

**A COMPLEX EVOLUTION SEQUENCE REVEALED BY THE TEXTURES OF FINE-GRAINED, SPINEL-RICH INCLUSIONS FROM THE LEOVILLE CV3 CHONDRITE: A GENETIC LINK BETWEEN FLUFFY TYPE-A CAIS, SPINEL-RICH INCLUSIONS AND AMOEBOID OLIVINE AGGREGATES.** S. Che and A. J. Brearley, Department of Earth and Planetary Sciences, MSC03-2040, 1University of New Mexico, Albuquerque, NM 87131, USA. (E-mail: shaofanche@unm.edu; brearley@unm.edu).

**Introduction:** Fine-grained, spinel-rich inclusions are characterized by aggregations of nodules separated from each other by sinuous diopside layers; the detailed mineralogies of individual nodules vary, but a layered sequence of spinel-anorthite-Al-rich diopside is commonly observed. Studies of spinel-rich inclusions in relatively less-altered chondrite samples [e.g., 1-4] have proposed various formation reactions for the primary phases; however, many of the reactions are not fully consistent with the observed textures and mineralogical relationships. Here, we report detailed petrological and mineralogical observations of several fine-grained, spinel-rich inclusions from the Leoville CV3 chondrite, and propose that they record a complex evolution sequence. Based on this sequence, we discuss the genetic relationship of these inclusions with fluffy Type A CAIs (FTAs) and amoeboid olivine aggregates (AOAs).

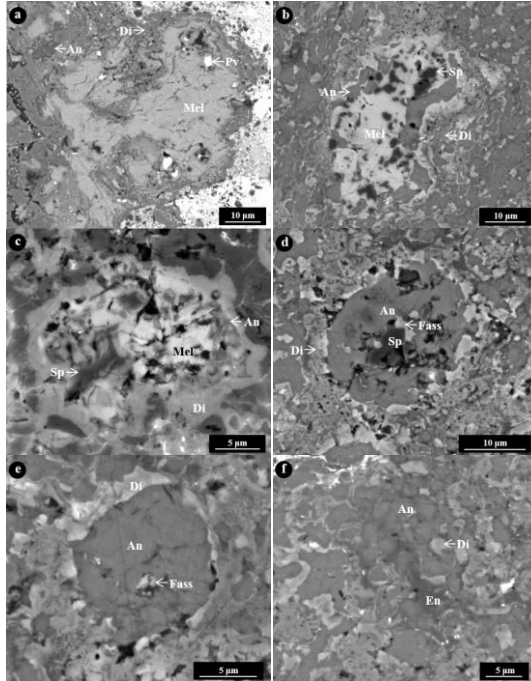
**Methodology:** High-resolution backscattered electron (BSE) images and X-ray maps were obtained using a FEI Quanta 3D FEG-SEM/FIB instrument.

**Results:** The Leoville thin section (UNM-577) we studied consists of the host lithology and a dark inclusion [5]. The fine-grained, spinel-rich inclusions in this thin section can be divided into four groups, based on their mineralogy. Most of the inclusions are from the host, and the rest are from the dark inclusion. Typical inclusions in each group are described in detail below.

Group A is represented by Leo-H09, which is a melilite-rich inclusion consisting of spinel-melilite-anorthite-diopside nodules. Perovskite is a common phase enclosed in melilite. Four mineralogically distinct zones are present in this CAI: (1) a melilite-dominant zone with a minor amount of anorthite existing between melilite and diopside in individual nodules; (2) a diopside-rich zone with the same mineralogy as zone 1; (3) an anorthite-dominant zone; and (4) a spinel-rich zone. Reaction relationships are present between different phases: spinel grains are corroded by melilite; diopside is replacing melilite and/or perovskite; melilite is also replaced by anorthite which commonly contains tiny Fe-bearing spinel grains. The Fe-bearing chemistry of these spinel grains is likely attributable to parent body metamorphism. Zone 3 seems to represent a transition stage between zone 1 and 2.

Group B inclusions include three large CAIs (Leo-H01, -H03, -H07; >500  $\mu\text{m}$  in diameter) and their fragments. Mineralogical heterogeneities are obvious in the EDS X-ray maps. Nodules in individual inclusions show a continuous replacement sequence similar to that recorded in Leo-H09. This sequence can be described as:  $\text{Sp}+(\text{Pv})+\text{Mel} \rightarrow \text{Sp}+(\text{Pv})+\text{Mel}+\text{Di} \rightarrow \text{Sp}+(\text{Pv})+\text{Mel}+\text{An}+\text{Di} \rightarrow \text{Sp}+\text{An}+\text{Di} \rightarrow \text{An}+\text{Di} \rightarrow \text{An}+\text{Al-En}+(\text{Di})$ . Each mineral assemblage in the sequence is represented in the nodules in these CAIs. In addition, texturally, the first assemblage is very similar to FTAs from Allende and other carbonaceous chondrites. Some replacement relationships are quite obvious from the textures: melilite replaces spinel, diopside replaces melilite+perovskite+(spinel), and anorthite replaces melilite. Other relationships are, however, ambiguous. For example, in some anorthite-rich nodules, anorthite encloses euhedral-to-subhedral spinel grains, which are commonly associated with Al,Ti-rich diopside grains. The boundaries between spinel and anorthite are sharp, and thus do not exhibit a replacement relationship between them. The relation between anorthite and diopside, on the other hand, is difficult to interpret: Al,Ti-rich diopside appears to be a reactant in the formation reaction of anorthite, but it is also possible that the diopside grains are relicts of a precursor assemblage. Diopside in anorthite-rich nodules is Al,Ti-poor, and a high-Z contrast layer exists between anorthite and diopside, which may indicate that Al,Ti-rich and Al-rich diopside were involved in the formation reaction of anorthite. Diopside shows compositional zoning in individual nodules, with the aluminum and titanium contents decreasing from the contacts with spinel, perovskite, and melilite to the peripheries of nodules. Aluminum- and Ti-poor diopside also seems to be replaced by anorthite. A similar microscale zonation in diopside has been previously described by [4] in refractory CAI-like objects in AOAs from ALHA77307 CO3.0 chondrite, and was interpreted as evidence for a gradual depletion of Ti in the nebular gas and isolation of the reactants from the gas. The presence of Al-rich enstatite surrounding anorthite has not been described previously in fine-grained, spinel-rich inclusions. These enstatite grains are closely associated with diopside, which may imply a replacement relationship.

Inclusions (Leo-H12, -H13, -H14, -H15) in group C are composed of Sp+(Pv)+(Mel)+An+Di nodules



*Fig 1. Nodules with different mineralogies show an evolution sequence: (a) Sp+(Pv)+Mel; (b-c) Sp+(Pv)+Mel+Di and Sp+(Pv)+Mel+An+Di; (d) Sp+An+Di; (e) An+Di; (f) An+Al-En+(Di)*

enclosed by AOA-like materials. Some spinel grains display elongated shapes, which are reminiscent of the pseudomorphic replacement texture between spinel and hibonite [e.g., 6]. Melilite grains in many nodules show clear replacement relations with anorthite and diopside. The EDS spectra of melilite show excess Mg and Ti, indicating the presence of fine-grained, intergrown Al-Ti-rich diopside. Forsterite surrounding the nodules commonly shows triple junctions, and its boundaries with diopside are sharp.

Group D inclusions (Leo-DI09, -DI30) are from the dark inclusion. They are also associated with AOA-like materials, but do not contain melilite and anorthite. Spinel is intimately associated with diopside, and, in some cases, they exhibit symplectic textures in which spinel is being replaced by diopside.

**Discussion:** The complex replacement textures of these CAIs imply a continuous evolution sequence. The similarity of melilite-rich nodules in some of these CAIs with nodules in FTAs, as well as the presence of AOA-like materials, indicate that a genetic relationship may exist between these objects. This sequence is illustrated in Fig. 1, using examples of nodules from different CAIs to show the continuous changes in mineralogy. However, the complete sequence is observed entirely within several of the CAIs.

We propose that nodules in these CAIs began as FTAs, and then were modified to spinel-anorthite-diopside inclusions via a series of gas-solid reactions. Subsequent condensation of forsterite around the nodules formed the AOA-like materials. Different groups represent different stages in this evolution sequence. [1] have previously proposed FTA precursors for fine-grained, Sp-rich inclusions. Here we show additional clear evidence (e.g., relict FTA nodules and gradual depletion of melilite) to support such a relationship.

Possible reactions involved in the sequence, based on the observed phase relationships, are listed below:

- (1)  $\text{Sp} + \text{Geh} + 2\text{Pv} + 4\text{SiO}_{(\text{g})} + 3\text{H}_2\text{O}_{(\text{g})} = [\text{CATS} + \text{Di} + 2\text{Gro}]_{(\text{px ss})} + 3\text{H}_2(\text{g})$
- (2)  $2\text{Sp} + 2\text{Pv} + 3\text{Ca}_{(\text{g})} + 7\text{SiO}_{(\text{g})} + 9\text{H}_2\text{O}_{(\text{g})} = [\text{CATS} + 2\text{Di} + 2\text{Gro}]_{(\text{px ss})} + 9\text{H}_2(\text{g})$
- (3)  $\text{Sp} + 2\text{Geh} + 7\text{SiO}_{(\text{g})} + 3\text{H}_2\text{O}_{(\text{g})} = 2\text{An} + [\text{CATS} + \text{Di}]_{(\text{px ss})} + 3\text{H}_2(\text{g})$
- (4)  $\text{CATS} + \text{SiO}_{(\text{g})} + \text{H}_2\text{O}_{(\text{g})} = \text{An} + \text{H}_2(\text{g})$
- (5)  $\text{Sp} + \text{Di} + 2\text{SiO}_{(\text{g})} + 2\text{H}_2\text{O}_{(\text{g})} = \text{An} + 2\text{En} + \text{H}_2(\text{g})$

Three generations of anorthite are produced via reactions (3), (4) and (5), with gradual consumption of melilite and Al-rich diopside. It is not clear whether Al,Ti-rich diopside was also replaced by anorthite, but if such a reaction exists, a Ti-rich product should be present to serve as the sink for Ti, which is not observed. The continuous growth of anorthite, despite the presence of an outer diopside layer, probably means that the nebular gas was not completely isolated from the nodule cores. Pathways for infiltration of gaseous reactants, possibly in the form of pores, were present during the reactions, but were lost during later annealing processes. Group D differs from other groups in that no melilite or anorthite is observed; therefore, a reaction involving only spinel, diopside, and gas may be responsible for their textures. Such a reaction has been proposed by [6].

In the evolution sequence described above, FTAs may represent transitional objects, and Sp-rich inclusions and AOAs represent two final products in the evolution sequence. In this case, the presence of these objects in many chondrites implies their isolation from the gas. Alternatively, different inclusions may record variations of nebular conditions or transportation between different gaseous reservoirs.

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**References:** [1] Lin Y. and Kimura M. (1998) *MAPS*, 33(3), 435-446. [2] Krot A. N. et al. (2004) *MAPS*, 39(9), 1517-1553. [3] Weisberg M. K. et al. (2004) *MAPS*, 39(10), 1741-1753. [4] Han J. and Brearley A. J. (2016) *GCA*, 183, 176-197. [5] Kracher A. et al. (1985) *JGR*, 90(S01), 123-135. [6] Simon S. B. et al. (2006) *AM*, 91(10), 1675-1687.