DARK INCLUSION ALLENDE 4884-2B PROVIDES NEW INSIGHTS ON THE FORMATION OF FAYALITIC OLIVINE

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Introduction: Dark Inclusions (DIs) are complex objects whose genesis is considered to be the result of two contrasting processes: a) those active in the CV3 chondrite parent body including metamorphism, fragmentation, melting, aqueous alteration and subsequent dehydration [e.g. 1-7] and, b) those taking place in the solar nebula including aggregation and subsequent secondary alteration [e.g. 8-11]. Here, we combine a chemical and petrographic study of the Allende DI 4884-2B [12-13] and a ATEM study of Allende DI All-AF (NHM, Vienna) in order to get new insights onto the genesis of these objects.

Samples and methods: The Allende DI 4884-2B (PTS, AMNH, New York) thin section was studied by microscopic and micro-analytical techniques following standard procedures. ATEM studies were performed on a small fragment of the DI All-AF by H-T. Chu (Central Geological Survey, Tapei, Taiwan).

Results: Allende DI 4884-2B consists mainly of aggregates of fluffy, non-transparent fayalitic olivines, very similar to rock All-AF [9] and to the Allende DI 4884-2 [11]. A few aggregates, however, (e.g., aggregate A) also contain some relic transparent forsterite. Aggregate A, has a zoned structure with a core consisting of transparent, mostly euhedral olivines (100–300 μm) poor in FeO (0.8 wt%) and rich in CaO (0.4%), set into a very fine-grained, non-transparent mesostasis rich in CaO (24 wt%), TiO_2 (1.2%), FeO (10.4%) and MgO (11.3%), but poor in Al_2O_3 (2.1%) and Na_2O (0.1%). The core is surrounded by mostly euhedral, porous and non-transparent olivines rich in FeO (20–30 wt%) and rich in minor elements, consisting of olivine skeletons and platelets and containing some nepheline in the pore space (Fig. 1). Clear olivines are host of glass inclusions (up to 20 μm) rich in SiO_2 (~50 wt%), Al_2O_3 (~24 wt%) and CaO (~18 wt%).

The ATEM study, performed on a small (~ 1 mm) fragment of DI All-AF shows that the dominant phase is a porous, coarse-grained olivine, with very fine-grained phases (typically spinel (~50% Hc), pentlandite ($(Ni_3Fe_6)S_8$, *Fm3m*), taenite ($Ni_{6.3}Fe_{3.4}Co_{0.3}$), chromite (~30% Hc), and occasionally diopside, feldspar, apatite, and amorphous alumina silicate) occurring in some cavities between olivine grains.

Besides metal and sulfide inclusions, dendritic spinel arms and tiny oriented spinel platelets as well as euhedral chromite crystals are found in olivine grains.

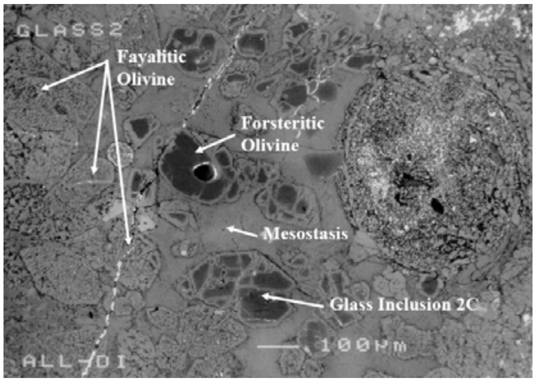

Figure 1: Aggregate A in Allende DI 4884-2B. BSE image.

Occasionally, euhedral spinel is rimmed by epitaxial spinel with high iron content, ~ 75% Hc, and pentlandite. Only one diopside grain was observed during an extended TEM search. No low calcium pyroxene was found.

Discussion: Debates about the genesis of DIs are mainly focussed on deciphering the origin of its major component: the fayalitic olivine. Up to date, there is no consensus about the primary or secondary nature of these olivines. If primary, they formed by condensation and aggregation in the solar nebular, followed by gas-solid exchange reactions [8-9]. If secondary, they are the result of a) nebular vaporization/recondensation [11] or b) hydration/dehydration occurring in the CV3 parent body [7, 15, 16].

Petrograhic evidence in aggregate A constrains severely many of the previous genetic models. The existence of euhedral olivine (with fluffy interiors) occurring in a fine-grain mesostasis suggests that these crystals formed from this liquid. This excludes their formation by primary condensation [8-9] or direct recondensation [10] in the solar nebula. Its origin must be related to a secondary process. Hydration/dehydration [7-15-16] seems also very unlikely, since it is difficult to conceive a process so highly selective as to completely transform a clear forsterite crystal into a fluffy fayalitic one, but to produce minimal alteration in the co-existing mesostasis glass. In addition, recent Li isotope measurements show that if DIs were exposed to extended periods of fluid interactions, they should be enriched in the heavier isotope compared to the host meteorite [16]. But this is not the case. Also, electron backscatter diffraction (EBSD) studies in Allende suggest that hydration/dehydration processes cannot generate a fabric such as that observed in Allende, but mainly destroy any pre-existing fabric [17].

Formation of olivine-rich aggregates: A SIMS study of aggregate A shows that the olivine crystals are rich in trace elements. Their high contents of Ti (~ 1 x CI) and of the REEs point towards growth from the vapor phase [12]. The co-existing liquids (e.g., precursor of the primary glass inclusions and the fine-grained mesostasis) have patterns governed by volatility and also document vapor fractionation [13]. Therefore, phases in aggregate A appear to have a primitive origin by condensation, possibly in the solar nebula [12-13]. The FeO/MnO ratio (~solar) of the fayalitic olivine in All DI 4884-2B and other DIs [10] clearly shows addition of these elements from a chondritic reservoir. This scenario fits the recently formulated Primary Liquid Condensation Model (PLCM) [18] that envisages formation of clear olivine crystals with the help of a liquid that is constantly replenished in olivine components from the vapor. The abundance of mesostasis in aggregate A as compared to other objects also agrees with the PLCM, which considers variations in the quantity of liquid available during the early growth process. Aggregate A could have been formed as an irregular aggregate of euhedral forsterite crystals. The abundances of trace elements in olivine and glass, however, are not governed by crystal-liquid distribution coefficient as experimentally determined (Fig 2). Olivine growth seems not to be governed by an igneous process but by other factors such as a high degree of undercooling of the liquid and, consequently, very fast crystallization of the olivine.

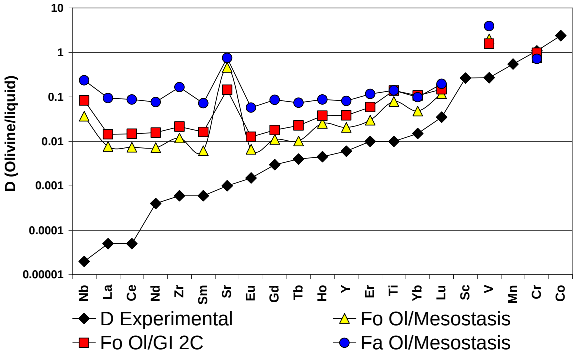

Figure 2: Crystal/liquid partition coefficients. Fo: forsterite, Fa: fayalite.

The fayalitic fluffy olivine: Strong variation in temperature seems to affect DIs, as indicated by the dendritic spinel in the All-AF olivine that reflects solidification at supercooling conditions. This drop in temperature was apparently followed by an intense metasomatic process that radically changed the chemical composition of the initial phases. Replacement of Mg by Fe+Mn in the olivine. and increase of Fe+Mg in the surrounding mesostasis, in which Al+Sr+Ba were mobilized, are among the main changes observed in aggregate A. Mobilization of Fe, Al, Mg, Ni and S is also indicated by the presence of polycrystalline spinel with taenite at its center in between All-AF olivine clasts. Because formation of these phases appears to be related to a combined process of condensation/coalescence/sintering, atom diffusion could be the underlying mechanism of this mobilization. The secondary process involved in the transformation of a forsteritic olivine into a fayalitic one could be diffusion, in which non-volatile major elements such as Mg and Fe may be removed (or added) via a ‘‘dry’’ vapor phase [19]. An increase in the ambient O fugacity – as evidenced by the FeO/MnO ratio of the fayalitic olivine – will affect the solubility of Mg in the vapor and ultimately the Fe content of the formed silicates [19]. The euhedral spinel with hercynite rim in epitaxy with pentlandite is suggestive of solid-state transformation and diffusion processes under variable O and S fugacities. Under these conditions, S can condense, causing transformation of some of the Fe-Ni phases (e.g., taenite) to sulfides (e.g., pentlandite). This diffusion process was highly effective in those crystals that were directly exposed to the vapor phase [e.g., 9-10]. However, in aggregate A, the mesostasis glass acted as a barrier that allowed only complete transformation of the small euhedral crystals while big crystal preserved the relict forsterite core (Fig 1). This extreme diffusion process also revealed the growth patterns of the olivine (e.g., stacked platelets of olivine due to quick growth). Metasomatic alteration enters the crystal along zones of weakness. However these zones of weakness were the first to recrystallized and thus turn out into zone of strength as they transformed the clear olivine into fluffy-looking pseudomorphs.

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