**AMOEBOID OLIVINE AGGREGATE CONDENSATES AND THE ORIGIN OF THE REFRACTORY ELEMENT FRACTIONATION.**

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Introduction: Amoeboid olivine aggregates (AOAs) constitute a significant fraction of some C chondrites but are only rarely found in other chondrite groups [1-3]. They are composed chiefly of fine-grained (<5-10 µm grain diameter) olivine but also contain refactory materials including Al-clinopyroxene + anorthite (cpx+anor) patches and spinel-rich CAI nodules. Our data support the inference of Larimer and Wasson [4] that AOAs were an important fractionating constituent in the solar nebula and could have helped to establish chondrite compositions. In particular, it appears that the "refractory element fractionation" experienced by chondrites [5-8] can be explained by the removal of an AOA condensate.

Techniques: We estimated the bulk compositions of AOAs using EMPA and SIMS analyses in a "broad-beam" (40-50-µm-diameter) mode. Broad or "defocused" beam EMPA data (DB-EMPA) for inclusions were obtained using a combination of grid patterns, traverses, and targeted analyses in the inclusions. For comparison to AOA data, a version of the CWPI thermodynamic code [9-10] was used to model equilibrium condensate compositions.

Results: The bulk compositions of AOAs are similar to model equilibrium condensate compositions formed in a system of near-solar (CI-chondrite-like) overall composition at low pressures (10^{-6} to 10^{-4} bar) over a range of temperatures (mainly ~1200-1384 K). The compositions of bulk AOAs and cpx+anor patches significantly overlap the predicted condensate trends, with the latter corresponding to higher temperature and the former to lower temperature (Fig. 1a). Spinel-rich nodules correspond to a higher temperature still. These data are consistent with trace element compositions, which imply higher formation temperatures for cpx+anor areas and spinel-rich nodules and an important role for fractional condensation in AOA genesis [11-12]. Some AOA compositions extend past the condensate trend and can be explained by fractional condensation. It is clear that AOAs must have formed largely above the temperature at which low-Ca pyroxene condensates become stable, as the bulk compositions of AOAs do not deviate to higher Si/Al at low temperature as predicted for lower-temperature, pyroxene-rich condensates (Fig. 1a, 1b). These data strongly support a condensation origin for AOAs and suggest that AOAs incorporated variable amounts of refractory material and olivine.
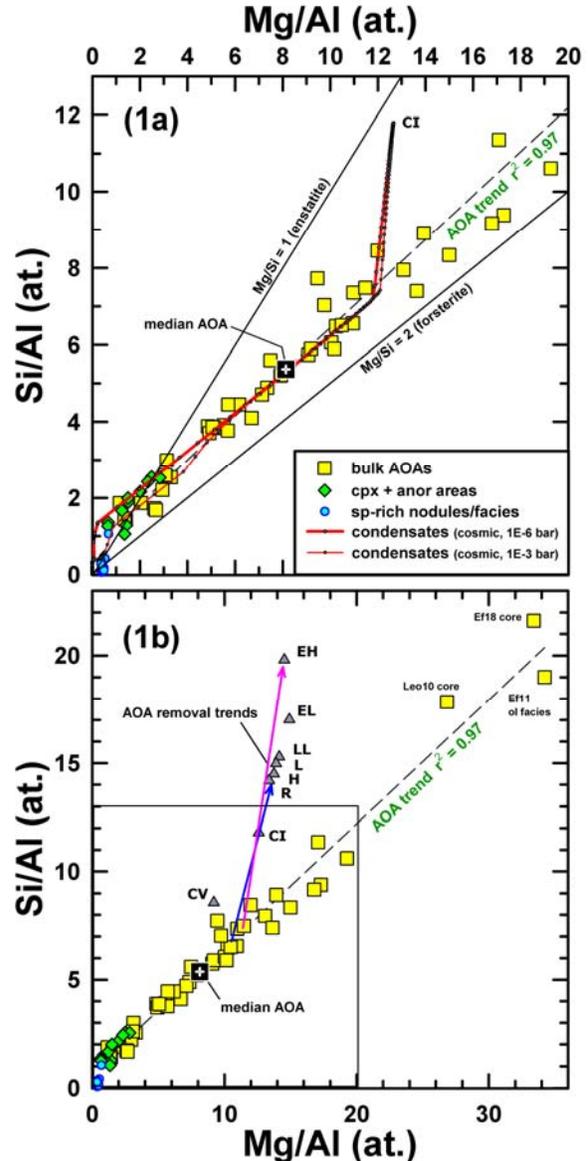
Fig. 1. *(a) The bulk compositions of AOAs and some of their constituents (yellow, green and blue data points) are compared to equilibrium condensate compositions in a system of solar composition (red lines). (b) Larger view showing AOA removal paths that extend from the AOA trend line through CI chondrite composition to R, H, L, LL, EL and EH chondrites.*

Fig. 1b shows that possible fractionation paths can be projected from the whole-rock compositions of various non-C chondrites through average CI chon-

drite composition onto a portion of the observed AOA trend line. One path leads from the trend line to average H, L, LL and EL chondrites and another to average EH chondrite (Fig. 1b). A slightly different fractionation path between these two can be drawn to average R chondrite. This implies that the composition of these chondrites could have been established, in part, by the removal of an AOA fractionate. In contrast, the bulk compositions of C chondrites such as the CV group cannot be explained by this model (Fig. 1b).

We used Mg/Al and Si/Al ratios as constraints to model both the composition and amount of the AOA fractionate that would need to be removed from various chondrite groups, assuming a system of overall CI chondrite composition (Table 1). For this calculation, each ratio provides an independent constraint on fractionating proportion, but only one ratio is needed to constrain the fractionating composition as it is assumed to lie on the AOA trend line. A "best fit" is obtained when nearly the same value of fractionate removal (f) is obtained for Mg/Al and Si/Al. For H, L, LL and EL chhondrites, a single fractionate composition with Mg/Al = 10.5 and Si/Al = 6.7 (at.) removed in different proportions (as little as 35% for H, as much as 52% for EL) can explain the data (Table 1). For R and EH chondrites, we obtain two slightly different AOA fractionates, with 33% removed to produce R, and 64% removed to produce EH chondrites (Table 1).

The different AOA fractionates can be approximated as equilibrium condensates that have different formation temperatures. With a pressure of 10^{-6} bar, these correspond to condensates produced at ~1208 K (H, L, LL, EL fractionate), ~1201 K (R), and ~1195 K (EH). With 10^{-4} bar, the corresponding temperatures are about 1324 K, 1315 K, and 1305 K, respectively. Thus, nebular separation of AOAs occurred over a fairly narrow temperature interval (12-19 K). The implied AOA components correspond to olivine-rich assemblages that have a relatively dilute proportion of refractory material.

This model can explain the abundance of elements as refractory as and more refractory than Si, including many trace elements. As Si is less abundant than more refractory elements in AOAs, the fractionation will result in Si-normalized abundances of refractory elements that are <1, a defining chemical characteristic for non-C-group chondrites [3]. However, the model fails badly for volatile lithophile elements and for siderophile elements. In effect, the assumed AOA fractionates are too depleted in volatile elements and metal to be the only relevant component for chondrites. Instead, whole-rock chondrite compositions must have been affected by both AOA and other types of frac-

tionations. A decoupling between refractory and siderophile element fractionations is well established [8, 13].

The fractionation of AOAs has important implications for nebular processes. We suggest that it originated by aerodynamic sorting that concentrated AOAs in the source regions of some chondrites (C chondrites) and depleted them in others (non-C-chondrites). The similar compositions of fractionating AOAs suggest that fundamental physical and dynamical properties of the nebula and the dust within it were controlling variables. These variables could have included gas pressure, the amount of turbulence, and the stopping times of AOA condensates that had grown to a particular size.

Table 1. *Composition and fraction of AOA component removed (f) from CI chondrite composition to make other chondrite groups based on Mg/Al and Si/Al (at.) ratios.*

Group	Parameter	f, H/L/LL/ EL best fit	f, R best fit	f, EH best fit	AOA composition
H	Mg/Al	0.35	--	--	10.5
	Si/Al	0.35	--	--	6.7
L	Mg/Al	0.38	--	--	10.5
	Si/Al	0.39	--	--	6.7
LL	Mg/Al	0.42	--	--	10.5
	Si/Al	0.41	--	--	6.7
EL	Mg/Al	0.52	--	--	10.5
	Si/Al	0.51	--	--	6.7
R	Mg/Al	--	0.33	--	11.0
	Si/Al	--	0.33	--	7.0
EH	Mg/Al	--	--	0.64	11.5
	Si/Al	--	--	0.64	7.3

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