Meteoritics & Planetary Science 42, Nr 7/8, 1241–1247 (2007)
Abstract available online at http://meteoritics.org

Oxygen and magnesium isotopic compositions of amoeboid olivine aggregates from the Semarkona LL3.0 chondrite

Shoichi ITOH[1, 2], Sara S. RUSSELL[2], and Hisayoshi YURIMOTO[1]

[1]Department of Natural History Sciences, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan
[2]Impacts and Astromaterials Research Centre, Department of Mineralogy, The Natural History Museum,
Cromwell Road, London, SW7 5BD, UK
[*]Corresponding author. E-mail: sitoh@ep.sci.hokudai.ac.jp

(Received 04 October 2006; revision accepted 25 January 2007)

Abstract–Amoeboid olivine aggregates (AOAs) in the LL3.0 Semarkona chondrite have been studied by secondary ion mass spectrometry. The AOAs mainly consist of aggregates of olivine grains with interstitial Al-Ti-rich diopside and anorthite. Oxygen-isotopic compositions of all phases are consistently enriched in ^{16}O, with $\delta^{17,18}$O = ~−50‰. The initial ^{26}Al/^{27}Al ratios are calculated to be 5.6 ± 0.9 (2σ) $\times 10^{-5}$. These values are equivalent to those of AOAs and fine-grained calcium-aluminum-rich inclusions (FGIs) from pristine carbonaceous chondrites. This suggests that AOAs in ordinary chondrites formed in the same ^{16}O-rich calcium-aluminum-rich inclusion (CAI)-forming region of the solar nebula as AOAs and FGIs in carbonaceous chondrites, and subsequently moved to the accretion region of the ordinary chondrite parent body in the solar nebula.

INTRODUCTION

Calcium-aluminum-rich inclusions (CAIs) are widely believed to be among the oldest material formed in the solar system (Amelin et al. 2002). Amoeboid olivine aggregates (AOAs) are considered to have a close genetic relationship with CAIs because of their condensation textures (Grossman and Steele 1976) and ^{16}O-rich O-isotopic compositions (Hiyagon and Hashimoto 1999). The Al-Mg systematics of AOAs, which have ^{26}Mg excesses, also support this relationship (Itoh et al. 2002).

AOAs from primitive carbonaceous chondrites (unaltered and unmetamorphosed) are mainly composed of numerous μm-sized olivine grains with minor abundances of Ca-Al-rich phases, e.g., Al-Ti-rich diopside, anorthite, spinel, and very rarely melilite (Komatsu et al. 2001; Itoh et al. 2002; Krot et al. 2004; Weisberg et al. 2004). On the other hand, secondary minerals in the AOAs of metamorphosed and altered host meteorites usually include phyllosilicates, magnetite, nepheline, sodalite, hedenbergite, and ferrous olivine (Chizmadia et al. 2002; Krot et al. 2004). The textures of AOAs from primitive carbonaceous chondrites indicates that they have not experienced a large amount of melting, but small amounts of interstitial melt may have existed (Komatsu et al. 2002; Komatsu et al. 2003). AOAs are commonly observed in carbonaceous chondrites and their abundance in these meteorites is greater than the abundance of CAIs (Krot et al. 2004). Itoh et al. (2002) suggested that AOAs and fine-grained CAIs (FGIs) are not clearly distinguishable in CO chondrites because the ratio of olivine to Ca-Al-rich phases in AOAs changes along a continuum. A continuum between AOAs and FGIs has been also observed in the Ningqiang carbonaceous chondrite (Lin and Kimura 2003). These observations support the theory that AOAs condensed from the same cooling hot solar nebula gas as CAIs (Krot et al. 2004).

The oxygen isotopic ratios of AOAs in carbonaceous chondrites are normally enriched in ^{16}O except for secondary alteration phases (Hiyagon and Hashimoto 1999; Aléon et al. 2002; Itoh et al. 2002; Krot et al. 2002; Imai and Yurimoto 2003; Fagan et al. 2004; Krot et al. 2005). Clear ^{26}Mg excesses attributable to the decay of live ^{26}Al have also been found in AOAs of carbonaceous chondrites (Itoh et al. 2002; Sugiura and Krot 2006), with values that correspond to the canonical ^{26}Al/^{27}Al ratios observed in many CAIs.

In contrast to the case of carbonaceous chondrites, AOAs and CAIs of ordinary chondrites have not been extensively studied. There are a few oxygen (McKeegan et al. 1998) and Al-Mg (Huss et al. 2001) isotopic studies for FGIs from ordinary chondrites, but there are no reports for AOAs from Semarkona. Here we report results from three AOAs from the Semarkona LL3.0 chondrite. We describe the petrography, oxygen and Al-Mg isotopic compositions of the AOAs. Based on these results, we discuss the relationship of AOAs between ordinary chondrites and carbonaceous chondrites.

Table 1. Representative chemical compositions of minerals of Semarkona AOAs.

Inclusion	AOA1			AOA2			AOA3	
Phase	Al-Ti-Di	Olivine	Anorthite	Al-Ti-Di	Olivine	Anorthite	Al-Ti-Di	Olivine
MgO	17.3	56.7	4.2	15.7	55.7	3.0	18.7	55.6
Al_2O_3	6.4	n.d.	30.1	7.6	n.d.	30.3	3.0	n.d.
SiO_2	51.2	42.9	45.5	51.0	43.3	46.4	53.8	43.4
CaO	23.9	n.d.	19.3	24.7	n.d.	19.7	24.1	n.d.
TiO_2	1.0	n.d.	n.d.	0.8	n.d.	n.d.	0.2	n.d.
Cr_2O_3	n.d.	0.3	n.d.	n.d.	0.3	n.d.	n.d.	0.3
MnO	n.d.	<0.1	n.d.	n.d.	0.5	n.d.	n.d.	0.3
FeO	n.d.	0.3	n.d.	n.d.	0.2	n.d.	0.7	0.6
Total	99.8	100.2	99.1	99.7	100.0	99.4	100.5	100.2
O	6	4	8	6	4	8	6	4
Mg	0.93	1.98	0.29	0.84	1.95	0.21	1.00	1.94
Al	0.27	n.d.	1.65	0.32	n.d.	1.66	0.13	n.d.
Si	1.84	1.00	2.12	1.84	1.02	2.16	1.93	1.02
Ca	0.92	n.d.	0.96	0.95	n.d.	0.98	0.92	n.d.
Ti	0.03	n.d.	n.d.	0.02	n.d.	n.d.	<0.01	n.d.
Cr	n.d.	0.01	n.d.	n.d.	0.01	n.d.	n.d.	0.01
Mn	n.d.	<0.01	n.d.	n.d.	0.01	n.d.	n.d.	0.01
Fe	n.d.	0.01	n.d.	n.d.	<0.01	n.d.	0.02	0.01
Cation	3.99	3.00	5.02	3.97	2.99	5.01	4.00	2.99

n.d. = not detected. Al-Ti-Di = Al-Ti rich diopside.

EXPERIMENTAL

Two thin sections of the Semarkona LL3.0 chondrite (from the collection of the Natural History Museum, London) were prepared for this study. AOAs in the sections were examined with a petrographic microscope and by X-ray microanalysis using the JEOL 5900LV scanning electron microscope (SEM), the LEO 1455 SEM with Oxford INCA energy dispersive X-ray spectroscopy (EDS) system, the Phillips XL-30 field emission (FE) SEM and the Cameca SX-50 electron microprobe at the Natural History Museum, London. The JEOL JSM-7000F FE SEM with Oxford INCA EDS system at Hokkaido University (Hokudai) was also used to quantitatively measure minerals compositions (Table 1).

The oxygen and magnesium isotopic microanalyses were performed by secondary ion mass spectrometry (SIMS) using the Hokudai Cameca IMS 1270 instrument. The analytical procedures are described in detail elsewhere (Yurimoto et al. 1998; Yurimoto and Wasson 2002). For the measurement of O isotopes, the primary ion beam consists of mass-filtered positive 20 keV Cs^+ ions. The typical spot size was ~2 μm. The primary beam current was 3 pA, adjusted to obtain a count rate of ~4 × 10^5 cps for negative ^{16}O ions. A normal incident electron gun was utilized for electrostatic charge compensation. Negative secondary ions corresponding to the ^{16}O tail, ^{16}O, ^{17}O, ^{16}OH, and ^{18}O were analyzed at a mass resolution of M/ΔM ~6000. A Russian spinel standard of known oxygen isotopic composition was used for calculation of the δO-values. The precision of each analysis was determined by secondary ion intensity statistics (Table 2). The overall analytical accuracy is estimated to be about ±5‰ (1σ) (Yurimoto et al. 1998).

For Mg isotopic analyses, the primary ion beam consists of mass-filtered negative 23 keV $^{16}O^-$ ions. The beam diameter was ~2 μm. Primary beam currents ranged from 30 to 60 pA and were adjusted for each run to obtain a count rate of ^{27}Al or ^{24}Mg not more than 4 × 10^5 cps. Positive secondary ions corresponding to ^{24}Mg, ^{25}Mg, ^{26}Mg, and ^{27}Al were analyzed at a mass resolution of M/ΔM ~4000. We determined the sensitivity factor to calculate the Al/Mg ratio of the sample using a Miyakejima anorthite standard. We also carefully rechecked the Al-Mg ratios of the analysis spots by FE-SEM-EDS after the ion probe measurements. The following terrestrial values were used for the Mg isotope corrections: $^{25}Mg/^{24}Mg = 0.12663$, $^{26}Mg/^{24}Mg = 0.13932$ (Catanzaro et al. 1966). Since the AOA minerals are fine-grained, we carefully evaluated overlapping of the primary beam among mineral phases by scanning electron microscope after SIMS analysis.

RESULTS

Petrography of Amoeboid Olivine Aggregates in Semarkona

We carried out a petrographic study on two thin sections of the Semarkona LL 3.0 chondrite. We observed no CAIs, but three AOAs were found in one of the two sections. This suggests that the distribution of AOAs in the ordinary chondrites is very heterogeneous. The AOAs are irregularly

Table 2. The oxygen isotopic compositions of minerals of Semarkona AOAs.

	Phase	$\delta^{17}O_{SMOW}$ (‰)	σ_m	$\delta^{18}O_{SMOW}$ (‰)	σ_m	$\Delta^{17}O$ (‰)	σ_m
AOA1							
a1	an50di50	–48.2	2.5	–48.9	1.7	–23.9	3.0
a2	olivine	–47.8	2.3	–48.9	1.7	–24.0	2.9
a3	an80di20	–48.8	2.4	–51.8	1.6	–26.4	2.9
a4	olivine	–49.6	2.2	–48.6	1.8	–22.8	2.8
AOA2							
a5	olivine	–46.6	2.2	–47.0	1.8	–22.7	2.9
a6	an80di20	–48.4	2.2	–50.6	1.9	–25.5	2.9
AOA3							
a8	olivine	–50.5	2.1	–45.6	1.6	–19.3	2.6
a9	diopside	–50.0	2.2	–48.1	1.7	–22.1	2.8

an50di50 = beam overlap of anorthite (50%) and diopside (50%). an80di20 = beam overlap of anorthite (80%) and diopside (20%). σ_m = standard deviation of the mean determined by statistical variation of secondary ion intensities corresponding to the precision for a series of measurements. $\Delta^{17}O = \delta^{18}O - 0.52 \times \delta^{17}O$.

shaped with fluffy textures and range from 50 to 500 µm across in size. The AOAs are composed of µm-sized Mg-olivine and Ca-Al-rich components consisting of Al-Ti-rich diopside and anorthite (Fig. 1). The Ca-Al-rich components exist interstitially between the olivine aggregates and are composed of µm-sized grains, and exhibit textures similar to those in primitive carbonaceous chondrites (Chizmadia et al. 2002; Itoh et al. 2002; Krot et al. 2004; Weisberg et al. 2004). Some AOAs in CR primitive carbonaceous chondrites (Aléon et al. 2002; Krot et al. 2004; Weisberg et al. 2004) contain a variety of refractory-rich nodules, such as spinel-rich inclusions. In contrast, AOAs in Semarkona do not have such refractory inclusions.

Iron-nickel metal in Semarkona AOAs occurs as very tiny grains (2–10 µm) surrounded by olivine. Iron-nickel metal is also reported in AOAs from primitive carbonaceous chondrites (e.g., Weisberg et al. 2004).

The AOAs in Semarkona contain no secondary alteration minerals such as nepheline and fayalitic olivine, which is consistent with the small degree of alteration and metamorphism in this meteorite (Grossman and Brearley 2005). The lack of secondary minerals in Semarkona AOAs is also consistent with observations of previous AOAs from primitive carbonaceous chondrites (e.g., Chizmadia et al. 2002; Itoh et al. 2002; Krot et al. 2004; Weisberg et al. 2004).

Table 1 shows chemical compositions of representative phases in the AOAs. Olivine in Semarkona AOAs contains detectable MnO (up to ~0.5 wt%) and Cr_2O_3 (up to 0.4 wt%) by FE-SEM-EDS (Table 1). There is no clear difference between these compositions from Semarkona AOAs compared to those from primitive carbonaceous chondrites (Krot et al. 2004).

Magnesium concentrations of anorthite in Semarkona AOAs are clearly higher than those in carbonaceous chondrites (e.g., Aléon et al. 2002; Itoh et al. 2002; Krot et al. 2004). However, comparisons are difficult because there are few anorthites large enough (>2 µm) to measure successfully by FE-SEM-EDS. Thus, it is not clear whether all anorthite in Semarkona AOAs is so Mg-rich.

AOA1

AOA1 is irregularly shaped and ~200 × ~200 µm in size (Figs. 1a and 1b). The AOA is composed of olivine (Fo_{99-100}) and Ca-Al-rich components consisting of Al-Ti-rich diopside (TiO_2 = ~2 wt%; Al_2O_3 = 4–8 wt%) and anorthite. The Ca-Al-rich components occur interstitially among olivine grains. The anorthite is partly attached to olivine, but almost enclosed by Al-Ti-rich diopside. Iron-nickel metal blebs occur among olivine grains.

AOA2

AOA2 is irregularly shaped and ~200 × ~500 µm in size (Figs. 1c and 1d). The AOA is composed of olivine (Fo_{99-100}) and Ca-Al-rich components consisting of Al-Ti-rich diopside (TiO_2 = ~1 wt%; Al_2O_3 = 8–10 wt%) and anorthite. The textural relationship of these minerals is the same as those of AOA1.

AOA3

AOA3 is irregularly shaped and 30 × 50 µm in size (Fig. 1e). The AOA is composed of olivine (Fo_{99-100}) and Al-Ti-rich diopside (TiO_2 = ~0.2 wt%; Al_2O_3 = 4–8 wt%). Anorthite is absent in this AOA. There are many holes adjacent to Al-Ti-rich diopside. The position of the holes corresponds to the sites where anorthite was present in AOA1 and AOA2. Thus, the anorthite may have been removed by polishing or corroded by alteration.

Oxygen Isotopic Distribution in Amoeboid Olivine Aggregates

The O-isotopic compositions of each phase are shown in Table 2 and plotted in Fig. 2. The O-isotopic compositions of

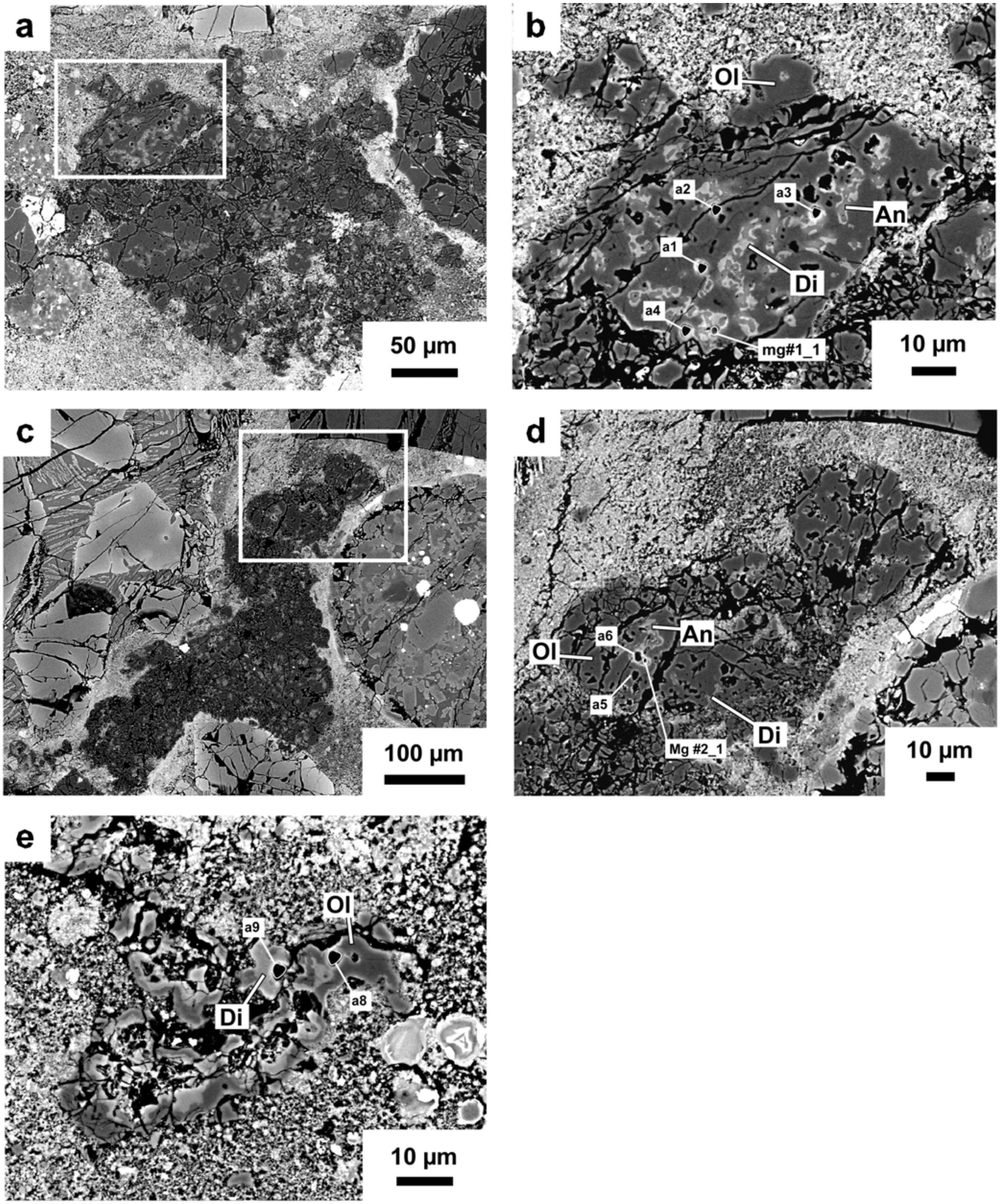

Fig. 1. Backscattered electron images of AOAs in Semarkona. The numbers in the figure indicate locations of the O- and Mg-isotopic analyses shown in Table 2 and Table 3, respectively. Di = Al-Ti-rich diopside; An = anorthite; Ol = olivine. a) Whole image of AOA1. The region surrounded by a square is shown in (b). b) Enlarged image of AOA1. c) Whole image of AOA2. The region surrounded by a square is shown in (d). d) Enlarged image of AOA2. e) Whole image of AOA3.

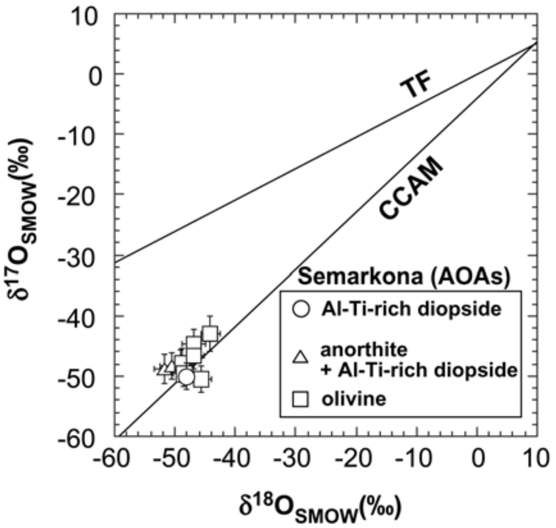

Fig. 2. Three O-isotope diagram of AOAs in Semarkona. All phases in AOAs from Semarkona are enriched in ^{16}O ($\delta^{17,18}$O= ~–50‰). “Anorthite + Al-Ti-rich diopside” indicates measurements overlapping both of these minerals. Errors are one statistical standard error (σ_{mean}).

individual anorthite and Al-Ti-rich diopside grains in AOA1 and AOA2 could not be measured because their grain size (<3 µm) was smaller than the primary beam size. However, the overlapping analyses including anorthite and Al-Ti-rich diopside of AOA1 and AOA2 show essentially the same O-isotopic compositions within error in spite of containing different proportions of these minerals. Therefore, anorthite and Al-Ti-rich diopside are likely to have the same O-isotopic composition. We conclude that all minerals (Al-Ti-rich diopside, anorthite, and olivine) comprising the AOAs are enriched in ^{16}O, with Δ^{17}O= –25 to –20‰.

Al-Mg Isotope Systematics of Amoeboid Olivine Aggregates

We measured Al-Mg isotopes of anorthite in AOA1 and AOA2. Since the size of the anorthite regions in AOA1 and AOA2 are less than 3 µm, only one Al-Mg isotopic measurement was successful for each of these AOAs (Table 3). Figure 3 shows the results presented as an ^{26}Al-^{26}Mg isochron diagram. Because the anorthite grains contain relatively high concentrations of Mg (Al/Mg ~4–8) (Tables 1 and 3), it is difficult to observe clear excesses of ^{26}Mg from one point. However, using the two analyses points and forcing the line to go through zero, we calculate an initial ^{26}Al/^{27}Al ratio of 5.6 ± 0.9 (2σ) × 10^{-5}, which is indistinguishable from the canonical value (5.0 × 10^{-5}) for CAIs.

DISCUSSION

The AOAs in the Semarkona have irregular shapes and fluffy textures, suggesting that they are aggregates similar to those reported from CV chondrites (Grossman and Steele 1976). The sizes of Semarkona AOAs are <500 µm, mostly similar to those of CO and CM chondrites (Rubin et al. 1985). The Ca-Al-rich components (anorthite and Al-Ti-rich diopside) in Semarkona AOAs exist interstitially between the olivine aggregates and are composed of µm-sized grains, with textures similar to those reported from primitive carbonaceous chondrites (e.g., Chizmadia et al. 2002; Itoh et al. 2002; Krot et al. 2004; Weisberg et al. 2004). The chemical compositions of olivine in AOAs from Semarkona are also similar to those of AOAs in primitive carbonaceous chondrites (Krot et al. 2004). Therefore, AOAs from Semarkona are both texturally and mineralogically similar to those from primitive carbonaceous chondrites (Krot et al. 2004), suggesting that the physical and chemical conditions of formation are equivalent for AOAs from ordinary chondrites and carbonaceous chondrites. Because the AOAs from carbonaceous chondrites are considered to be direct condensates from a cooling hot nebula gas (Aléon et al. 2002; Itoh et al. 2002; Krot et al. 2004; Weisberg et al. 2004), a condensation origin is plausible for the AOAs from the Semarkona as well.

Table 3. Mg isotope compositions of anorthite in AOAs.

	^{27}Al/^{24}Mg ± 2σ	$F_{Mg} \pm 2\sigma_m$ (‰)	δ^{26}Mg ± $2\sigma_m$ (‰)
AOA1			
mg#1_1	6.0 ± 1.7	3.4 ± 1.3	2.6 ± 2.4
AOA2			
mg#2_1	4.7 ± 0.6	2.0 ± 1.1	1.7 ± 2.0

F_{Mg} = intrinsic mass fractionation from terrestrial standard value.
δ^{26}Mg = deviation of the ^{26}Mg/^{24}Mg ratio from terrestrial value.
σ = standard deviation.
σ_m = standard deviation of the mean.

The oxygen isotopic composition of the solar nebular gas is variable in ^{16}O components with a constant ^{17}O/^{18}O ratio (Yurimoto et al. 2006). The ^{16}O-rich characteristics of AOAs from carbonaceous chondrites (Itoh et al. 2002; Krot et al. 2004) and from the ordinary chondrite in this study suggest that the AOA-forming nebular gas was enriched in ^{16}O corresponding to Δ^{17}O ~ –25 to –20‰. These characteristics strongly suggest that AOAs from ordinary chondrites and carbonaceous chondrites have the same origin.

AOAs in Semarkona appear to show excesses of ^{26}Mg corresponding to an initial ^{26}Al/^{27}Al ratio of 5.6 ± 0.9 (2σ) × 10^{-5}, which is essentially equivalent to those of AOAs in the Yamato-81020 CO3.0 chondrite (Itoh et al. 2002) and in Acfer 094 (Sugiura and Krot 2006). Thus, both the O and Al-Mg isotopic systematics suggest that AOAs from ordinary chondrites and carbonaceous chondrites formed at the same time and in the same space, in the earliest epoch of the solar system. Petrographic evidence also shows no difference between AOAs from Semarkona and those from primitive carbonaceous chondrites.

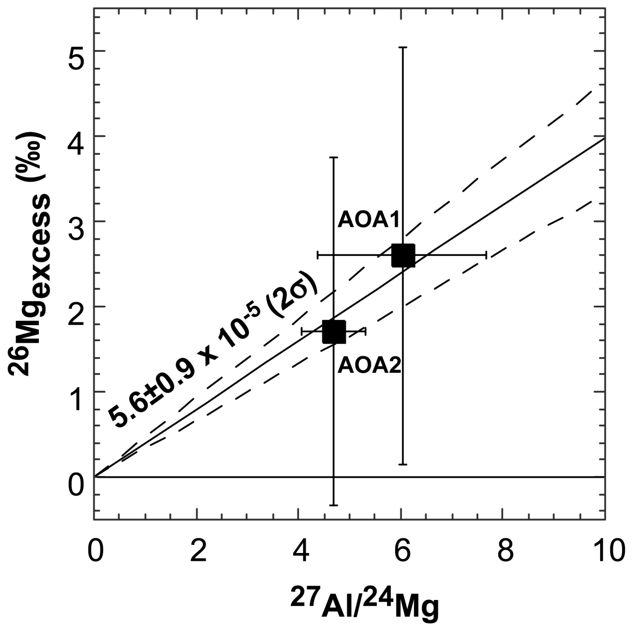

Fig. 3. Al-Mg evolution diagram of AOAs in Semarkona. Errors are 2σ and the dashed lines indicate the 2σ error for the isochron regression curve. The curve is calculated by the York method (York 1969).

McKeegan et al. (1998) suggest that FGIs in ordinary chondrites and carbonaceous chondrites have the same origin based on their O-isotopic characteristics, which show a ^{16}O-enrichment (Δ^{17}O ~−20‰) similar to that of the AOAs studied here. Moreover, Russell et al. (1996, 1998) suggest that FGIs in ordinary chondrites and carbonaceous chondrites formed in the same time and space in the early solar system because they both exhibit canonical values of initial ^{26}Al/^{27}Al. The AOAs from Semarkona studied here are also ^{16}O-enriched and seem to have canonical values of ^{26}Al/^{27}Al. Thus, we suggest that AOAs and FGIs from ordinary chondrites and carbonaceous chondrites formed co-genetically in the same region of the solar nebula.

CONCLUSIONS

Three amoeboid olivine aggregates (AOAs) were found in the Semarkona LL3.0 chondrite. The AOAs consist of aggregates of Mg-rich olivine grains with interstitial Al-Ti-rich diopside and anorthite. No secondary alteration minerals were observed, consistent with the low degree of alteration of Semarkona. The AOAs from Semarkona have similar textures and mineralogy to AOAs from pristine carbonaceous chondrites.

Oxygen isotopic compositions are homogeneously distributed among the constituent minerals of the AOAs and are enriched in ^{16}O (Δ^{17}O = ~−25 to −20‰). The ^{16}O-rich characteristics of AOAs from this ordinary chondrite are similar to AOAs from pristine carbonaceous chondrites.

AOAs in Semarkona show excesses of ^{26}Mg corresponding to an initial ^{26}Al/^{27}Al ratio of 5.6 ± 0.9 (2σ) × 10^{-5}. This is essentially equivalent to those of AOAs in pristine carbonaceous chondrites.

The petrographic and isotopic data for AOAs in Semarkona show no difference to those from primitive carbonaceous chondrites and probably formed in a similar restricted region of the solar nebula. With respect to the O isotopic distributions of AOAs from ordinary chondrites and carbonaceous chondrites, they were formed from the same reservoir in the early solar system. We conclude that ^{16}O-rich components were dominant in the AOA formation region of the solar nebula.

The ^{16}O-rich characteristics and the canonical values of initial ^{26}Al/^{27}Al ratios in fine-grained CAIs from ordinary chondrites and carbonaceous chondrites are also similar to those of AOAs from ordinary chondrites and carbonaceous chondrites. This suggests that AOAs and FGIs from ordinary chondrites and carbonaceous chondrites were formed co-genetically in the same region of the solar nebula and in the same epoch of the early solar system. These components were then distributed throughout the carbonaceous and ordinary chondrite accretion region.

Acknowledgments–This article is dedicated to Ernst Zinner in honor of his outstanding contributions to cosmochemistry, geochemistry, and nuclear astrophysics. We thank the EMMA staff at the Natural History Museum for technical assistance with the SEM and EPMA. We are grateful to associate editor Dr. C. Floss for improving our English and for her constructive comments and suggestions. Extensive reviews by Drs. M. K. Weisberg, J. Aléon, and Y. Lin significantly improved the quality of the article. This study is partly supported by the Royal Society/Daiwa Anglo-Japanese foundation fellowship and Monbu-Kagaku-Sho grants.

Editorial Handling—Dr. Christine Floss

REFERENCES

Aléon J., Krot A. N., and McKeegan K., D. 2002. Calcium-aluminum-rich inclusions and amoeboid olivine aggregates from the CR carbonaceous chondrites. *Meteoritics & Planetary Science* 37:1729–1755.

Amelin Y., Krot A. N., Hutcheon I. D., and Ulyanov A. A. 2002. Lead isotopic ages of chondrules and calcium-aluminum-rich inclusions. *Science* 297:1678–1683.

Catanzaro E. J., Murphy T. J., Garner E. L., and Shields W. R. 1966. Absolute isotopic abundance ratios and atomic weights of magnesium. *Journal of Research of the National Bureau of Standards* 70a:453–458.

Chizmadia L. J., Rubin A., and Wasson J. T. 2002. Mineralogy and petrology of amoeboid olivine inclusions in CO3 chondrites: Relationship to parent-body aqueous alteration. *Meteoritics & Planetary Science* 37:1781–1796.

Fagan T. J., Krot A. N., Keil K., and Yurimoto H. 2004. Oxygen isotopic compositions of amoeboid olivine aggregates in the reduced CV3 chondrites Efremovka, Vigarano, and Leoville. *Geochimica et Cosmochimica Acta* 68:2591–2611.

Grossman J. N. and Brearley A. J. 2005. The onset of metamorphism in ordinary and carbonaceous chondrites. *Meteoritics & Planetary Science* 40:87–122.

Grossman L. and Steele I. M. 1976. Amoeboid olivine aggregates in the Allende meteorite. *Geochimica et Cosmochimica Acta* 40: 149–155.

Hiyagon H. and Hashimoto A. 1999. ^{16}O excesses in olivine inclusions in Yamato-86009 and Murchison chondrites and their relation to CAIs. *Science* 283:828–831.

Huss G. R., MacPherson G. J., Wasserburg G. J., Russell S. S., and Srinivasan G. 2001. Aluminum-26 in calcium-aluminum-rich inclusions and chondrules from unequilibrated ordinary chondrites. *Meteoritics & Planetary Science* 36:975–997.

Imai H. and Yurimoto H. 2003. Oxygen isotopic distribution in an amoeboid olivine aggregate from the Allende CV chondrite: Primary and secondary processes. *Geochimica et Cosmochimica Acta* 67:765–772.

Itoh S., Rubin A. E., Kojima H., Wasson J. T., and Yurimoto H. 2002. Amoeboid olivine aggregates and AOA-bearing chondrule from Y-81020 CO3.0 chondrite: Distributions of oxygen and magnesium isotopes (abstract #1490). 33rd Lunar and Planetary Science Conference. CD-ROM.

Komatsu M., Krot A. N., Petaev M. I., Ulyanov A. A., Keil K., and Miyamoto M. 2001. Mineralogy and petrography of amoeboid olivine aggregates from the reduced CV3 chondrites Efremovka, Leoville, and Vigarano: Products of nebular condensation, accretion and annealing. *Meteoritics & Planetary Science* 36: 629–641.

Komatsu M., Miyamoto M., Mikouchi T., Kogure T., Krot A. N., and Keil K. 2003. Examination of high-temperature annealing of amoeboid olivine aggregates: Heating experiments of forsterite and anorthite mixtures. (abstract #1521). 34th Lunar and Planetary Science Conference. CD-ROM.

Komatsu M., Miyamoto M., Mikouchi T., Krot A. N., and Keil K. 2002. Heating experiments of olivine-anorthite mixtures: Clues to understanding the textural relationships among olivine, Al-diopside, and anorthite in amoeboid olivine aggregates (abstract #1258). 33rd Lunar and Planetary Science Conference. CD-ROM.

Krot A. N., Fagan T. J., Nagashima K., Petaev M. I., and Yurimoto H. 2005. Origin of low-Ca pyroxene in amoeboid olivine aggregates: Evidence from oxygen isotopic compositions. *Geochimica et Cosmochimica Acta* 69:1873–1881.

Krot A. N., Meibom A., Weisberg M. K., and Keil K. 2002. The CR chondrite clan: Implications for early solar system process. *Meteoritics & Planetary Science* 37:1451–1490.

Krot A. N., Petaev M. I., Russell S. S., Itoh S., Fagan T. J., Yurimoto H., Chizmadia L. J., Weisberg M. K., Komatsu M., Ulyanov A. A., and Keil K. 2004. Amoeboid olivine aggregates and related objects in carbonaceous chondrites: Records of nebular and asteroid processes. *Chemie der Erde* 64:185–239.

Lin Y. and Kimura M. 2003. Ca-Al-rich inclusions from the Ningqiang meteorite: Continuous assemblages of nebular condensates and genetic link to type B inclusions. *Geochimica et Cosmochimica Acta* 67:2251–2267.

McKeegan K. D., Leshin L. A., Russell S. S., and MacPherson G. J. 1998. Oxygen isotopic abundances in calcium-aluminum-rich inclusions from ordinary chondrites: Implications for nebular heterogeneity. *Science* 280:414–418.

Rubin A. E., James J. A., Keck B. D., Weeks K. S., Sears D. W. G., and Jarosewich E. 1985. The Colony meteorite and variations in CO3 chondrite properties. *Meteoritics* 20:175–196.

Russell S. S., Huss G. R., Fahey A. J., Greenwood R. C., Hutchison R., and Wasserburg G. J. 1998. An isotopic and petrologic study of calcium-aluminum-rich inclusions from CO3 meteorites. *Geochimica et Cosmochimica Acta* 62:689–714.

Russell S. S., Srinivasan G., Huss G. R., Wasserburg G. J., and MacPherson G. J. 1996. Evidence for widespread ^{26}Al in the solar nebula and constraints for nebula time scales. *Science* 273:757–762.

Sugiura N. and Krot A. N. 2006. Al-Mg dating of Ca-Al-rich inclusions in Acfer 094 chondrite (abstract # 1264). 37th Lunar and Planetary Science Conference. CD-ROM.

Weisberg M. K., Connolly J. H. C., and Ebel D. S. 2004. Petrology and origin of amoeboid olivine aggregates in CR chondrites. *Meteoritics & Planetary Science* 39:1741–1753.

York D. 1969. Least square fitting of straight line with correlated errors. *Earth and Planetary Science Letters* 5:320–325.

Yurimoto H., Ito M., and Nagasawa H. 1998. Oxygen isotope exchange between refractory inclusion in Allende and solar nebula gas. *Science* 282:1874–1877.

Yurimoto H., Kuramoto K., Krot A. N., Scott E. R. D., Cuzzi J. N., Thiemens M. H., and Lyon J. R. 2007. Origin and evolution of oxygen isotopic compositions of the solar system. In *Protostars and planets V.* Tucson, Arizona: The University of Arizona Press. 1024 p.

Yurimoto H. and Wasson J. T. 2002. Extremely rapid cooling of a carbonaceous-chondrite chondrule containing very ^{16}O-rich olivine and a ^{26}Mg excess. *Geochimica et Cosmochimica Acta* 66:4355–4363.