Aluminous spinels in ferromagnesian chondrules from Allende

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Introduction: Ferromagnesian chondrules in highly unequilibrated ordinary chondrites average several wt% CaO + Al_2O_3 and several lines of evidence suggest that this refractory component is ultimately derived from Ca-, Al-rich inclusions (CAIs) or similar refractory material [e.g., 1,2]. The precise nature of the relationship is, however, uncertain because, although relict CAIs and aluminous phases are moderately common in Al-rich chondrules, they are generally viewed as very rare in ferromagnesian chondrules [3-4]. In this study, we describe six occurrences of Mg-Al-rich spinel grains in Allende, five from chondrules or chondrule fragments and a sixth from an isolated olivine grain in matrix. Chondrule chromites were also observed but are excluded from this work.

Techniques: A total of 27 thick sections were prepared serially from two ~1 cm^3 samples of Allende. Six occurrences of aluminous spinel were identified in four sections from BSE images and characterized using FESEM and EPMA. All of the chondrules containing aluminous spinel were FeO-poor, by far the most common type in Allende.

Types of occurrrence: We arbitrarily divide the aluminous spinels into two categories for convenience in exposition: (1) inclusions within ferromagnesian chondrules, and (2) inclusions in isolated olivine grains within matrix. We emphasize that these are descriptive categories as an isolated grain in matrix may have originally been part of a chondrule.

Inclusions in ferromagnesian chondrules. We observed aluminous spinels in five chondrules or chondrule fragments and *all* were either interstitial or had at least some portion of the spinel in contact with mesostasis or alteration (i.e., these grains are not wholly included in olivine). Where in contact with mesostasis/alteration, grain boundaries range from corroded (Fig. 3) to smooth (Fig. 2) or even straight (Figs. 1,4). With one exception, an anhedral grain in a barred olivine chondrule (Fig. 2), spinel occurs in clusters of two to several grains in contact or in close proximity to each other. One porphyritic olivine chondrule contains a cluster of intergrown olivine and spinel such that olivine is partially included in the spinel (Fig. 4; i.e., spinel is texturally later than the olivine). Grains in two of the chondrules are skeletal (e.g., Fig. 1), consistent with rapid crystal growth.

TiO_2 is low (0.2-0.3 wt %) in all of the chondrule spinels. Cr_2O_3 contents vary from sample to sample with the spinel inclusion in the barred olivine chondrule (Fig. 2) at the low end (0.2-0.5 wt%), approaching values observed in CAI spinels ([5-6]; Fig. 5), spinels from three other occurrences at intermediate concentrations (~1 wt%), and spinel in the olivine-spinel intergrowth (Fig. 4) at the high end (2.6-3.7 wt%). Fe-Cr variations for low Fe-Cr spinels suggests that the Cr is substituting primarily with Fe (i.e. as chromite not picrochromite). Within individual crystals, Cr zoning is either flat or asymmetric and, where multiple crystals were analyzed in a given chondrule, there appears to be a systematic regional variation in Cr contents of the spinel. Fe contents of the spinels are highly variable especially near grain boundaries (0.2-7.6 wt% overall). Olivine is generally Fo_{98-100}.

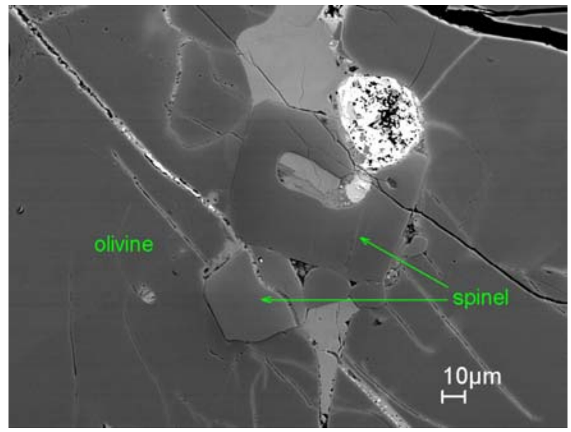

Fig. 1. Spinel grains in porphyritic olivine chondrule.

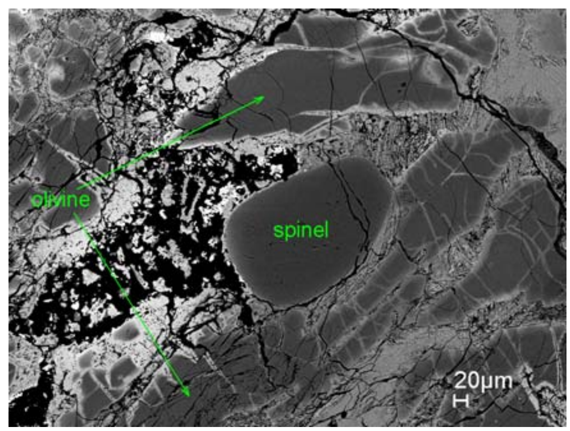

Fig. 2. Rounded spinel grain in barred olivine olivine chondrule.

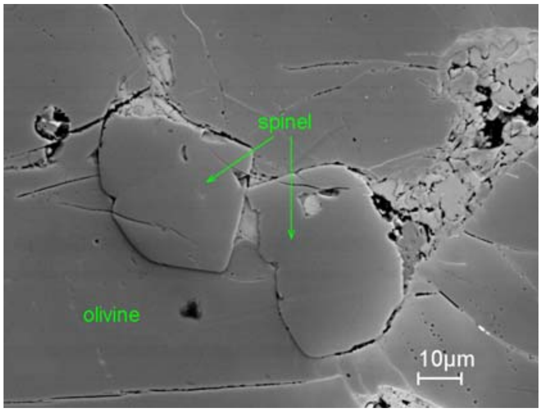

Fig. 3. Corroded spinel grains in porphyritic olivine chondrule.

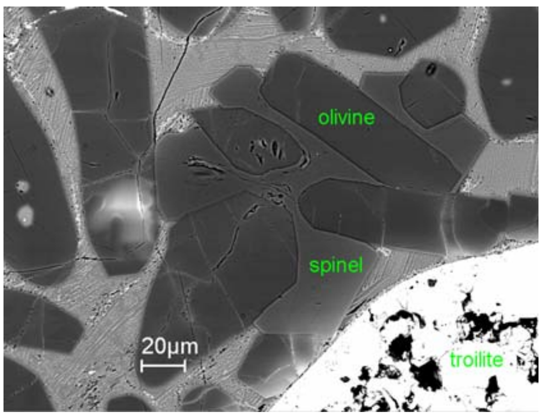

Fig. 4. Intergrown spinel and olivine in porphyritic olivine chondrule.

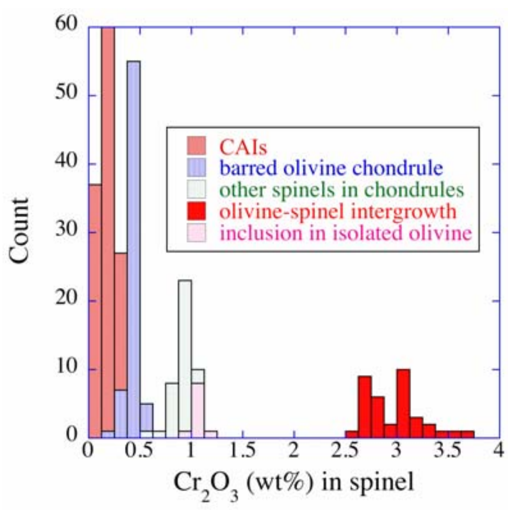

Fig. 5. Histogram of Cr_2O_3 in spinel. CAI data from [5-6]; CAI peak is truncated for clarity.

The olivine-spinel intergrowth (Fig. 4) has the most Cr-rich spinels we studied. FeO (total Fe) is modest (1.3-2.3 wt%) except near a large sulfide bleb (up to 7.6 wt%) with Fe^{3+}/Fe^{2+} ~ 0.3 for spinels with FeO (total Fe) > 4 wt%. Cr_2O_3 in spinel (2.6-3.7 wt%) generally increasing systematically away from the sulfide bleb. The sulfide bleb consists mostly of troilite+pentlandite with inclusions of chromite scattered thoughout and rare olivine. Ca-phosphate inclusions are common near the rim and a thin layer of fayalite rims the outside. The Olivine phenocrysts are Fo_{98-99} except within ~10 μm of the sulfide bleb where they can reach ~Fo_{80}.

Inclusion in isolated olivine in matrix. The spinel grains described above were enclosed in chondrules or chondrule fragments and invariably in contact with olivine but they were not wholly included in olivine. We also observed a single rounded ~10 μm spinel grain included in an isolated 75x130 μm olivine grain in matrix. The host olivine is ~Fo_{98-99} except in the outer 5-10 μm and in a central 25x25 μm region adjacent to the spinel grain where substantial iron enrichment occurs. The spinel has modest Cr_2O_3 (~1.0 wt %) and TiO_2 (~0.2 wt %), consistent with some chondrule spinel (Fig. 5); it is Fe-poor in the core (~0.2 wt%) but Fe-rich (FeO(total Fe)= 8-9 wt%) near the grain boundary; Fe in the Fe-rich spinel is mostly hercynite but with some magnetite component (Fe^{3+}/Fe^{2+} = 0.1-0.3).

Implications: Possible sources for aluminous spinels in Allende FeO-poor chondrules include relict crystals from CAIs or previous generations of Al-rich or ferromagnesian chondrules, and crystallization within the host chondrule. The chondrule spinels we examined are typically interstitial (not completely enclosed in early crystallizing olivine crystals) and, in one case, appear to have co-crystallized with olivine (Fig. 4), suggesting that these are not generally relict crystals. High Cr relative to CAI spinels (Fig. 5) also argues against a direct CAI lineage for most of the grains. Cr zoning is usually not symmetric across spinel grains but concentrations often vary systematically from grain to grain, perhaps due to growth of a cluster of spinels in an existing Cr gradient in the liquid. Skeletal spinel crystals in two occurrences (e.g., Fig. 1) are consistent with rapid crystal growth, presumably following substantial undercooling. The corroded form of some grains may reflect a later reaction relation between spinel and liquid. We conclude that spinels in Allende ferromagnesian chondrules are generally home-grown.

References: [1] Misawa K, and Nakamura N. (1988) *GCA* 52, 1669-1710. [2] Hezel D.C. and Palme H. (2007) *GCA* 71, 4092-4107. [3] Misawa K. and Fujita T. (1994) *Nature* 368, 723-726. [4] Krot A.N. et al. (2006) *App. J.* 639, 1227-1237. [5] Connolly H.C. and Burnett D.S. (1999) *MPS* 34, 829-848. [6] Connolly H.C. et al. (2003) *MPS* 38, 197-224.