AGGLOMERATIC OLIVINE (AO) CHONDRULES IN ORDINARY CHONDRITES.

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Agglomeratic olivine (AO) chondrules in ordinary chondrites are olivine-rich aggregates of nebular materials which contain olivine and pyroxene crystals, chondrule fragments and refractory inclusions. These chondrules have been heated to a lesser degree or for a shorter time than that of other chondrules. Thus, they provide information about materials that were present in the nebula, prior to and during chondrule formation. AO chondrules have refractory element (Si/Al, Mg/Al) ratios similar to many of the common porphyritic olivine-pyroxene (POP) as well as some barred olivine (BO) chondrules. They appear to represent POP and/or BO chondrule precursor materials that were not heated to liquidus or subliquidus temperatures.

Introduction. Unequilibrated ordinary chondrites (UOC) are mixtures of chondrules, mineral and lithic fragments, and matrix. Chondrules are believed to have formed from molten or partially molten droplets in the early solar nebula, whereas matrix is a mechanical mixture of nebular particles which may include primitive nebular condensates and are not derived from broken chondrules. In addition to matrix, other agglomerational objects in UOCs include dark inclusions, chondrule rims and AO chondrules. AO chondrules were defined by Van Schmus [1] as "a type of chondrule that has internal textures that suggest that they are mechanical mixtures of individual small crystal fragments of silicates, oxides, sulfides, and metal rather than a crystalline assemblage that is the result of crystallization from a melt". Dodd [2] called these chondrules "granular" and Dodd and Van Schmus [3] called them "dark-zoned chondrules". We have studied AO chondrules because they may represent materials that were available in the nebula prior to and during chondrule formation. This is a detailed SEM-petrographic study of AO chondrules in five of the least equilibrated ordinary chondrites: Krymka (LL3.0), Semarkona (LL3.0), Bishunpur (L3.1), Chainpur (LL3.4) and Sharps (H3.4). Our goals are (1) to petrologically characterize these chondrules and compare them to other chondrule types, (2) compare AO chondrules with opaque matrix and chondrule rims, (3) determine if they contain materials that may be precursors of other chondrule types.

Results. A total of 42 AO chondrules were studied. They were found in all the UOCs studied, and make up to ~5 vol.% of the chondrules. **Textures.** AO chondrules are fine-grained (>50% of grains are 2-5μm), olivine-rich (>50% of grains are olivine) objects that are generally similar in size to coexisting chondrules. Their shapes range from irregular to round; many round ones have angular or irregular-shaped silicate-rich cores surrounded by FeS-rich rims that fill irregularities on the surface and render the objects spherical. AO chondrules appear dark to opaque in thin section due to their fine grain size and a high FeS abundance, in some cases. Many contain one or more large (up to 600μm) euhedral to subhedral transparent olivine crystals. The fine-grained olivine ranges from euhedral to anhedral in shape and some occur as blades, similar to some of the olivine in chondrule rims and in the matrix. **Modes.** AO chondrules contain 57-94 vol.% olivine, up to 20% pyroxene, 6-20% plagioclase (glassy to microcrystalline), up to 1% chromite, 1% metal and 5% sulfide. **Mineral compositions.** The fine-grained olivine is Fe-rich and ranges from Fa_{28-51}. Olivine in chondrule rims is similar in composition. Much of the fine-grained olivine (blades and anhedral crystals) in the matrix, however, is more Fe-rich (>Fa_{70}). In some AO chondrules, olivines near the chondrule periphery are finer grained and slightly more Fe-rich. Larger olivines are much more magnesian (Fa_{2-6}), but are rimmed (up to 5μm) by overgrowths of olivine similar in composition to the surrounding fine-grained olivine. These large Mg-rich olivines represent fragments from an earlier generation of chondrule formation. Compositional traverses across large olivine crystals show steep increases in Fe/Mg and Mn at the overgrowth rim, and include sharp spikes of Cr, suggesting the presence of chromite at the core-rim interface. These zoning profiles are reminiscent of those in Allende chondrules [4,5,6] and reflect rapid, disequilibrium growth of olivine. Low-Ca Pyroxene is generally magnesian (Fs_{6-10}) and is in gross disequilibrium with the surrounding fine-grained olivine. The plag mesostasis has ~63 wt.% SiO_2, 17 Al_2O_3, 5 FeO, 2 MgO, 4 CaO, 9 Na_2O, and <0.1 K_2O; some plag has up to 1.4 K_2O. The K_2O-rich ones occur near the periphery of the chondrule, in some cases. Chromites occur in clusters of euhedral crystals and are essentially $FeCr_2O_4$. Other minerals include troilite, plus high- and low-Ni, Fe-metal. **Other components.** AO chondrules contain a variety of other components that may be nebular, attesting to the relatively low degree of melting that AO chondrules experienced. These include poikilitic pyroxene inclusions, BO microchondrules, fluffy particles, and refractory inclusions. Poikilitic pyroxene inclusions are irregular-shaped objects consisting of Mg-rich pyroxene (~Fs_2) that contain inclusions of Mg-rich olivine (~Fa_6). These inclusions also occur as isolated objects in the chondrite matrix, and within matrix lumps and chondrule rims. Some AO chondrules contains BO microchondrules (~20µm). Some have portions that are texturally and mineralogically similar to opaque matrix, consisting of fluffy porous masses of submicrometer-sized olivine. One AO chondrule has three spinel-rich inclusions within its FeS-rich rim; these inclusions consist of a core of Fe-Al spinel surrounded by feldspar, and rimmed by Ca-pyroxene. Texturally, they are spinel-pyroxene refractory inclusions, but their Fe-rich spinel suggests that they have reequilibrated with a more oxidizing nebular environment. **Bulk compositions.** AO chondrules have compositions (determined by defocused beam electron probe technique) that are similar to matrix and chondrule rims, having higher Fe and S than most chondrules. Their refractory lithophile ratios, however, (Si/Al, Mg/Al) are similar to those of many of the common POP chondrules and some BO chondrules. Many non-porphyritic (radial pyroxene and cryptocrystalline) chondrules have higher Si/Al ratios.

Discussion: AO chondrules are agglomerations of nebular materials that have been heated to a lesser degree or for a shorter time than other chondrules. Whatever the transient heat source responsible for heating chondrule precursors, AO chondrules must have been far enough from the source to receive relatively little energy. Texturally and compositionally AO chondrules resemble silicate rims on chondrules. AO chondrules and chondrule rims have similar olivine compositions, whereas much of the olivine in opaque matrix is more Fe-rich, suggesting that AO chondrules and matrix differ in their oxidation histories. AO chondrules may have formed by heating of clumps of opaque matrix material to subsolidus and subliquidus temperatures, accompained by reduction of Fe [7]. However, we suggest that the olivine compositions of AO chondrules are primary and formed under different conditions than matrix olivine. Similarities in refractory lithophile abundances between AO and the common POP and some barred olivine chondrules suggest that AO chondrules represent chondrule precursors that were not heated to high enough temperatures to form POP or BO chondrules. If AO chondrules consist of chondrule precursors, the presence of chondrule fragments, BO microchondrules, and refractory inclusions implies that some chondrules formed from material that have had considerable prehistory. Formation of AO chondrules can be summarized in a three stage model. Stage 1: Formation of free-floating or loose agglomerates of fine olivine crystals in the nebula. These crystals may have formed by the reaction of condensed forsterite or enstatite with Fe^0, at lower nebular temperatures. Alternatively, these olivines may have formed at the higher temperatures, in a nebular region with an enhanced oxygen fugacity [6]. Stage 2: Agglomeration of the fine olivines with other nebular components that include microchondrules, poikilitic pyroxene and refractory inclusions. Stage 3: A transient heat source sintered these agglomerations, resulting in small degrees of melting and solid state recrystallization. More intense heating of these agglomerations to liquidus or subliquidus temperatures may have resulted in the formation of POP or BO chondrules. Most of the FeS may have been expelled from the chondrules at their time of formation. Non-porphyritic chondrules (e.g. RP, C) require a somewhat different set of precursors.

References: **[1]** Van Schmus, W. R. (1969) Earth Sci. Rev. 5, 145-184. **[2]** Dodd, R. T. (1971) Contr. Mineral. Petrol. 31, 201-227. **[3]** Dodd, R. T. and Van Schmus, W. R. (1971) Chem. Erde 30, 59-69. **[4]** Peck, J. A. and Wood, J. A. (1987) GCA 51, 1503-1510. **[5]** Hua, X. et al. (1988) GCA 52, 1389-1408. **[6]** Weinbruch, S. et al. (1990) Meteoritics 25, 115-125. **[7]** Rubin, A. E. (1984) GCA 48, 1779-1789.