Antarct. Meteorite Res., **10**, 203–215, 1997

# A FINE-GRAINED DARK INCLUSION IN THE VIGARANO CV3 CHONDRITE: RECORD OF ACCUMULATION PROCESSES ON THE METEORITE PARENT BODY

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***Abstract:*** Mineralogy and petrography of an unusual dark inclusion (DI) from the Vigarano CV3 chondrite (AMNH 2226-7) has been studied in detail. Formerly, this DI was briefly described by JOHNSON *et al.* (Geochim. Cosmochim. Acta, **54**, 819, 1990). Unlike most common types of DIs, AMNH 2226-7 consists almost exclusively of fine grains (<5 $\mu$m in diameter) of mainly Fe-rich olivine and is devoid of chondrules, large mineral fragments and Fe-rich olivine aggregates (chondrule pseudomorphs). The Fe-rich olivine grains are mostly granular and equidimensional in morphology, and acicular to fibrous olivine grains, common in other types of DIs, are absent. Lesser amounts of relatively coarse grains (10–60 $\mu$m) of Mg-rich olivine, Fe-rich olivine, enstatite, spinel, melilite, and perovskite are dispersed throughout the DI. A most distinguished feature of this DI is a network of arcuate bands (each 10–500 $\mu$m wide and 250 $\mu$m–3.5 mm long) which exhibit peculiar textures. The bands consist mainly of olivine grains which are slightly finer-grained and more Fe-rich than those in other areas. Several bands commonly occur roughly parallel to each other with equal spacing, forming a set of consecutive parallel bands. Different sets of parallel bands crosscut one another, some almost orthogonally. These mineralogical and textural features differ from the major group of DIs which contain chondrules and/or chondrule pseudomorphs, and indicate that the formation of AMNH 2226-7 cannot be explained by the direct replacement of a precursor chondrite. Probably, the origin of this DI is not directly related to that of the major types of DIs. We support the interpretation of JOHNSON *et al.* (1990) that the arcuate bands resemble fluvial sedimentary deposits and may reflect particle settling processes on the meteorite parent body. We suggest AMNH 2226-7 to be the product of reaccumulation of a fragmented and comminuted C3 chondrite. The predominant occurrence of fine-grained components in this DI may have resulted from either a grain size sorting process during reaccumulation or the disaggregation of already fine-grained precursor material such as type B DIs.

## 1. Introduction

Dark inclusions (DIs) in CV3 chondrites have been the subject of much attention in recent years, and it has been argued by some investigators that they may have experienced aqueous alteration and subsequent thermal dehydration on the meteorite parent body (KOJIMA *et al.*, 1993; KROT *et al.*, 1995; KOJIMA and TOMEOKA, 1996), thus potentially providing valuable information regarding the early evolution of the CV parent body. DIs comprise a petrographic sequence; one endmember contains chon-

*Table 1. Petrologic types of dark inclusions in CV3 chondrites.*

| Type: JOHNSON *et al.* (1990) | Type: KROT *et al.* (1995) | Petrographic characteristics | |
|---|---|---|---|
| c | A | • Chondrules, CAIs, mineral fragments + Fine-grained matrix | chondritic |
| ca | A/B | • Both chondrules and rounded aggregates | intermediate |
| a | B | • Rounded to oval aggregates composed of fine grains of Fe-rich olivine | |
| m | C | • Fine-grained, matrix-like material without chondrules and rounded aggregates | fine-grained |

drules and Ca-Al-rich inclusions (CAIs) embedded in a fine-grained matrix resembling the host CV3 meteorites, and the other endmember lacks chondrules and CAIs but instead contains rounded to ovally-shaped aggregates of Fe-rich olivine (JOHNSON *et al.*, 1990) (Table 1). These endmembers were named type A and B, respectively, by KROT *et al.* (1995). Based on the studies of DIs in Allende, KOJIMA and TOMEOKA (1995, 1996) suggested that the chondrule-bearing DIs (type A) were affected by relatively minor aqueous alteration, thus only the fine-grained matrix was selectively altered, while the chondrule-lacking DIs (type B) were altered extensively so that chondrules and CAIs were almost completely replaced by phyllosilicates. They were subsequently heated, and phyllosilicates were dehydrated to form fine-grained Fe-rich olivine. We consider the oxygen isotopic data of the DIs to be consistent with this interpretation (JOHNSON *et al.*, 1990; CLAYTON and MAYEDA, 1996).

Apart from these types of DIs, JOHNSON *et al.* (1990) reported two unusual DIs (one from Vigarano and the other from Allende) that appear to be unrelated in any obvious way to the sequence which has just been described. They consist almost exclusively of fine grains of mainly Fe-rich olivine and are devoid of chondrules, large mineral fragments and Fe-rich olivine aggregates (chondrule pseudomorphs). Among them, the DI from Vigarano (AMNH 2226-7) has an especially unusual texture, *i.e.*, a network of arcuate bands, some crosscutting one another. JOHNSON *et al.* (1990) pointed out that the bands resemble fluvial sedimentary deposits and suggested that the material accumulated by a particle settling process on a parent body surface. Despite the interesting and potentially important nature of this DI, the mineralogical and petrographic details were not described, and it is still uncertain how it is related to other types of DIs (type A and B). By courtesy of Dr. M. PRINZ, American Museum of Natural History, we were granted the opportunity to study this DI. In the process of our study, we found that this DI was also being studied and described by ZOLENSKY *et al.* (1996). We here present the results of our detailed mineralogical and petrographic study of AMNH 2226-7. In this study, we compare AMNH 2226-7 with the other types of DIs reported from Vigarano and Allende and discuss the genetic relationships between them.

## 2. Material and Methods

A polished thin section (~4.0 cm$^2$ total area ) provided by the American Museum of Natural History was used in this study. AMNH 2226-7, which we hereafter call I-2226-7, is angular and irregular in shape, approximately 1.3×0.7 cm in size in the thin section. It was examined with an optical microscope and a scanning electron microscope (SEM) (JEOL JSM-5800). The SEM is equipped with an Oxford ISIS energy-dispersive X-ray spectrometer (EDS) microanalysis system. EDS analyses were obtained at 15 kV and 0.4 nA, with a focused electron beam of ~2 $\mu$m in diameter. Corrections were made by the Phi-Rho-Z method, using well-characterized natural and synthetic minerals as standards. For the analysis of the fine-grained materials in the DI, we used a defocused electron beam ~10 $\mu$m in diameter.

## 3. Results

I-2226-7 is dark and featureless under an optical microscope, showing a sharp boundary with the host Vigarano (Fig. 1). It consists predominantly (~85 volume %) of extremely fine grains (<5 $\mu$m in diameter) of olivine ($Fo_{49-65}$) and contains neither chondrules (of normal size) nor rounded Fe-rich olivine aggregates (chondrule pseudomorphs). Minor mineral grains <5 $\mu$m in diameter include Ca-rich pyroxene, Fe-Ni metal and chromite. Fe-Ni sulfide occurs in trace amounts. Most olivine grains are so small (<1 $\mu$m) that each grain is hardly resolvable by SEM. Relatively coarse olivine grains (2–5 $\mu$m) have granular, equidimensional morphologies (Fig. 2), some of which show Fe-Mg zoning, with a relatively high Mg content (<$Fo_{94}$) in the core. The olivine grains in I-2226-7 resemble those in the matrix and chondrule rims of the host Vigarano meteorite, although the former are slightly poorer in Fe ($Fo_{49-57}$ *vs.* $Fo_{38-53}$) (The former compositional range does not include the data of apparently zoned grains). Olivine grains having an elongated morphology occur sparsely as individual grains. EDS broad beam analysis of the fine-grained components of I-2226-7 reveals that they are more homogeneous and significantly lower in Fe/(Fe+Mg) ratio than those in the matrix of host Vigarano (Fig. 3); the lower Fe/(Fe+Mg) ratio is due to the lower Fe content of olivine and less abundant Fe-Ni metal and/or sulfide grains. Matrix of type B DIs from Vigarano (DC1 & DC2) (Kojima *et al.*, 1993) shows a similar Fe/(Fe+Mg) distribution to I-2226-7, but is slightly enriched in Fe (Fig. 3), due to more ubiquitous Fe-Ni metal grains. Chondrule pseudomorphs from type B DIs range widely in Fe/(Fe+Mg) ratio (0.40–0.64); the ratios vary significantly between pseudomorphs. Generally, chondrule pseudomorphs are poorer in Fe than fine-grained olivine in I-2226-7.

Relatively coarse grains (10–60 $\mu$m in diameter) of Mg-rich olivine ($Fo_{83-98}$), Fe-rich olivine ($Fo_{28-70}$), enstatite, spinel, melilite and perovskite are dispersed throughout the DI (Fig. 4). They are mostly angular in shape, suggesting a clastic origin. In addition to these monomineralic grains, there are small polymineralic aggregates (20–60 $\mu$m in diameter). For example, enstatite enclosing forsterite or Fe-Ni metal, and spinel surrounded by thin rims of Ca-rich pyroxene are common (Figs. 5a, b); from their textures, they are likely to be fragments of olivine-pyroxene chondrules and CAIs.

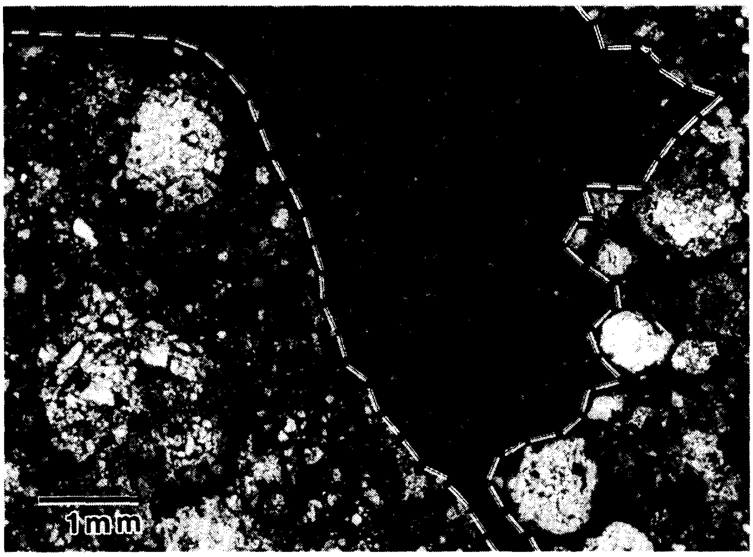


*Fig. 1. Transmitted light optical microscope image of I-2226-7 (dark part). The boundary between the DI and host Vigarano is indicated by a broken line.*

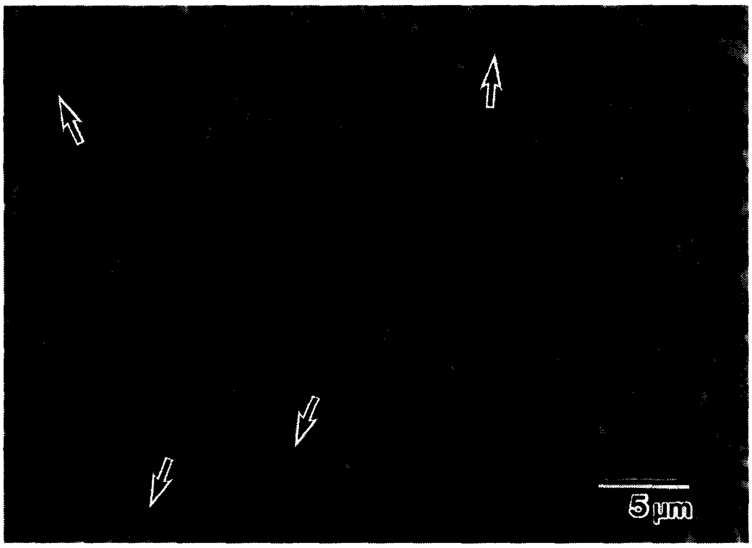


*Fig. 2. High-magnification backscattered electron (BSE) image of a portion of I-2226-7. Some of relatively coarse olivine grains show Fe-Mg zoning (arrowed).*

Very small chondrule-like objects (<60 $\mu$m in diameter) occur as rare constituents (Fig. 5c). Many of the coarse grains of Mg-rich olivine, enstatite and spinel show Fe enrichment at their edges and along grain boundaries and cracks. Some Fe-rich olivine grains contain minute inclusions (<0.5 $\mu$m) of Fe-Ni metal and sulfide (Fig. 6), resembling those in a type B Allende DI (cf. Fig. 12 in KOJIMA and TOMEOKA, 1996).

A striking feature of I-2226-7 is a network of arcuate bands. They appear bright and distinctive in reflected light and in backscattered electron (BSE) imaging (Figs. 7–10). Several bands commonly occur roughly parallel to each other, forming a set of consecutive parallel bands (Fig. 7a). A more peculiar feature is that different sets of parallel bands crosscut one another, some almost orthogonally (Figs. 7b, 8, 9). The widths of bands and the interband spacings are roughly equal in each set of bands but differ greatly between sets; the widths vary in the range from <10 to 500 $\mu$m, and the interband spacings from 50 $\mu$m to 1 mm. The lengths of the bands extend from 250 $\mu$m to 3.5 mm. An important feature is that the boundary between the band and the matrix is sharp on the outer side of each arc, while it is commonly gradational on the inner side (Figs. 7b, 8); the gradation is correlated with a decrease of Fe content. The gradation is particularly pronounced in bands having relatively long interband spacing and extends over a distance of 300–500 $\mu$m (Figs. 7b, 8). In portions, a set of narrow (~10 $\mu$m in width), strongly-curved bands occur in a concentric manner, exhibiting a peculiar ripple-like texture (Fig. 9).

The bands are composed mainly of fine grains of Fe-rich olivine, which are similar in morphology to those in other areas but relatively smaller in size and more densely packed (Fig. 10). The olivines are slightly more enriched in Fe than those in other areas ($Fo_{49-54}$ *vs.* $Fo_{51-57}$). Particles (~2 $\mu$m in diameter) rich in Fe and Ni are dispersed in the bands (Fig. 10b). The denser packing and the higher Fe content of the olivine grains in the bands are probably the causes of the high optical reflectance and high BSE scattering. The results of EDS broad beam analysis are shown in Table 2

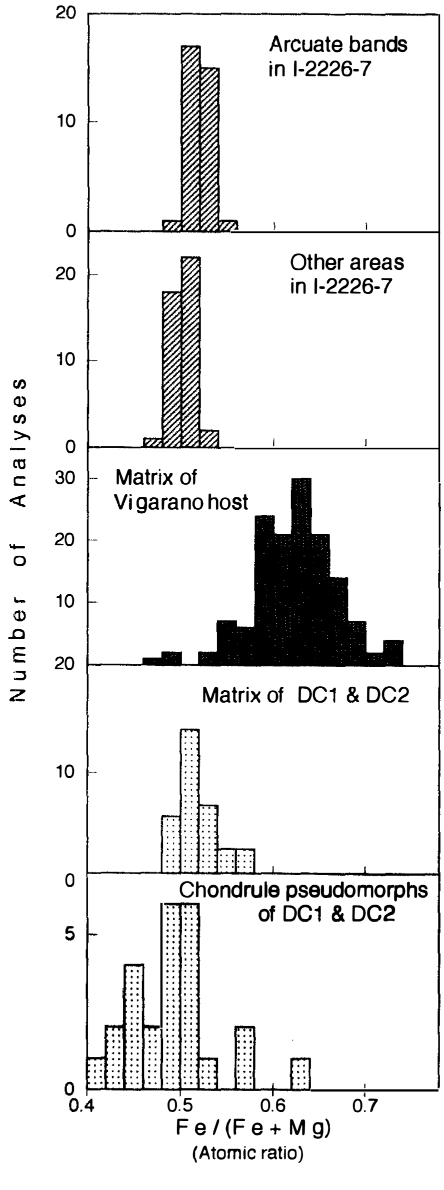


*Fig. 3. Fe/(Fe+Mg) ratios of the fine-grained components (<3 μm in diameter) in I-2226-7, matrix of host Vigarano and type B DIs from Vigarano (DC1 & DC2). Randomly selected points were analyzed using a defocused electron beam of 10 μm in diameter. Mineral grains >3μm in diameter were avoided.*

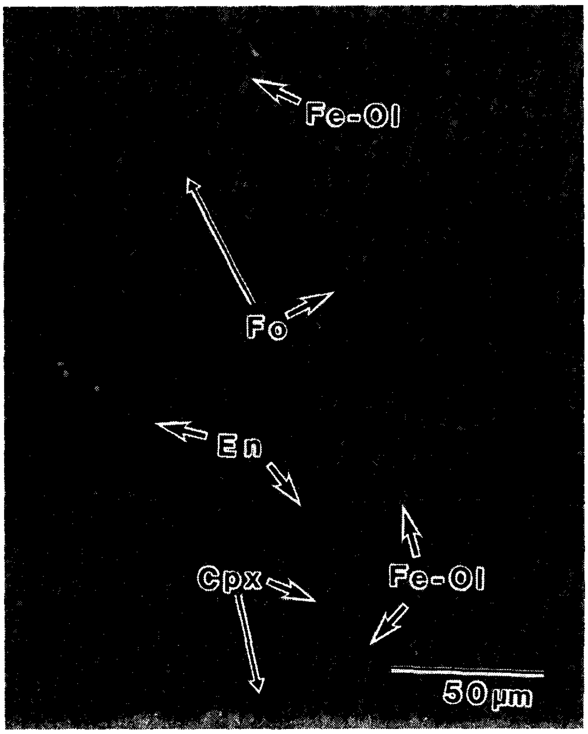


*Fig. 4. A portion of I-2226-7. Relatively coarse grains of forsterite (Fo), Fe-rich olivine (Fe-Ol), enstatite (En), and Ca-rich pyroxene (Cpx) occur in the matrix consisting of fine grains of Fe-rich olivine. Some of the coarse grains have angular shapes, suggesting a clastic origin.*

and Fig. 11. In addition to their Fe enrichment, the bands are slightly richer in Ni than are other areas, which can be explained by a higher amount of Fe-Ni-rich particles. Otherwise there is no significant difference in major elements. The ranges of Fe/(Fe+Mg) and Ni/Si ratios of I-2226-7 overlap those of the matrix of type B DIs from Vigarano, but are distinctly higher than those of chondrule pseudomorphs (Fig. 11). Coarser monomineralic grains and fragments of chondrules and CAIs also occur in the bands (Fig. 10). There is no difference in the size and frequency of these grains and fragments between bands and other areas.

In some interband areas, there are randomly-distributed regions (typically 30–200 μm in diameter) rich in Fe, some as rich as in the bands, exhibiting a somewhat mottled appearance in BSE imaging (Fig. 7a). Those areas have mineralogy and texture similar to the bands, suggesting a genetic relationship between them.

Although not described by previous authors (JOHNSON *et al.*, 1990; ZOLENSKY *et al.*, 1996), a minor amount of calcite is found to occur in I-2226-7 commonly as fracture filling veins having a width of ~5 μm and extending to a distance of ~1 mm. One of the veins crosscuts a set of parallel arcuate bands. Calcite is also found in the host Vigarano meteorite, being particularly abundant in the vicinity of I-2226-7. Calcite in the host meteorite occurs mainly as a replacement product of chondrules and also a vein filling; some calcite veins crosscut several chondrules and matrix. From these observations, calcite formation probably postdated both the incorporation of the I-2226-7 clast to the host meteorite and the consolidation of the host meteorite.

## 4. Discussion

It is clear that the textures and mineralogy of I-2226-7 are distinct from the major

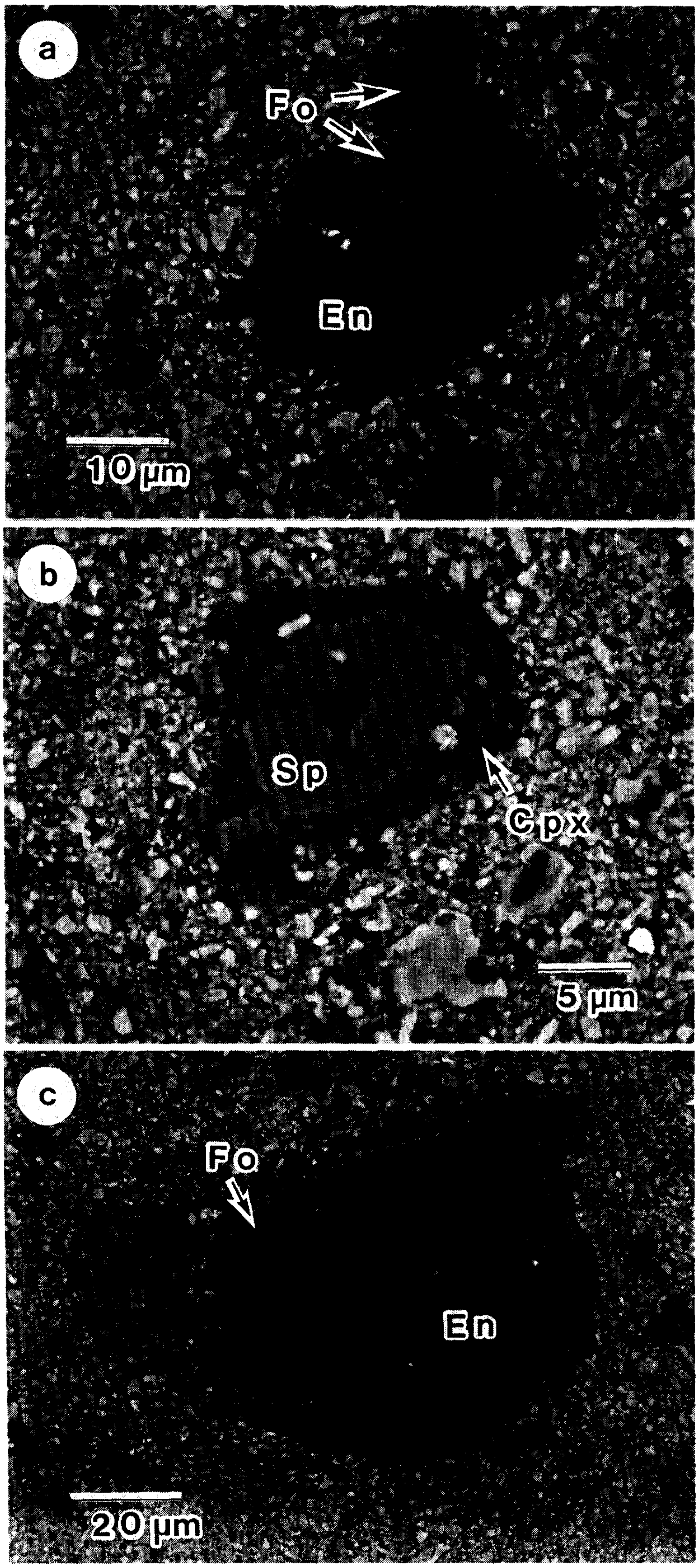


*Fig. 5. A variety of polymineralic aggregates in I-2226-7. (a) Enstatite (En) poikilitically enclosing rounded forsterite grains (Fo). (b) Fe-rich spinel (Sp) surrounded by a thin rim of Ca-rich pyroxene (Cpx). (c) A round object composed of enstatite and forsterite having a chondrule-like appearance.*

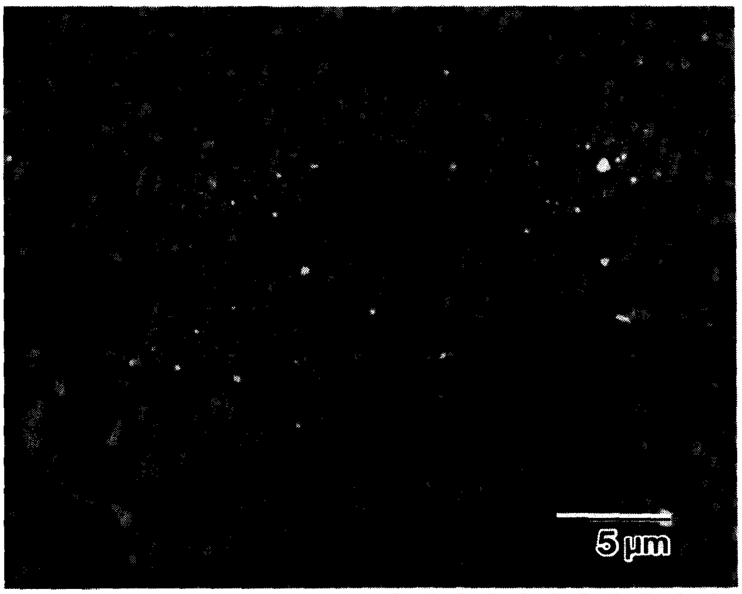


*Fig. 6. An Fe-rich olivine grain containing minute inclusions of Fe-Ni metal and sulfide (bright specks). The core (dark rounded area) of the grain is relatively poor in Fe, free of inclusions, and appears smooth on the surface.*

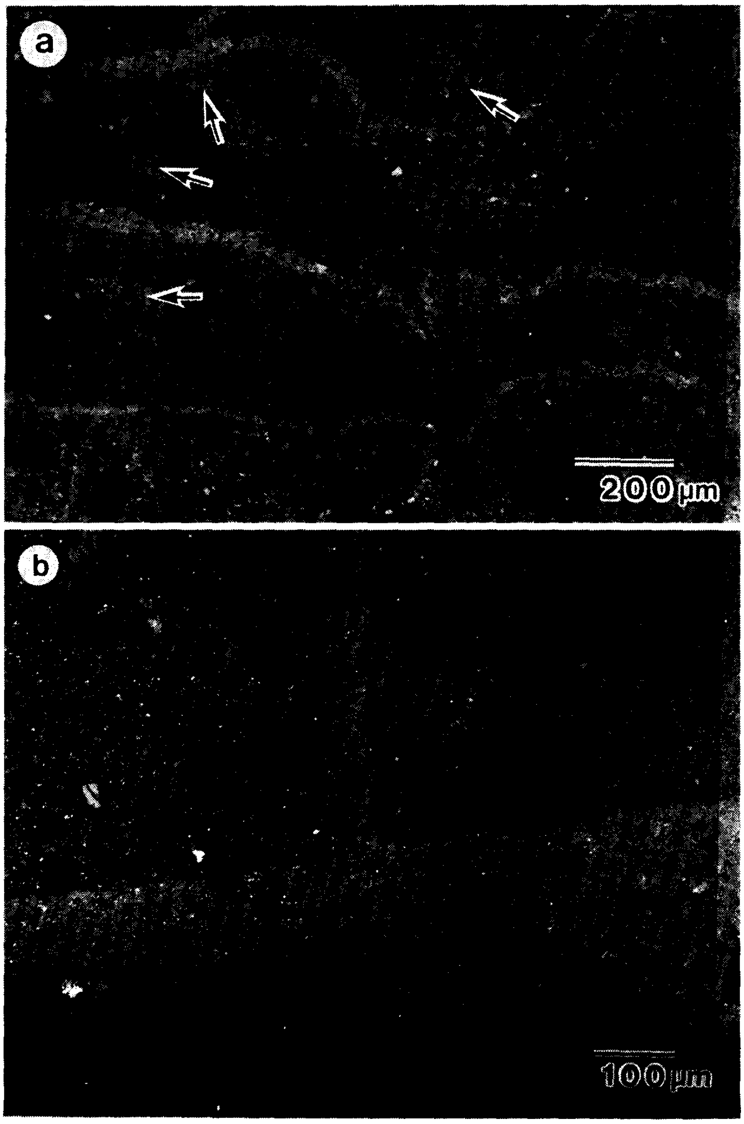


*Fig. 7. (a) A set of arcuate bands that occur roughly parallel to one another. Regions (arrowed) that appear as bright as the bands occur in the interband areas. (b) Arcuate bands crosscutting one another almost orthogonally. The crosscutting band shows a sharp edge on the outer side of the arc (upside) but a long gradational change (~400 μm) on the inner (downward) side of the arc.*

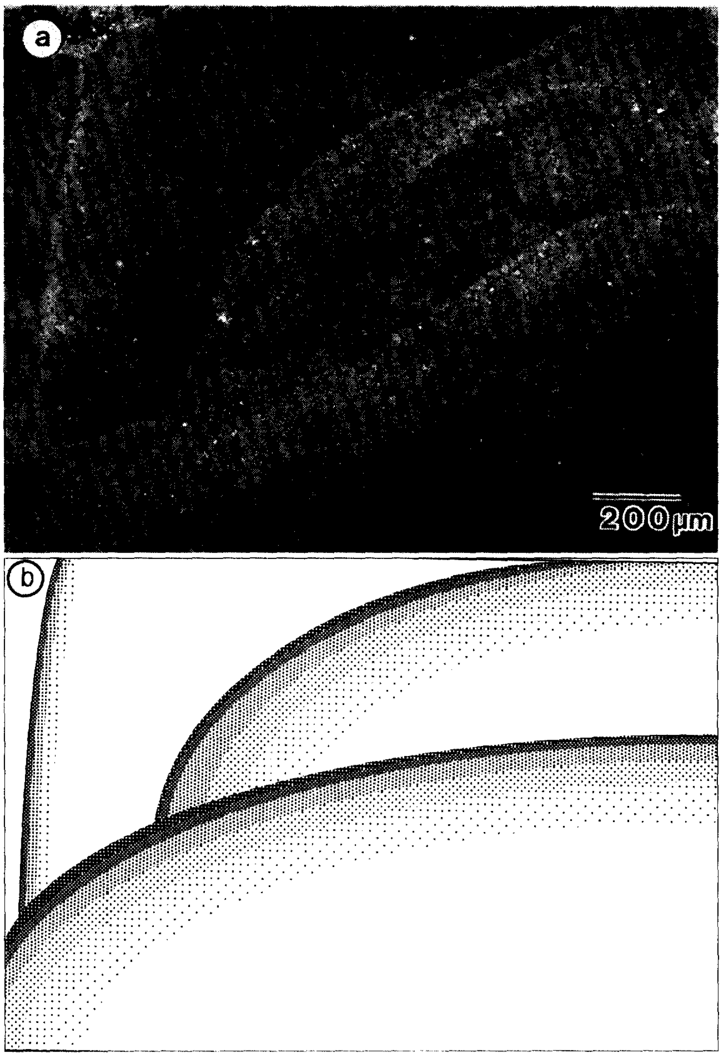


*Fig. 8. (a) An arcuate band (the lowest) crosscutting a set of two bands. Note that the outer sides of the arcs are sharp, while the inner sides are gradational over a distance of 200-400 µm. (b) A schematic illustration of (a), which is somewhat simplified to emphasize the gradational feature.*

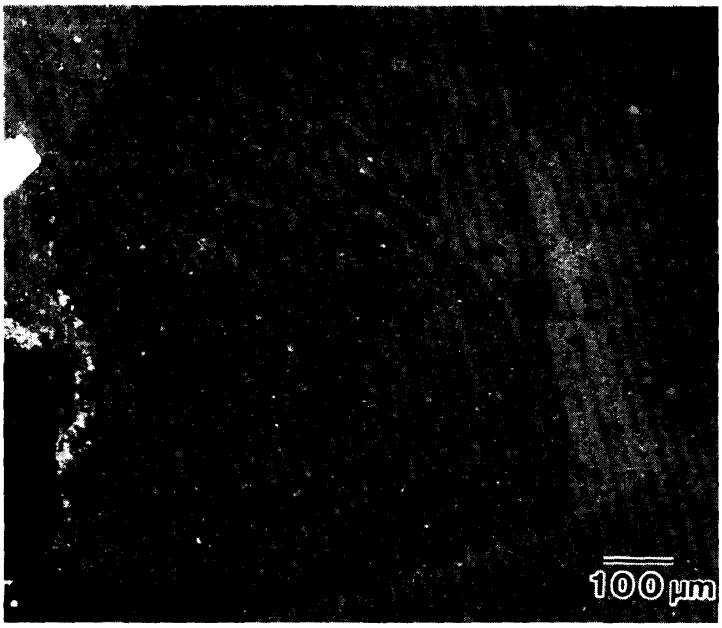


*Fig. 9. A set of strongly-curved narrow bands showing a ripple-like texture. A nearly orthogonal crosscutting of bands is seen at the lower-right corner.*

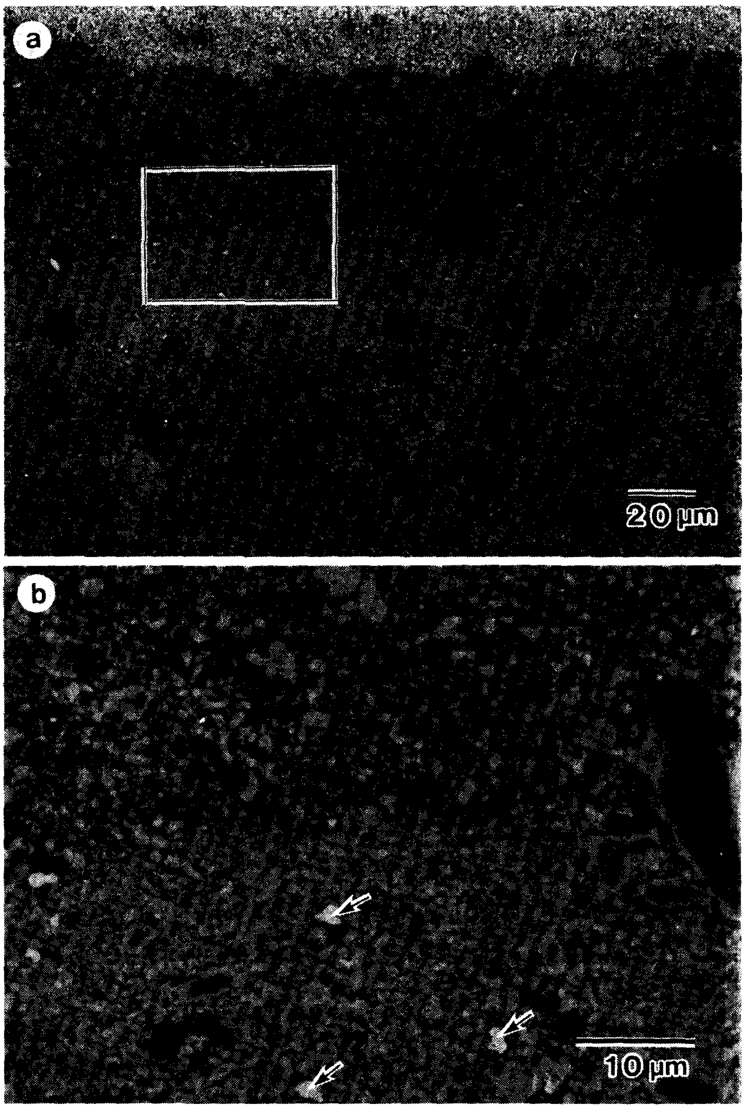


*Fig. 10. (a) A portion of an arcuate band. (b) High-magnification image of the boxed area in (a). The band contains a higher amount of Fe-Ni rich particles (arrowed) than other areas.*

group of DIs (types A and B). Although it consists predominantly of fine grains of Fe-rich olivine as in the highly replaced DIs (type B), no chondrule pseudomorphs are found. Only tiny fragments of chondrules and CAIs are dispersed throughout the DI. The aggregate of olivine grains having acicular to fibrous morphologies, characteristic of dehydrated phyllosilicates and one of the major morphologies of olivine in type A and B DIs, is completely absent. Tiny grains (<5 $\mu$m) of zoned olivine, which are extremely rare or absent in highly replaced DIs (type B), are common. These observations indicate that the formation of I-2226-7 cannot be explained by direct replacement of a precursor chondrite, *i.e.*, a sequence of aqueous alteration and dehydration of a chondrite. I-2226-7 probably represents a clast having an origin not directly related to the DIs containing chondrules and/or chondrule pseudomorphs (types A and B). Our observations support the interpretation of JOHNSON *et al.* (1990) that this DI formed by the accumulation of fine grains on the meteorite parent body.

The texture of cross cutting arcuate bands is unique and apparently provides a key to understanding the formation history of I-2226-7. ZOLENSKY *et al.* (1996) sug-

*Table 2. Bulk compositions of I-2226-7 and host Vigarano (w%).*

| | I-2226-7 | | | | Vigarano host | | Vigarano Type B DI |
|---|---|---|---|---|---|---|---|
| | *Fine-grained material | | Bulk[1] | Bulk[2] | Matrix[3] | Bulk[4] | DC1 & DC2[5] |
| | Arcuate bands | Other areas | | | | | |
| $SiO_2$ | 28.5 | 29.1 | 31.4 | 29.7 | 28.4 | 29.6 | 31.7 |
| $Al_2O_3$ | 3.02 | 3.52 | 2.10 | 4.33 | 4.33 | 2.98 | 2.64 |
| $TiO_2$ | n. d. | n. d. | 0.10 | 0.07 | 0.07 | 0.21 | 0.09 |
| FeO | 35.0 | 33.0 | 30.8 | 37.0 | 41.5 | 28.6 | 30.3 |
| MnO | 0.37 | 0.48 | 0.31 | 0.32 | 0.25 | 0.19 | 0.23 |
| MgO | 19.9 | 20.0 | 21.7 | 20.8 | 16.6 | 21.3 | 21.8 |
| CaO | 1.85 | 1.74 | 3.00 | 3.80 | 1.13 | 2.31 | 1.33 |
| $Na_2O$ | 0.38 | 0.48 | 0.09 | 0.17 | 0.59 | 0.44 | 0.28 |
| $K_2O$ | n. d. | 0.03 | 0.01 | 0.01 | 0.03 | 0.05 | 0.08 |
| $Cr_2O_3$ | 0.45 | 0.46 | 0.51 | 0.68 | 0.44 | 0.46 | 0.56 |
| NiO | 2.24 | 1.49 | 1.64 | 1.78 | 3.40 | 1.51 | 1.20 |
| S | 0.22 | 0.21 | n. a. | 0.11 | 0.16 | 2.09 | 0.16 |
| Total | 91.9 | 90.5 | 91.7 | 97.9 | 96.8 | 90.0 | 90.1 |

n. d.=below detection limit. n. a.=not analyzed.

* Average of more than 40 analyses of randomly selected areas of 10 μm in diameter. Areas including grains of >3 μm in diameter were avoided.

References:

[1] JOHNSON *et al.* (1990); [2] ZOLENSKY *et al.* (1996); [3] ZOLENSKY *et al.* (1993);
[4] MASON (1963). Normalized to total 90%. [5] KOJIMA *et al.* (1993). Average of 64 analyses.

gested that the bands are healed fractures and fine grains of Fe-rich olivine in the bands formed during a post-accretional reaction with an Fe-rich gas introduced through fractures. However, the following features cannot be explained by such a fracture healing process: (1) gradation of Fe-rich bands which always extends toward the *inner side* of arc (Figs. 7b, 8), over a distance of 300–500 μm, (2) the consecutive, equally-spaced parallel arrangement of bands, especially concentric, ripple-like texture (Fig. 9) , (3) the crosscutting of different sets of roughly parallel bands such as the one illustrated in Fig. 8, (4) the occurrence of mottled regions in the interband areas that are similar in mineralogy and texture to the bands (Fig. 7a). We agree with JOHNSON *et al.* (1990) that the general appearance of the bands resembles fluvial sedimentary deposits and they may have formed by sedimentary processes on the meteorite parent body. Although it is still uncertain what kind of events are actually responsible for such deposition process, we suggest that the formation of the bands proceeded in the presence of fluid, possibly water in the parent body.

Assuming our interpretation for the accumulation process is valid, a next important question is what is the source of the fine-grained components in I-2226-7. An important feature of this DI is the abundant and dispersive occurrence of tiny fragments of chondrules and CAIs, which suggests that there was a significant degree of brecciation and comminution of a precursor C3 chondrite probably due to impact. Taking into account that the Vigarano host itself is highly brecciated, the brecciation and comminution process may be somewhat related to the brecciation process for the host meteorite, but may be even more intensive and thorough. The predominant occur-

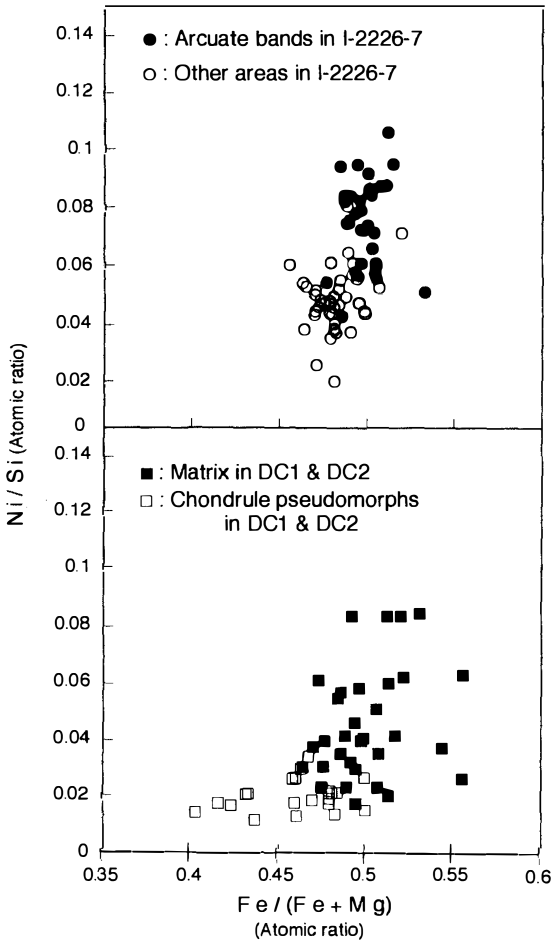


*Fig. 11. Plot of Fe/(Fe+Mg) vs. Ni/Si ratios of the fine-grained components in I-2226-7 and in type B dark inclusion from Vigarano (DC1 and DC2). Analyzed using a defocused electron beam 10 μm in diameter.*

rence of extremely fine olivine grains (<1 μm) may indicate that broken fragments and comminuted grains went through some kind of grain separation or sorting processes before final accumulation. Alternatively, the fine grains of I-2226-7 may have resulted from the disaggregation of already fine-grained material such as type B DIs. Although I-2226-7 shows texture most plausibly explained by the accumulation of fine particles (not by replacement of a chondrite), there are common features in composition (Figs. 3, 11), morphology and grain size between olivines in I-2226-7 and type B DIs in Vigarano (KOJIMA *et al.*, 1993), except that the acicular to fibrous grains are much less common in I-2226-7. The presence of Fe-rich olivine containing minute inclusions of Fe-Ni metal and sulfide (Fig. 6) also supports a relationship between I-2226-7 and type B DIs.

The presence of calcite veins in I-2226-7 suggests that this DI has been involved in some kind of aqueous activity on the meteorite parent body. However, as mentioned above, the occurrence of the calcite veins indicates that the aqueous activity responsible for the formation of calcite occurred after the incorporation of I-2226-7 to the present location. A recent TEM study of LEE *et al.* (1996) showed that the matrix of Vigarano contains small amounts of ferrihydrite and smectite that were probably formed by aqueous alteration of matrix olivines. TANIMURA *et al.* (1996) also showed evidence that some chondrules in Vigarano appear to have been partly replaced by phyllosilicates after accretion. All of these observations are consistent with the interpretation that Vigarano was involved in aqueous alteration even after consolidation, although relatively minor in degree.

## Acknowledgments

We thank Dr. M. PRINZ for providing the AMNH 2226-7 sample and helpful review and Drs. K. KAMATA and N. NAKAMURA for valuable discussion. We also thank an anonymous reviewer for useful comments. This work was supported by Grant-in-Aid of Japan Ministry of Education, Science and Culture (No. 06403001).

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*(Received September 24, 1996; Revised manuscript accepted December 16, 1996)*