Amoeboid Olivine Aggregates in CR Chondrites. M. K. Weisberg[1,2], H. C. Connolly Jr.[1,2,3] and D. S. Ebel[2]. [1]Dept. Physical Sciences, Kingsborough College of the City University of New York, 2001 Oriental Blvd., Brooklyn, NY 11235, [2]Dept. Earth and Planetary Sciences, American Museum Natural History, NY, NY 10024, [3]Dept. Geological Sci., Rutgers University, Pistcataway, NJ 08854.

Introduction: Amoeboid Olivine Aggregates (AOAs) are irregular-shaped, fine-grained aggregates of olivine and refractory minerals and are important components of C chondrites. The AOAs in CV chondrites have been interpreted to be primary nebular condensates [1] and therefore, can provide constraints on models for nebular condensation. AOAs are intermediate in composition, and may be a link, between the older, refractory calcium-aluminum-rich inclusions (CAIs) and the younger, moderately volatile ferromagnesian chondrules [2, 3], and can provide information on the astrophysical settings of CAI and chondrule formation [e.g., 4]. Additionally, AOAs may be among the precursor solid materials that accreted and were melted to form chondrules [5]. In the highly primitive CR chondrites, AOAs are rare but intriguing components. Some of the AOAs in CRs contain FeNi metal [6] and Mn-enriched forsterite, in which Fe and Mn are decoupled with Fe/Mn ratios less than one [7,8]. Similar Mn-enriched olivine has been described in interplanetary dust particles (IDPs) and chondrite matrices [9]. Herein we present the preliminary results of our re-examination of the AOAs in the CR chondrites, which include detailed petrologic analyses and a SEM-cathodoluminescence study. Our goals are to complete a comprehensive petrologic study of the AOAs in CR chondrites, understand their petrogenesis and their relationship to other chondritic components in the CRs and to AOAs and chondritic components in other chondrite groups.

Results: We are studying 19 AOAs from 5 CR chondrites. *Petrography.* The AOAs in the CR chondrites are irregular-shaped aggregates of olivine and, in many cases, the olivine surrounds nodules of refractory-rich phases that include Ti-, Al-rich Ca-pyroxene, anorthite and in some cases submicron-size spinel and perovskite (Fig. 1, 2). In some AOAs, Ca-pyroxene appears to be an overgrowth on the olivine. Some AOAs contain tiny blebs of FeNi metal. The AOAs lack the spherical (melt-droplet) form and interstitial glassy mesostasis that is characteristic of many chondrules. Texturally, the AOAs in the CR chondrites are very similar to AOA's in the Allende CV chondrite described by Grossman and Steele [1]. The AOAs in the CRs range in size from about 70 µm to 1.2 mm, whereas in CV chondrites they are larger, up to 5mm in size. The larger AOAs in the CRs appear to be composed of numerous nodules consisting of refractory phases and each nodule is surrounded by fine olivine (Fig. 1). Some of the smaller AOAs appear to be fragments from larger aggregates and others may be isolated nodules that never accreted into larger aggregates. Some of the smaller aggregates are located in dark inclusions (DIs) within the CR chondrites and their small sizes (<100µm) are compatible with the other fine scale objects found in the DIs. Individual mineral grains in the AOAs are generally very fine ranging from <1 to 7 µm in size. Metal blebs range in size from ~0.2 to 7 µm.

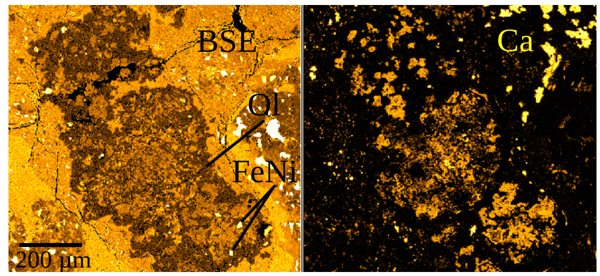

Figure 1. Backscattered Electron (BSE) image of a large AOA from the Renazzo CR chondrite showing the distribution of olivine (dark) and FeNi metal (white) and a Ca x-ray map showing the distribution of Ca-, Al-rich phases, which appear to be nodules surrounded by olivine.

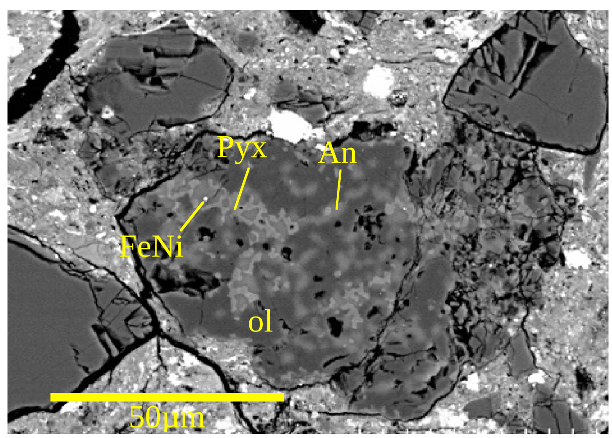

Figure 2. BSE image of an AOA in the EET96259 CR chondrite showing forsterite grains (dark gray) surrounding an assemblage of anorthite (medium gray), Ca-pyx (light gray) and FeNi metal (white).

Mineral Compositions. The olivine in the AOAs is near-pure forsterite. Some AOA's in CR chondrites contain two different types of forsterite. One type has blue cathodoluminescence (CL) and the other red. The red olivine is less common and it appears to occur on the edges of the blue. The CL characteristics of olivine are a result of its low Fe content and trace element composition. Compositionally, the blue forsterite is minor element-poor having <0.05 MnO and <0.15 Cr_2O_3. The red olivine has up to 0.5 Cr_2O_3 and up to

1.0% MnO. In some cases MnO content of the red olivine equals or exceeds FeO. We are currently applying a Field Emission (FE) SEM with a CL detector to study the fine scale distribution of trace elements in the olivine in the AOAs. The red forsterites have minor element compositions that are similar to LIME (Low-Iron Mn-Enriched) olivine that has been described in interplanetary dust particles (IDP's), as well as isolated Mn-rich forsterite grains in the opaque matrices of the Murchison (CM) and Semarkona (LL3) chondrites [9].

Ca pyroxene contains (in wt. %) up to 1.6 TiO_2 and 6 Al_2O_3, and is similar in composition to the pyroxene in AOAs in the Allende CV chondrite [1]. REE's were measured in the Ca-pyroxene from the AOA in Renazzo shown in Fig. 1. Its pattern is essentially flat, but exhibits a slight enrichment in the heavy REE's. La is ~15-25x chondritic and Lu is 28-40x chondritic, and there is a small negative Eu anomaly especially in the pattern from one pyroxene [8]. Anorthite in the AOAs is pure with Na and K below microprobe detection limits (~0.05). Spinel and perovskite, when present, are generally too fine (less than ~2µm) to analyze by EPMA. Metal in the AOAs is compositionally similar to metal in chondrules and matrix in the CR chondrites. It has 5 to 7.2 wt.% Ni and has a solar Ni:Co ratio.

Discussion: The AOAs in CV chondrites have been interpreted to be aggregates of solid nebular condensates [1] and the AOAs in the CR chondrites have similar characteristics that suggest they too did not crystallize from a liquid. They have highly irregular shapes that differ from the spherical to semi-spherical molten chondrules. They do not appear to contain glassy mesostasis like that found in molten chondrules. The roughly flat REE pattern of the pyroxene is consistent with a condensation origin.

We suggest that the AOAs in CR chondrites had a complex petrogenetic history that included nebular gas-solid condensation, reaction of mineral phases with the nebular gas, followed by sintering and coarsening of the assemblage. Spinel and perovskite were the first condensing phases (at ~1600K), followed by melilite and metal. Melilite continued to react with the nebular gas to form anorthite and Ca-pyroxene. Olivine condenses at about 1450K and is the last condensing phase and accretes onto the earlier condensed assemblage. The aggregates remained hot long enough for their grains to coarsen. Another possibility is that the Ca-pyroxene in some AOAs formed by small degrees of melting of anorthite and olivine [10].

It is difficult to imagine a process that could produce Mn-rich forsterite by crystallization from a melt. Klöck et al. [9] offered a condensation scenario for the "LIME" olivine in IDPs and the Mn-rich forsterite in the AOA's may be explained in a similar manner. Since the Mn-rich forsterite surrounds the pure forsterite, when both occur within an AOA, formation of Mn-rich forsterite later than the pure forsterite is a requirement of our model for their origin. The pure forsterite appears at ~1450K (at 10^{-3} atm), according to classic thermodynamic modeling of the order of condensing phases from a solar gas [11]. The pure forsterite may have nucleated or aggregated onto the surface of earlier-formed (1600-1400K) refractory nodules. These aggregates later equilibrated with the nebula down to about 1100K, the temperature at which Mn_2SiO_4, the tephroite molecule, forms in solid solution with forsterite. Fayalitic olivine forms at much lower temperatures (~500K) via reaction of Fe-metal with forsteritic olivine. The high Mn/Fe ratio of the Mn-rich forsterite suggests the forsterite did not equilibrate with Fe-metal at lower nebular temperatures. The Mn-rich forsterite rims on some AOAs may represent olivine grains that aggregated onto the outer surface of AOAs or are the result of partial equilibration of the outer portions of existing aggregates with the surrounding nebular gas.

Reduction of iron from olivine could also yield olivine with a high Mn/Fe ratio. In this model, the Mn-rich forsterite may have lost Fe through reduction reactions between the olivine and the surrounding nebular gas or the surrounding matrix on the parent body. Lee et al. [12] found that some metal in the Renazzo CR chondrite is zoned with Ni and Co decreasing and Fe increasing at the edges of the grains. They interpreted the low Ni and Co to be the result of dilution by Fe, produced by FeO reduction during metamorphism on the CR parent body. The occurrence of Mn-rich forsterite on the edges of the AOAs is consistent with this interpretation. However, the presence of Mn-rich forsterite in the least equilibrated meteorites (including Murchison and Semarkona) and in IDPs [9] is inconsistent with formation of Mn-rich forsterite by parent body metamorphism and favors formation of the Mn-rich olivine by solid-gas reactions in the nebula.

References: [1] Grossman L. and Steele I. M. (1976) *GCA, 40,* 149-155. [2] Komatsu et al. (2001) *MAPS, 36*, 629. [3] Krot et al. (2001) *MAPS, 36*, 611. [4] Krot et al. (2002) *Science, 295*, 1051-1054. [5] Yurimoto H. and Wasson J. T. (2002) *GCA, 66,* 4355-4363. [6] Weisberg et al. (2002) *MAPS,X*, xx. [7] Weisberg M. K. et al. (1997) *GCA, 57,* 1567-1586. [8] Weisberg M. K. et al. (2003) *MAPS*, submitted. [9] Klöck et al., *Nature, 339,* 126-128. [10] Komatsu M. et al. (2002) *LPSC, XXXIII*, #1258. [11] Grossman (1972) *GCA, 49,* 2433-2444 [12] Lee et al. (1991) *GCA, 56,* 2521-2533.