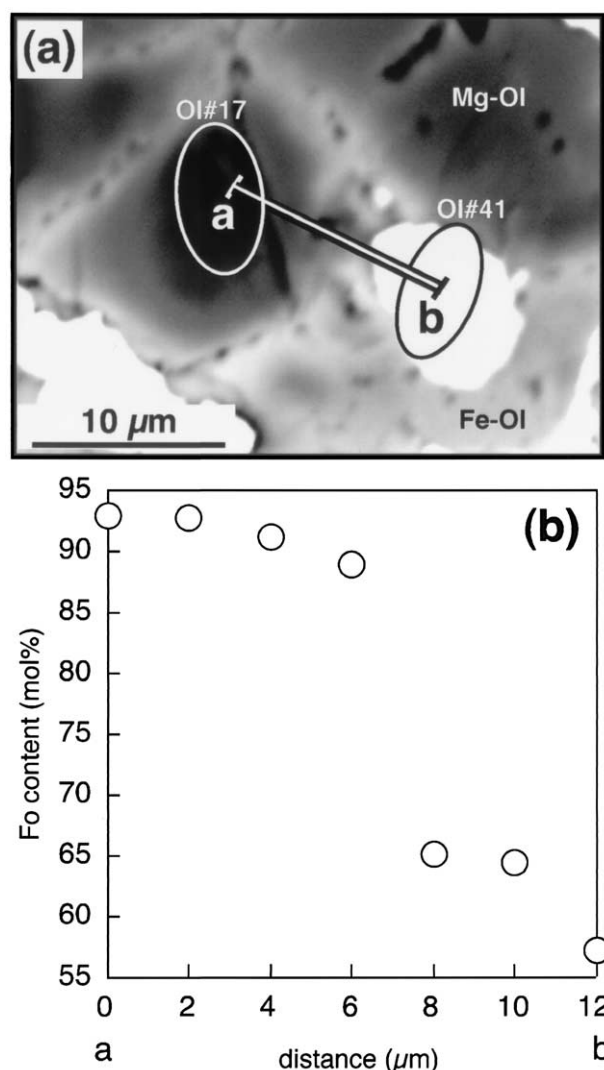


Fig. 7. Line profile of forsterite content. (a) BSE image of olivine cluster in TTA1-02. This area is located at D in Figure 2. The brightest areas including some of the cavities are such covered by the thin Au film cover for SIMS analyses. Abbreviations as used previously. The two ellipses show locations of SIMS analyses, Ol#17 and Ol#41 (Table 4). The Ol#41 is covered by Au thin film. (b) Line profile of Fo content from a to b in (a). A clear compositional change is observed at $x = 7 \mu\text{m}$.

ogy and petrology, the formation process of TTA1-02 has implication for most AOAs from CV chondrites.

4.1. Olivine

Olivine clusters basically consist of Mg-rich and Fe-rich types of olivine grains. Fe-rich olivine in TTA1-02 has several characteristics: (1) sharp compositional boundaries towards Mg-rich olivine grains (Fig. 7); (2) Interstitial location between Mg-rich olivine grains (Figs. 3 and 4); (3) presence of many cavities (Figs. 3 and 4); and (4) depletion in ^{16}O (Fig. 1). In contrast, Mg-rich olivine has characteristic (5) enrichment in ^{16}O (Fig. 1). In addition, olivine clusters near the rim of

Table 2. Composition of fassaite (fas), perovskite (pv), anorthite (an) and hedenbergite (hd) in TTA1-02 AOA

	fas#2	fas#3	fas#5	pv	an	hd
SiO ₂	40.1	26.7	54.1	n. d.	42.9	48.4
TiO ₂	7.1	15.8	n. d.	57.3	n. d.	n. d.
Al ₂ O ₃	17.2	30.0	3.6	0.9	36.5	n. d.
FeO	n. d. ^a	n. d.	n. d.	n. d.	n. d.	27.9
MgO	10.1	7.4	17.9	n. d.	n. d.	n. d.
CaO	25.8	21.9	25.8	40.9	20.6	23.4
total	100.3	101.8	101.4	99.1	100.0	99.7
Number of cations per formula unit						
Si	1.47	0.97	1.92	n. d.	1.99	2.00
Ti	0.20	0.43	n. d.	0.98	n. d.	n. d.
Al	0.74	1.29	0.15	0.03	2.00	n. d.
Fe	n. d.	n. d.	n. d.	n. d.	n. d.	0.96
Mg	0.55	0.40	0.95	n. d.	n. d.	n. d.
Ca	1.01	0.85	0.98	1.00	1.02	1.04
O	6.00	6.00	6.00	3.00	8.00	6.00
cation sum	3.97	3.94	4.00	2.01	5.01	4.00

^a not detected.

TTA1-02 have characteristic (6) low modal ratio of Mg-rich to Fe-rich olivines (Figs. 2 and 3).

The texture shows that the Mg-rich olivine grains condensed directly from a ^{16}O -rich gas or the Mg-rich olivine grains crystallized from a melt that had a ^{16}O -rich oxygen isotopic composition. The melt itself could have been generated by nebula heating of very fine ^{16}O -rich olivine dust grains. Such conditions could be realized in the solar nebula (Yurimoto et al., 2001; Krot et al., 2002).

On the other hand, Fe-rich olivine grains formed in a different environment of ^{16}O -poor oxygen isotopic composition on the preexisting Mg-rich olivine. In the following, three possible formation models of Fe-rich olivine grains are considered:

Table 3. Composition of nepheline (np) and phyllosilicate (phy) in TTA1-02 AOA

	np#1	np#2	np#3	np#4	phy#1	phy#3	phy#4
SiO ₂	40.3	41.4	44.0	39.9	39.6	44.9	42.0
Al ₂ O ₃	36.0	38.7	35.8	39.5	33.3	38.6	38.7
FeO	0.8	n. d.	n. d.	n. d.	1.0	0.6	1.2
MgO	1.2	1.0	n. d.	1.8	2.3	0.8	1.2
CaO	5.8	2.2	2.5	4.7	3.8	3.3	2.9
Na ₂ O	13.0	12.6	16.9	13.6	1.3	2.3	4.1
K ₂ O	n. d. ^a	2.3	1.9	1.5	1.4	1.6	2.0
total	97.1	98.2	101.1	101.0	82.7	92.1	92.1
Number of cations per formula unit							
Si	0.98	0.98	1.03	0.93	2.93	2.97	2.82
Al	1.03	1.08	0.98	1.09	2.91	3.00	3.07
Fe	0.02	n. d.	n. d.	n. d.	0.06	0.03	0.07
Mg	0.04	0.03	n. d.	0.06	0.25	0.08	0.12
Ca	0.15	0.06	0.06	0.12	0.30	0.24	0.21
Na	0.61	0.58	0.77	0.62	0.19	0.30	0.53
K	n. d.	0.07	0.06	0.05	0.13	0.13	0.17
O	4.00	4.00	4.00	4.00	11.00	11.00	11.00
cation sum	2.83	2.80	2.90	2.87	6.77	6.75	6.99

^a not detected.

Table 4. O isotopic compositions (‰) of olivine in TTA1-02 AOA

Spot Num.	$\delta^{17}\text{O}_{\text{SMOW}}$ ($\pm \sigma_{\text{mean}}$)	$\delta^{18}\text{O}_{\text{SMOW}}$ ($\pm \sigma_{\text{mean}}$)	$\Delta^{17}\text{O}^a$ ($\pm \sigma_{\text{mean}}$)	Fo ^b
ol#1	-1.4 $\pm$ 3.0	-0.3 $\pm$ 1.6	-1.2 $\pm$ 3.1	63
ol#10	-11.4 $\pm$ 2.2	-6.6 $\pm$ 1.0	-8.0 $\pm$ 2.2	69
ol#11	-53.2 $\pm$ 2.7	-44.0 $\pm$ 1.0	-30.3 $\pm$ 2.7	97
ol#17	-52.2 $\pm$ 2.1	-46.4 $\pm$ 1.0	-28.1 $\pm$ 2.2	92
ol#21	-46.0 $\pm$ 2.4	-36.0 $\pm$ 1.1	-27.2 $\pm$ 2.4	94
ol#34	-48.8 $\pm$ 2.5	-41.7 $\pm$ 1.6	-27.1 $\pm$ 2.6	96
ol#38	-47.7 $\pm$ 2.2	-50.1 $\pm$ 1.4	-21.7 $\pm$ 2.3	92
ol#40	-11.0 $\pm$ 2.5	-3.3 $\pm$ 1.3	-9.2 $\pm$ 2.6	67
ol#41	-11.4 $\pm$ 2.7	-9.8 $\pm$ 1.3	-6.3 $\pm$ 2.8	69
ol#42	-43.2 $\pm$ 2.6	-42.0 $\pm$ 1.7	-21.4 $\pm$ 2.7	99
ol#45	-45.0 $\pm$ 2.3	-41.9 $\pm$ 1.1	-23.2 $\pm$ 2.4	96
ol#48	-44.3 $\pm$ 2.4	-38.2 $\pm$ 1.2	-24.4 $\pm$ 2.4	98
ol#49	-43.8 $\pm$ 2.2	-38.6 $\pm$ 1.3	-23.7 $\pm$ 2.3	98
ol#50	-13.4 $\pm$ 2.0	-9.4 $\pm$ 1.0	-8.5 $\pm$ 2.1	65
ol#55	-46.9 $\pm$ 2.2	-41.7 $\pm$ 1.1	-25.2 $\pm$ 2.3	97
ol#56	-47.6 $\pm$ 2.2	-40.7 $\pm$ 1.2	-26.4 $\pm$ 2.3	98
ol#60	-40.2 $\pm$ 2.1	-33.6 $\pm$ 1.3	-22.7 $\pm$ 2.2	90
ol#61	-44.7 $\pm$ 1.7	-39.8 $\pm$ 1.2	-24.0 $\pm$ 1.8	97
ol#62	-42.0 $\pm$ 2.4	-36.9 $\pm$ 0.9	-22.8 $\pm$ 2.4	94
ol#70	-40.7 $\pm$ 2.3	-37.6 $\pm$ 1.3	-21.1 $\pm$ 2.4	93
ol#80	-46.4 $\pm$ 3.2	-41.7 $\pm$ 1.9	-24.7 $\pm$ 3.4	98
ol#131	-44.2 $\pm$ 2.2	-37.7 $\pm$ 1.3	-24.6 $\pm$ 2.3	94

^a $\delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$.^b $100 \times \text{Mg}/(\text{Mg} + \text{Fe})[\text{mol}\%]$.

A. Fe-rich olivine grains formed by diffusion of Fe^{2+} and ^{16}O -poor oxygen into the pre-existing Mg-rich olivine grains.

Table 5. O isotopic compositions (‰) of fassaite in TTA1-02 AOA

Spot Num.	$\delta^{17}\text{O}_{\text{SMOW}}$ ($\pm \sigma_{\text{mean}}$)	$\delta^{18}\text{O}_{\text{SMOW}}$ ($\pm \sigma_{\text{mean}}$)	$\Delta^{17}\text{O}^a$ ($\pm \sigma_{\text{mean}}$)
fas#2	-21.9 $\pm$ 2.5	-19.3 $\pm$ 1.0	-11.9 $\pm$ 2.6
fas#4	-43.8 $\pm$ 2.9	-28.6 $\pm$ 1.5	-28.9 $\pm$ 3.0
fas#5	-43.1 $\pm$ 2.8	-31.5 $\pm$ 1.5	-26.7 $\pm$ 2.9
fas#6	-25.2 $\pm$ 2.7	-20.7 $\pm$ 1.0	-14.4 $\pm$ 2.7
fas#7	-38.1 $\pm$ 2.4	-33.5 $\pm$ 1.1	-20.7 $\pm$ 2.5
fas#8	-30.4 $\pm$ 2.0	-29.4 $\pm$ 1.1	-15.1 $\pm$ 2.1
fas#14	-39.6 $\pm$ 2.0	-30.7 $\pm$ 1.2	-23.7 $\pm$ 2.1
fas#15	-23.2 $\pm$ 2.0	-13.5 $\pm$ 1.0	-16.2 $\pm$ 2.1
fas#24	-42.3 $\pm$ 2.3	-39.4 $\pm$ 1.0	-21.8 $\pm$ 2.3
fas#26	-39.2 $\pm$ 2.4	-37.6 $\pm$ 0.8	-19.6 $\pm$ 2.4
fas#27	-39.1 $\pm$ 1.8	-36.6 $\pm$ 1.3	-20.1 $\pm$ 1.9
fas#29	-44.7 $\pm$ 2.0	-36.4 $\pm$ 1.1	-25.8 $\pm$ 2.1
fas#32	-36.5 $\pm$ 2.4	-35.7 $\pm$ 1.0	-17.9 $\pm$ 2.5
fas#33	-36.7 $\pm$ 2.2	-36.3 $\pm$ 1.1	-17.9 $\pm$ 2.3
fas#43	-37.1 $\pm$ 2.2	-38.6 $\pm$ 1.4	-17.1 $\pm$ 2.3
fas#46	-36.9 $\pm$ 2.1	-35.9 $\pm$ 1.1	-18.2 $\pm$ 2.2
fas#47	-42.8 $\pm$ 1.9	-35.5 $\pm$ 1.1	-24.3 $\pm$ 1.9
fas#53	-44.3 $\pm$ 2.3	-37.1 $\pm$ 1.0	-25.0 $\pm$ 2.4
fas#66	-41.8 $\pm$ 2.2	-41.4 $\pm$ 1.4	-20.3 $\pm$ 2.3
fas#68	-42.3 $\pm$ 2.3	-40.6 $\pm$ 1.1	-21.2 $\pm$ 2.4
fas#69	-42.4 $\pm$ 2.1	-37.3 $\pm$ 1.3	-23.0 $\pm$ 2.2
fas#71	-41.0 $\pm$ 2.1	-39.0 $\pm$ 1.3	-20.7 $\pm$ 2.2
fas#85	-33.4 $\pm$ 2.3	-27.4 $\pm$ 1.0	-19.1 $\pm$ 2.4
fas#90	-42.1 $\pm$ 2.2	-36.1 $\pm$ 1.3	-23.3 $\pm$ 2.4
fas#133	-47.8 $\pm$ 2.6	-39.2 $\pm$ 1.1	-27.4 $\pm$ 2.7

^a $\delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$.

Table 6. O isotopic compositions (‰) of spinel (sp), anorthite (an), nepheline (np) and phyllosilicate (phy) in TTA1-02 AOA

Spot Num.	$\delta^{17}\text{O}_{\text{SMOW}}$ ($\pm \sigma_{\text{mean}}$)	$\delta^{18}\text{O}_{\text{SMOW}}$ ($\pm \sigma_{\text{mean}}$)	$\Delta^{17}\text{O}^a$ ($\pm \sigma_{\text{mean}}$)
Sp#3	-38.5 $\pm$ 2.6	-36.4 $\pm$ 2.0	-19.6 $\pm$ 2.8
An#52	-5.2 $\pm$ 2.2	-2.1 $\pm$ 1.1	-4.1 $\pm$ 2.3
An#64	-1.5 $\pm$ 2.7	3.8 $\pm$ 1.7	-3.5 $\pm$ 2.9
An#88	-1.6 $\pm$ 2.3	6.5 $\pm$ 0.9	-5.0 $\pm$ 2.4
An#99	-3.9 $\pm$ 2.6	4.9 $\pm$ 1.3	-6.4 $\pm$ 2.6
An#103	-7.3 $\pm$ 2.2	-1.2 $\pm$ 1.1	-6.7 $\pm$ 2.3
Nep#51	-2.8 $\pm$ 1.8	-2.3 $\pm$ 1.1	-1.6 $\pm$ 1.9
Nep#132	-3.3 $\pm$ 2.8	4.3 $\pm$ 1.3	-5.5 $\pm$ 2.8
Phy#16	-8.6 $\pm$ 2.4	-0.5 $\pm$ 1.1	-8.4 $\pm$ 2.4

^a $\delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$.

B. After the formation of Mg-rich olivine grains, addition of oxygen with a ^{16}O -poor oxygen isotopic composition produced more oxidizing conditions. This enabled condensation of more Fe-rich olivine with ^{16}O -poor oxygen isotopic composition around preexisting Mg-rich olivine grains.

C. Fluid dissolved pre-existing ^{16}O -rich Mg-rich olivine grains on the parent body. Then Fe-rich olivine grains with ^{16}O -poor oxygen isotopic composition newly formed among them.

Because simple diffusion profiles gradually change the composition from Fe-rich to Mg-rich areas, sharp Fe-Mg boundaries shown by characteristic #1 indicate that diffusion model A is difficult to apply to the formation of Fe-rich olivine grains. This suggests that the Fe-rich olivine crystallized as new grains around preexisting Mg-rich olivine. Because O diffusion rate in olivine is much slower than Fe diffusion rate (Buening and Buseck, 1973; Misener, 1974; Jaoul et al., 1980; 1983; Reddy et al., 1980; Sockel et al., 1980; Yurimoto et al., 1992; Chakraborty, 1997), coincident distribution of Fe-rich and ^{16}O -poor characteristics in olivine observed in the AOA is not consistent with model A. Therefore, we rule out the first possibility as the main formation mechanism of Fe-rich olivine grains. The diffusion profiles showing Fe penetration are only observed in rims of smaller Mg-rich olivine grains (Figs. 3b and 3d). These indicate Fe-Mg inter diffusion between Mg-rich and Fe-rich olivine grains occurred after Fe-rich olivine crystallization.

Model B has been inferred for the formation of Fe-rich rims surrounding forsteritic cores of isolated olivine grains in Allende CV3 chondrite (Palme and Fegley 1990; Weinbruch et al., 1993). The low modal ratio of Mg-rich to Fe-rich olivines in the rim of TTA1-02 (characteristic #6) shows that Fe-rich olivine grains were produced after the original formation of TTA1-02, i.e., after the accretion of Mg-rich olivine grains. However, Fe-rich olivine grains exist interstitially among all Mg-rich olivine grains in TTA1-02 (characteristic #2) even in the center. After the accretion of Mg-rich olivine grains, condensation of Fe-rich olivine grains around each Mg-rich olivine grain in the interior of the AOA is difficult in model B.

We propose that model C can explain all of the six characteristics. The sharp compositional boundaries between Mg-rich and Fe-rich olivine grains (Characteristic #1) are easily explained by precipitation of Fe-rich olivine. The fluid that had penetrated along the grain boundary of original Mg-rich olivine

grains and dissolved them after formation of the original TTA1-02 explains the distribution of Fe-rich olivine grains (characteristic #2 and #6). Fe ions may have been transported from oxidized metal in the Allende parent body by the fluid. Small Fe-rich olivine grains precipitated to fill the grain boundary of Mg-rich olivine grains. Cavities (characteristics #3) are thought to have formed as the fluid channels around the precipitated Fe-rich olivine grains. The cavities were preserved after the sintering of Fe-rich olivine grains following the fluid disappearance by thermal metamorphism. The different oxygen isotopic compositions between Mg-rich and Fe-rich olivines (Characteristics #4 and #5) show that the two types olivines formed in two different environments.

Mg-rich olivine primarily formed in a ^{16}O -rich environment in the solar nebula. Secondary Fe-rich olivine formed in a ^{16}O -poor aqueous environment in the parent body. Rubin (1998) and Chizmadia and Rubin (2000) suggested similar mechanisms for the alteration of AOAs from CO3 chondrites. Choi et al. (1997) concluded that the $\Delta^{17}\text{O}$ values of aqueous fluid on the CV3 parent body are between -0.4 and -5.3% . This range is similar to that of Fe-rich olivine in TTA1-02, -1.2 to -9.2% , supporting that Fe-rich olivine in TTA1-02 formed in the Allende parent body. The Fe-rich olivine may have formed from Mg-rich olivine via phyllosilicates. This process was suggested by Kojima et al. (1993) for Fe-rich olivine in dark inclusions from the Vigarano CV3 meteorite and then expanded into the formation process for Fe-rich olivine rims of chondrule and matrix olivines in the Allende meteorite by Krot et al. (1995, 1997). These authors concluded that the process occurred in the parent body. Textures of Fe-rich olivine rims described by Krot et al. (1997) have almost the same characters as those of Fe-rich olivines in TTA1-02 (#1, #2 and #3 and Fo contents). Therefore, O isotopic, chemical and petrographical evidences support that the Fe-rich olivine in TTA1-02 has formed by aqueous alteration in the Allende parent body.

4.2. Al-Rich Inclusions

Al-rich inclusions consist of spinel, fassaite, perovskite, anorthite, nepheline and phyllosilicate. The oxygen isotopic composition of each mineral corresponds to the environment where it formed. The isotopic compositions of minerals in Al-rich inclusions from TTA1-02 show a bimodal distribution (Fig. 1). ^{16}O -rich minerals are spinel and fassaite, whereas ^{16}O -poor minerals are anorthite, nepheline and phyllosilicate. This indicates that spinel and fassaite formation occurred in a different environment from that of anorthite, nepheline and phyllosilicate. The existence of nepheline and phyllosilicate indicates Al-rich inclusions were altered aqueously after solidification. These secondary phases must have replaced some pre-existing minerals in Al-rich inclusions. Hashimoto and Grossman (1987) proposed nepheline and phyllosilicate might have replaced melilite.

The anorthite grains in the Al-rich inclusions are almost pure anorthite. However, the anorthite layer is extensively corroded by nepheline (Fig. 6b). Itoh et al. (2000) reported anorthite and melilite layers in CAIs from CO chondrites were corroded by nepheline through aqueous alteration as the petrographic subtype increased. They also reported oxygen isotopic composition

of anorthite changed from ^{16}O -rich to ^{16}O -poor with no chemical compositional changes. A similar oxygen isotopic change has been reported in CAI melilite in CO chondrites (Wasson et al., 2001). These observations support the interpretation that ^{16}O -poor anorthite in CAIs with nepheline is the result of aqueous alteration of ^{16}O -rich anorthite. The similarities of anorthite characteristics between AOAs from CVs and CAIs from COs indicate that the aqueous alteration of Al-rich inclusions occurred in the parent body.

There are two additional studies supporting that nepheline and phyllosilicate crystallized in the CV parent body. Kojima and Tomeoka (1996) reported veins consisting of nepheline, salitic pyroxene and Fe-rich olivine in a dark inclusion from the Allende meteorite. Veins are thought to have formed after accretion of the parent body. Therefore, their report shows that nepheline formed in the parent body. Keller et al. (1994) reported that phyllosilicate formed in the parent body on the basis of evidence in the Bali CV3 meteorite that alteration veins consisting of phyllosilicate formed along shock-induced foliations.

These studies of alteration in CV and CO chondrites combined with our textural observations and isotopic results suggest that the secondary minerals in TTA1-02 formed by aqueous alteration on the Allende parent body. The alteration minerals have ^{16}O -poor oxygen isotopic compositions, which contrast with the ^{16}O -rich oxygen isotopic compositions of primary spinel and fassaite (Fig. 1). The ^{16}O -rich oxygen isotopic compositions are similar to those of pristine and weakly altered refractory minerals in CAIs from CV and CO chondrites (Yurimoto et al., 1998; Wasson et al., 2001). Therefore, we conclude that the Al-rich inclusions primarily consist of spinel, fassaite and melilite and anorthite having ^{16}O -rich compositions and in addition secondary phases with ^{16}O -poor compositions formed in the Allende parent body.

5. CONCLUSION

We have determined the precise micro-distribution of oxygen isotopic compositions of minerals in an AOA from the Allende CV chondrite. According to the results, we suggest the most plausible formation process of AOA in the Allende CV chondrite to be the following:

1. Al-rich inclusions with ^{16}O -rich oxygen isotopic composition crystallized in the solar nebula.
2. Mg-rich olivine grains with ^{16}O -rich oxygen isotopic composition crystallized around the Al-rich inclusion in the solar nebula.
3. AOA accreted to the parent body.
4. Fluids with ^{16}O -poor oxygen isotopic composition penetrated between grain boundaries of Mg-rich olivine grains and Al-rich inclusions. Because the dissolution proceeded from the rim of AOA, the degree of dissolution is larger in the rim than at the center of AOA.
5. Small Fe-rich olivine precipitated to fill the grain boundaries between Mg-rich olivine grains. Secondary phases (anorthite, nepheline and phyllosilicate) in Al-rich inclusions replaced primary anorthite or melilite. As the fluid disappeared by thermal metamorphism, Fe-rich olivine grains were sintered.

As TTA1-02 is a typical AOA from the CV chondrite on the basis of mineralogy and petrology, this formation process has general implications for the origin of AOAs from the CV chondrites.

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