

EXAMINATION OF HIGH TEMPERATURE ANNEALING OF AMOEBOID OLIVINE AGGREGATES: HEATING EXPERIMENTS OF FORSTERITE AND ANORTHITE MIXTURES. M. Komatsu¹, M. Miyamoto¹, T. Mikouchi¹, T. Kogure¹, A. N. Krot², K. Keil², ¹Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan (mutsumi@space.eps.s.u-tokyo.ac.jp), ²Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawaii at Manoa, USA.

Introduction: Amoeboid Olivine Aggregates (AOAs) are irregularly-shaped, 100 μm to 5 mm in size, fine-grained objects that constitute a few vol% of meteorites in most carbonaceous chondrite groups. Previous studies concluded that AOAs are aggregates of solar nebula condensates which continued to react with the solar nebula vapor to the temperature to form phyllosilicates. However, these studies are largely from the AOAs from the oxidized CV3 chondrite Allende which experienced secondary alteration. Based on the mineralogical study of the reduced CV3 chondrites, we have recently suggested that AOAs experienced high temperature annealing without substantial melting and were subsequently isolated from high temperature nebular gas, possibly by physical removal, e.g. by X-wind [1]. Annealing and a small degree of melting of AOAs is supported by olivine triple junctions, “doughnut-shaped” forsterite, the presence of rounded FeNi-metal nodules in some AOAs and relatively compact textures. In order to examine the possibility of high-temperature annealing of AOAs, isothermal and cooling experiments of constituent minerals of AOAs have been performed.

Experiments: Pellets of powdered mixtures of synthetic forsterite (Fo_{100}) + terrestrial anorthite (An_{96}), terrestrial olivine (Fo_{91}) + anorthite, olivine + melilite were placed in Pt-wires and heated to temperatures to cause incomplete melting under the oxygen fugacity of the IW buffer. Pellets were heated at 1288 to 1450°C for 1-3 hours in isothermal experiments, and at 1288 to 1450°C for 1 hour and then cooled at rates between 10-500°C/h in the cooling experiments. The charges were made into thin sections for microscopy and measurements of the chemical compositions using JEOL 8900L and JEOL JSM 733II microprobes. Crystallographic information was obtained using a NORAN phase ID EBSP system attached to Hitachi S-4500 SEM.

Results:

Textures: Isothermal experiments of olivine+anorthite heated under the oxygen fugacity of IW showed that a high-Ca pyroxene-like phase was produced from the reaction of olivine and anorthite when they are heated at 1288-1320°C (Fig. 1a). The observed overgrowth of a high-Ca pyroxene-like phase around olivine is texturally similar to overgrowths of Al-diopside around forsterite in AOAs (Fig. 3). In contrast, no high-Ca pyroxene-like phase was found in olivine+anorthite charges after cooling experiments; glassy mesostasis was found instead (Fig. 1b). No high-Ca pyroxene-like phase overgrowths were found in the forsterite+anorthite charges from isothermal experiments; individual grains of a

high-Ca pyroxene phase were observed instead (Fig. 1c). In the cooling experiments of forsterite and anorthite mixtures, a high-Ca pyroxene-like phase was observed in the charges heated at >1308°C, which also resulted in incomplete melting of forsterite and anorthite (Fig. 1d). It appears that the slowly cooled charges have slightly less of the high-Ca pyroxene-like phase than the rapidly cooled charges. It also seems that the grain size of the high-Ca pyroxene-like phase becomes larger in the slowly cooled charges than in the rapidly cooled charges in which lath-shaped anorthite and high-Ca pyroxene are common.

Chemical compositions: The high-Ca pyroxene-like phase in olivine+anorthite and forsterite+anorthite of isothermal experiments has lower SiO_2 and CaO contents than high-Ca pyroxene of AOAs. The compositions of the high-Ca pyroxene-like phase in the forsterite+anorthite charges of cooling experiments overlap with those of Al-diopside in AOAs.

Heating experiments of olivine+melilite charges resulted in CaO enrichment of olivine and formation of glass inclusions in olivine. The absence of both Ca-rich olivine and glass inclusions in AOAs suggests that this reaction did not take place in the AOA-forming process.

Electron Back Scattering Diffraction pattern measurements (EBSD): The EBSD technique can provide crystallographic information from micron-sized regions. Clear Kikuchi bands appear in olivine and anorthite from all experiments. Although no Kikuchi bands were observed in the high-Ca pyroxene-like phases in the charges from isothermal experiments, clear Kikuchi bands were observed in the high-Ca pyroxene-like phase in the charges from cooling experiments, indicating they are crystalline (Fig. 2).

Discussion:

The most characteristic texture of AOAs is that the anorthite (sometimes associated with spinel and Al,Ti-diopside) core is rimmed by Al-diopside which overgrows olivine (Fig. 3). If AOAs originate as condensate assemblages, as proposed by [2], their textures can not be explained by a simple equilibrium condensation model. On the basis of mineralogical examinations, the mineralogical sequence observed in AOAs is from core to rim: spinel, accessory perovskite and melilite, Al, Ti-rich diopside \rightarrow anorthite \rightarrow Al-diopside \rightarrow forsterite. The observation that anorthite is rimmed by Al-diopside, which in turn is rimmed by forsterite, is in conflict with equilibrium condensation calculations [e.g., 3], which predict condensation of forsterite prior to anorthite. If anorthite in AOAs is not a condensation product, but a

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secondary mineral that replaced primary melilite, as suggested by [4], it also runs counter to the observation that spinel is rimmed by anorthite. The mineralogy of AOAs implies that spinel formed before melilite, and this is inconsistent with equilibrium condensation calculations that indicate that melilite should condense prior to spinel from a gas of solar composition. This inconsistency with the equilibrium condensation calculations is also observed in fine-grained spinel-rich CAIs [5].

In addition, the mineral chemistry is also at odds with the condensation origin of AOAs. The trend of bulk compositions of AOAs on the $\text{Ca}_2\text{SiO}_4\text{-Mg}_2\text{SiO}_4\text{-Ca}_2\text{SiO}_4$ plane does not seem to coincide with the composition of the trend of bulk condensed solids formed by equilibrium condensation as calculated by [6]. On the other hand, bulk compositions plot on the mixing line of olivine and anorthite, indicating their petrogenetic link to forsterite and anorthite.

Comparative studies of heating experiments and electron back scattering diffraction pattern with mineralogy of AOAs suggest that Al-diopside in AOAs can be produced by a small degree of melting of forsterite and anorthite. Formation of Al-diopside from forsterite and anorthite is consistent with the annealing textures observed in AOAs, and it may account for the inconsistency of the observed mineralogy of AOAs with the equilibrium condensation calculations, different occurrences of two types of diopside (Al,Ti-rich diopside and Al-diopside), and variable Al_2O_3 contents of Al-diopside.

References: [1] Komatsu M. et al. (2001) *MAPS*, 36, 629-641. [2] Grossman L. and Steele I. M. (1976) *GCA*, 40, 149-155. [3] Petaev M. I. and Wood J. A. (1998) *MAPS*, 33, 1123-1137. [4] Hashimoto A. and Grossman L. (1987) *GCA* 51, 1685-1704. [5] MacPherson G. J. et al. (2002) *LPS XXXIII*, #1526. [6] Grossman L. (1972) *GCA* 36, 597-619.

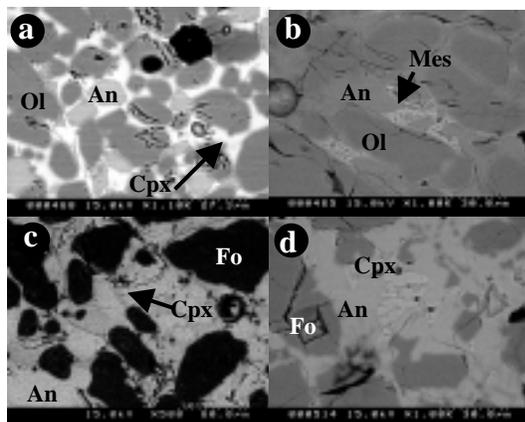


Fig.1. BSE images of experimental charges. (a) olivine:anorthite=1:1, heated at 1288°C for 3 hours and air quenched. (b) olivine:anorthite=1:1, heated at 1288°C and cooled at 100°C/h. (c) forsterite:anorthite=1:1, heated at 1313°C and air quenched. (d) forsterite:anorthite=1:1 and cooled at 100°C/h. Cpx:high-Ca pyroxene-like phases.

Table 1. Chemical compositions of high-Ca pyroxene phases in AOAs and experimental charges.

wt%	AOA		Infernal			Cooling
	Al-di	Al,Ti-di	ofan	ofan	ofan	ofan
SiO_2	48-53	36-38	40-45	43-48	36-41	43-54
Al_2O_3	0-17	20-30	10-20	15-25	2-14	7-23
TiO_2	0-3	7-10	0	0	0	0
FeO	0-1	0-1	6-7	0	0-5	0
MgO	14-16	9-10	11-30	13-14	10-26	11-24
CaO	17-25	25	5-16	15-17	29-40	14-20

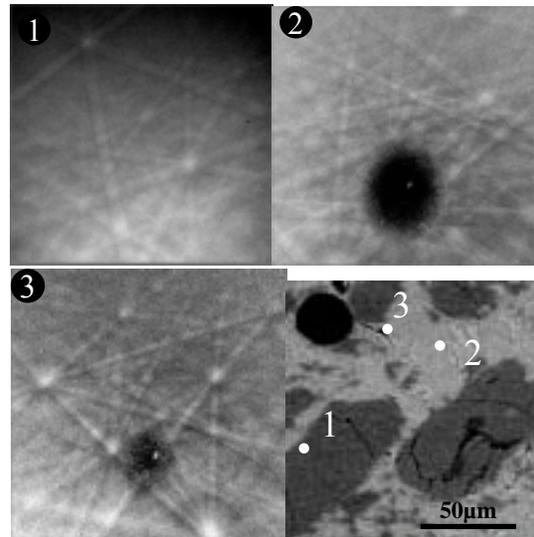


Fig.2. Electron backscattered pattern and BSE image of the charge from cooling experiments. (fo:an=1:1, heated at 1320°C and cooled at 300°C/h) The black stain in (2) and (3) is caused by trouble in charge. (1) forsterite (2) high-Ca pyroxene-like phase (3) anorthite.

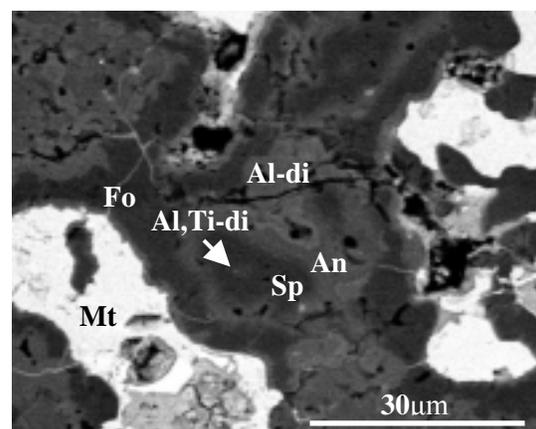


Fig.3. BSE image of AOA from Y81020. The cores consist of minor Al,Ti-diopside (Al,Ti-di) and spinel (Sp); the cores are surrounded by anorthite (An), Al-diopside (Al-di) and forsterite (Fo). Mt:Fe,Ni-metal.