A HIBONITE-RICH INCLUSION FROM ALLENDE: MINERALOGY, TEXTURE AND TRACE ELEMENT CHEMISTRY, A.M. Davis*, J.M. Allen*, I.D. Hutcheon[†] and L. Grossman*[†], University of Chicago, Chicago, IL 60637. *Dept. of Geophysical Sciences. [†]Enrico Fermi Institute.

Microscopic examination of a slab surface of the Allende meteorite revealed a very unusual coarse-grained, irregularly-shaped white inclusion, CG-11, about 7 mm in longest dimension. A pronounced rim structure was observed on some parts of the exterior surface of the inclusion and occasionally adjacent to a long stringer of dark, fine-grained material which penetrates its interior. Orange crystals up to 0.3 mm long make up about 20 volume % of CG-11. Powder patterns showed them to be hibonite. Cavities are common. During sampling, one was broken into which contains mats of colorless needle-like crystals. Fragments and powder were scraped from the interior of the inclusion, from which a representative bulk sample weighing 9 mg was selected for chemical analysis. From the remaining powder, small chips were hand-picked for microprobe and SEM mounts. Also selected for chemical studies were 1 hibonite-rich and 3 hibonite-poor fragments, identified by color and weighing 10 to 60 µg each.

Examination by SEM with an energy-dispersive X-ray analyser revealed cavities up to 1 mm across surrounded by melilite and hibonite which contain euhedral grossular crystals and beautiful sprays and mats of acicular wollastonite crystals (cf.1). Some of these needles are 1 µm thick and over 100 µm long. Others are bent through nearly 90[o], but are not broken, reminiscent of vapor-deposited whiskers. Sometimes, stubby prisms of a silicate of Na, Ca, K and Al (possibly nepheline) are intergrown with euhedral grossular crystals. These textural features are interpreted as very strong evidence for direct condensation of solids from a vapor. Because a post-condensation melting event would have destroyed these textural features, their presence indicates that CG-11 was not melted since their formation.

Electron microprobe and further petrographic studies were performed on polished sections whose total area is 1 mm^2. Each of the largest fragments in these sections contains a long trail of perovskite and spinel grains which separates it into two regions with different mineralogy and texture. One region contains 67% melilite, 20% grossular, 10% hibonite, 1% each of perovskite, spinel and anorthite, minor nepheline and, possibly, sodalite. Melilite grains, 100 µm in size, are shocked, have a mean composition of Ak_8 and contain sparse grains of perovskite (<30 µm) and spinel (<10 µm) which usually occur together. One melilite grain is zoned from a core of Ak_{19} to a rim of Ak_4, opposite to the zonation expected had the crystal condensed from a vapor or crystallized from a melt at equilibrium. Abundant fine-grained material, mostly grossular with minor anorthite and nepheline, coats rounded surfaces of melilite grains, fills regions between them and even penetrates fractures and cleavage planes. The zoning pattern of the melilite is intersected by the fine-grained material and therefore predates the alteration process during which the fine-grained phases were deposited. Presumably, the wollastonite-grossular assemblage seen with the SEM makes up part of the fine-grained material. Brown, prismatic hibonite crystals (15-40 µm) occur both in melilite and associated with grossular between melilite grains.

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It contains 2.35-4.68% MgO, 5.24-8.36% TiO_2, .28-1.40% V_2O_3 and .13-.41% Sc_2O_3 and luminesces blue. Spinel contains .05-.07% FeO, .13-1.07% V_2O_3 and $\leq$.38% Cr_2O_3. Grossular contains 0-3 mole % andradite. Nepheline contains about 3.7% CaO.

The other region of CG-11 contains 50% clinopyroxene, 50% wollastonite and rare andradite far from the perovskite trail. Individual wollastonites cannot be seen optically. The pyroxene occurs as a felted mass of prisms, some up to 40 μm long. It is Ti- and Al-poor and ranges from diopside with up to 5 mole % Ca-Ts and 1.35% TiO_2 to Hd_{100} with no Al or Ti. Wollastonite is >Wo_{96}. Garnet is pure andradite. Perovskite contains .07-.39% Sc_2O_3, .11-.53% FeO, .25-.32% ZrO_2, .08-.12% Y_2O_3 and .16-.19% V_2O_3. The spatial relations of this region to the rims seen on slab surface are not known. This region is similar in mineralogy to rims on Type A inclusions described by Wark and Lovering (2), except that minerals characteristic of layers 2 and 3 in that work, nepheline, forsterite, Ti-pyroxene, etc., were not found. Also, its thickness, 300 μm, is much greater than the 50-60 μm total thickness of rim sequences reported in (2).

At least 2 stages of condensation may be recorded in CG-11. The earliest, involving hibonite, melilite, perovskite and spinel, could have occurred above 1475°K at 10^{-3}atm P_t, although coexistence of hibonite and melilite indicates non-equilibrium. If the next stage, recorded by phases in fissures in melilite, occurred in a gas of solar composition, the presence of grossular and wollastonite indicates non-equilibrium. The genetic relationship of the wollastonite-pyroxene portion of CG-11 to the rest of the inclusion is not understood, but if it formed by condensation of a gas of solar composition, this process must have continued to temperatures near 800°K because of the high Hd content of some of the pyroxene.

All measured major and trace element abundances in the bulk sample of CG-11 (Na,Mg,Al,Si,Ca,Sc,Ti,V,Cr,Mn,Fe,Co,Ni,La,Ce,Sm,Eu,Dy,Yb,Lu,Ir and Au) lie within the concentration ranges seen in other coarse-grained inclusions. The mineralogy of the bulk sample and separated fragments cannot be unambiguously determined from major element abundances because of variations in mineral chemistry and the large number of phases possibly present. However, from the low spinel content of CG-11 and the Al and Ti contents of each fragment, the hibonite-rich one, 3, contains ∿70% hibonite and the hibonite-poor ones, 5, 6 and 7, contain <20% hibonite. Because dark-colored phases were avoided during sampling of the latter 3 fragments, a minimum of material is present from the clinopyroxene-wollastonite region described above.

The REE patterns of the bulk inclusion and the fragments are parallel to one another and are relatively flat with small positive Eu anomalies (Eu/Sm ∿ 1.5 times the Cl ratio). REE abundances are lowest in fragment 3 and are progressively higher in the bulk sample and fragments 6, 7 and 5. La is enriched from 10 to 18 times its Cl abundance. The parallel nature of the REE patterns indicates that a single phase, present in all fragments, contains the bulk of the REE. The absence of evidence for significant internal REE fractionation implies that REE were not redistributed during post-condensation thermal events, as has apparently occurred in other inclusions (3). Consequently, minor and trace refractory element contents of phases in CG-11

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give direct information about how the elements distributed themselves during condensation. Although the REE carrier phase cannot be unambiguously identified, hibonite can be eliminated, since 3 is poorest in REE. The major element abundances suggest decreasing melilite in the order 5 to 7 to 6; therefore, melilite is unlikely as the REE carrier. It may be perovskite, since there is a weak positive correlation between REE and Ti among hibonite-poor fragments. Since the REE pattern of the carrier phase was established during condensation, the fact that Eu follows the other REE implies that the bulk of the Eu condensed in and entered CG-11 in the same phase as other REE. This contrasts with an earlier observation that Eu was negatively correlated with other REE, implying that most of it entered the coarse-grained inclusions in a separate component (4). Analysis of additional material from previously analyzed inclusions (5) and of several more coarse-grained ones shows that the negative correlation between Eu and other REE was an artifact produced by sample inhomogeneity, allowing the possibility that all Eu entered the inclusions with the other REE. The lack of correlation between Eu and other REE is probably due to remaining sample inhomogeneity.

Fragment 3 is richest in Sc (598 ppm), consistent with the above microprobe data on hibonite. Only one Sc-bearing condensate component is required by the data for most coarse-grained inclusions (4), but microprobe data show that there are two such components in CG-11, perovskite and hibonite. Either hibonite and perovskite entered the coarse-grained inclusions in constant relative proportions or hibonite did not usually condense where most coarse-grained inclusions formed, so that gehlenite and spinel would have been the first Al-bearing phases to condense.

Three fragments contain comparatively low abundances of Ir, .5-8 times its abundance in Cl chondrites, while fragment 6 is enriched in Ir and Ru by factors of 57 and 61, resp. All samples are very low in Cr and Co, indicating that they contain <2% matrix contamination. Na, Mn and Fe (.60-.94%, 11-108 ppm and .85-1.50%, resp.) were probably introduced after the first condensation stage. High Fe/Co and Fe/Ni ratios of CG-11 (3.7 and 5.4 times their Cl ratios, resp.) indicate oxidizing conditions during the later condensation stages.

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