FINE-GRAINED INCLUSIONS IN TYPE 3 ORDINARY AND CARBONACEOUS CHONDRITES

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Abstract: We provide compositional and mineralogical characterization of a type C dark inclusion in Vigarano, and one matrix lump in Sharps. These inclusions are apparently unrelated to each other as well as the type A to B dark inclusions described from CV3 chondrites.

Introduction: Among dark inclusions (DIs) found in carbonaceous chondrites are those which are completely fine-grained; and totally lacking in larger components such as chondrules, aggregates or CAI. Similar-appearing objects are also occasionally reported from unequilibrated ordinary chondrites. Here we present detailed microprobe and transmission electron microscopy (TEM) characterizations of the composition and mineralogy of a fine-grained inclusion from Vigarano (CV3) and one from Sharps (H3). In order to better establish the relationship, if any, between these completely fine-grained inclusions and the coarser-grained inclusions containing chondrules (type A; see [1]) or chondrule polymorphs (type B) found in CV3s we compare our results to those for a type A/B Allende dark inclusion (#5a2).

Results: The Vigarano inclusion is 2226-7, previously studied by Johnson et al. [2] and described therein as a fine-grained dark inclusion. Krot et al. [1] have called this a type C dark inclusion. The bulk composition of this inclusion is given in Table 1, along with that for Vigarano matrix for comparison. This inclusion consists mainly of euhedral to anhedral olivine and pyroxene with a bimodal size distribution; the majority of material is between 0.02 and 1 micrometer in size, with a scattering of larger (5-20 micrometer), angular clastic grains. Olivine (Fo_{39-94}, with a significant distribution peak at Fo_{47}) predominates, with abundant enstatite, diopside, augite, pigeonite, and minor hercynite, melilite and Fe-Ni metal. All of the finest-sized olivine is ~Fo_{40-50}, as are the fayalitic rims found on all larger grains of olivine and pyroxene. An interesting feature of this particular inclusion, remarked upon by Johnson et al. [2], are thin arcuate cross-cutting bands. Backscattered electron imaging reveals these bands to contain relatively higher concentrations of the finest-grained, fayalitic olivine. Johnson et al. suggested that these features were caused by sedimentation/accumulation processes. However, some bands terminate abruptly at orthogonally-oriented straight bands, which resemble healed fractures. This would imply that the fayalitic olivine formed during a post-accretional, gas-solid reaction with gases exploiting the pathways provided by cracks, preferentially replacing the finest grained material in cracks and fine-grained sedimentary layers as these were encountered.

The matrix of Vigarano is not as well sorted as is this inclusion. The olivine in the matrix has the same distribution peak (near Fo_{47}) as the inclusion, however is more homogeneous in composition (Fo_{40-69}) [3]; the olivine compositional variation in the Vigarano inclusion is in fact more similar to the CV3 chondrite Mokoia [3]. Chromite rather than hercynite, is the typical spinel in Vigarano matrix. The higher Fe and Ni content of Vigarano matrix, relative to the inclusion, suggests the presence of a significantly higher metal in the former. We conclude that Vigarano inclusion 2226-7 formed by processes similar to those experienced by Vigarano matrix, but they are not identical material.

The inclusion in Sharps looks, at the petrographic scale, like the Vigarano inclusion, except it lacks the arcuate banding. This inclusion consists mainly of olivine (Fo_{54-94}) and low-calcium pyroxene (En_{87-99}) with interstitial ferromagnesian amorphous material and very minor saponite, the latter preferentially replacing amorphous material and pyroxene. The majority of the inclusion is very fine-grained (0.01 to 1 micrometer), although scattered euhedral to anhedral grains of olivine and pyroxene up to 100 micrometers are present. All of the finest grained olivine (those measuring only 10's of nanometers) are fayalitic ($<Fo_{60}$). Irregular, swirly, patches of containing a higher concentration of this fayalitic olivine are evident in the inclusion. Fayalitic rims are **not** evident in this inclusion. The compositional range of the inclusion olivine is essentially identical to that found for Sharps matrix olivine by Scott et al. [3]. Also noted in our study was one of the carbon-rich aggregates described from Sharps and other type 3.4-3.6 chondrites by Brearley [4]. This particular aggregate (10 micrometers in size) consists of metal ($Fe_{.95}Ni_{.05}$) set within poorly graphitized to amorphous carbon. The large interlayer carbon spacings of 3.55-3.59Å indicate that this aggregate witnessed very low temperatures (<350°C) [5], consistent with Brearley's results for Sharps. The composition of the Sharps inclusion is similar to that found by Huss et al. [6] for opaque Sharps matrix (Table 1), except for a higher iron content in the latter which likely indicates the presence of more metal in the matrix relative to the inclusion.

An Allende type A/B dark inclusion has recently been investigated by TEM [7]; this consists of fine-grained fayalitic olivine-rich matrix containing chondrules and isolated olivine grains rimmed by fine grained fayalitic olivine. Fayalitic olivine in this inclusion has been shown to have the platy, curved, dislocation- and void-rich morphology characteristic of recrystallization of phyllosilicates [8&9]. Between rim and matrix fayalitic olivines lie finer-grained masses of similarly iron-rich olivine, euhedral chromite and hercynite grains, pyrrhotite, pentlandite, nepheline and sodalite. This inclusion bears very little resemblance to the fine-grained Vigarano type C inclusion.

Discussion and Conclusions: These two inclusions are considerably more fine-grained than the so called fine-grained aggregates described from L3 chondrites by Watanabe et al. [10], although we hesitate to term them "ultra fine-grained". In most respects the Sharps inclusion can be considered a true matrix lump. The Vigarano inclusion appears to be distinct from Vigarano matrix, however, although of clastic origin. It may have experienced some event which caused fracturing - we are not really certain of the cause of the thin fayalitic bands. Following this fayalite formed, replacing grain boundaries; the smallest grains were naturally altered to the greatest degree. The specific reactions which provided the fayalite are not yet evident. Vigarano did not experience this fayalite-forming event to the same degree, which indicates that this episode predated final incorporation of the inclusion into Vigarano. We conclude that this fine-grained (type C) dark inclusion is not directly related to type A to B dark inclusions, lending support to the previous suggestion by Johnson et al. [2] and Krot et al. [1].

References: [1] Krot et al. (1995) *Meteoritics* **30**, 748-776; [2] Johnson et al. (1990) *GCA* **54**, 819-830; [3] Scott et al. (1988) In *Meteorites and the Early Solar System*, pp.718-745; [4] Brearley (1990) *GCA* **54**, 831-850; [5] Rietmeijer and Mackinnon (1985) *Nature* **316**, 733-736; [6] Huss et al. (1981) *GCA* **45**, 33-51; [7] Zolensky et al., this volume; [8] Kojima et al. (1993) *Meteoritics* **28**, 649-658; [9] Akai (1988) *GCA* **52**, 1593-1599; [10] Watanabe et al. (1987) *EPSL* **86**, 205-213; [11] Zolensky et al. (1993) *GCA* **57**, 3123-3148.

Table 1 Bulk Compositions of Fine-Grained Inclusions and Associated (?) Chondrite Matrix
Electron microprobe analyses, unless otherwise noted

	Sharps Inclusion[1]	Sharps Opaque Matrix[2]	Vigarano Inclusion 2226-7		Vigarano Matrix[5]
			This Work[3]	Johnson et al.[4]	
Na_2O	0.39	0.49	0.17	0.09	0.59
MgO	22.75	20.80	20.76	21.70	16.56
Al_2O_3	2.86	1.90	3.55	2.10	4.33
SiO_2	32.50	35.26	29.68	31.37	28.35
P_2O_5	nd	0.34	0.10	0.26	0.22
S	0.35	0.30	0.11	nd	0.16
K_2O	0.13	0.22	0.01	0.01	0.03
CaO	1.37	1.36	3.80	3.00	1.13
TiO_2	nd	0.11	0.08	0.10	0.07
Cr_2O_3	0.60	0.43	0.68	0.51	0.44
MnO	0.33	0.27	0.32	0.31	0.25
FeO	29.16	37.02	36.98	30.84	41.47
NiO	1.73	1.70	1.78	nr	3.40
Total	92.18	100.20	97.98	90.29	97.01

[1]Average of 141 analyses
[2]Adapted from Huss et al. [6]
[3]Average of 7 analyses
[4]Plasma emission spectrometry, Johnson et al. [2]
[5]Zolensky et al. [11]