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Arcuate band texture in a dark inclusion from the Vigarano CV3 chondrite: Possible evidence for early sedimentary processes

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Abstract–A dark inclusion in the Vigarano CV3 carbonaceous chondrite consists almost exclusively of small (<5 μm in diameter) grains of Fe-rich olivine and is devoid of chondrules, Ca-Al-rich inclusions (CAIs) and their pseudomorphs. In backscattered electron images, this dark inclusion shows an unusual texture comprising a network of arcuate bands. Two or more bands occur roughly parallel, forming a set of succesive parallel bands, some crosscutting one another. The bands contain slightly higher amounts of relatively small (<1 μm) olivine grains and so are more densely packed than other areas. The olivine grains in the bands are slightly more Fe-rich than those in other areas. The bands commonly show gradation on the concave side due to a decrease in the abundance of the small Fe-rich olivine grains. Texturally, the arcuate bands closely resemble "dish structures" that are commonly observed in siltstones and sandstones on Earth. Dish structures are characterized by thin, dark-colored, subhorizontal to concave-upward laminations that are rich in relatively fine-grained material. On Earth, dish structures form during compaction and dewatering of unconsolidated fine-grained sediments; they are one of the characteristic sedimentary structures formed through fluidization of fine grains. The dark inclusion in Vigarano, therefore, provides the first evidence that sedimentary processes due to water migration may have taken place within planetesimals and further suggests that fluidization may have played a significant role in the formation of the carbonaceous chondrites.

INTRODUCTION

Type 3 carbonaceous chondrites are commonly believed to have escaped major degrees of aqueous alteration and thermal metamorphism within meteorite parent bodies and, thus, may be petrologically the most primitive of the known meteorite types (*e.g.*, McSween, 1979). However, it has been suggested recently that dark inclusions (DIs) in CV3 chondrites were affected by extensive aqueous alteration and subsequent dehydration on the meteorite parent body (Kojima *et al.*, 1993; Krot *et al.*, 1995, 1997; Kojima and Tomeoka, 1996). There is also growing evidence that most of the CV3 chondrites were involved in various degrees of aqueous alteration (Tomeoka and Buseck, 1990; Keller and Buseck, 1990; Keller *et al.*, 1994; Lee *et al.*, 1996; Brearley, 1997). Many DIs contain chondrules, Ca-Al-rich inclusions (CAIs) and/or pseudomorphs of these objects. The pseudomorphs formed by aqueous alteration and subsequent dehydration. Thus, originally the DIs were probably lithic clasts of chondritic material, most likely the host CV3 chondrites (Kojima *et al.*, 1993; Kojima and Tomeoka, 1996). This implies that there was a local region (or regions) in the CV parent body that at one time was involved in extensive aqueous activity.

In contrast to most DIs, which contain chondrules, CAIs and/or their pseudomorphs, Johnson *et al.* (1990) reported an unusual DI (AMNH 2226-7) from Vigarano. Inclusion AMNH 2226-7 consists almost exclusively of fine mineral grains, mainly Fe-rich olivine, and is devoid of chondrules, CAIs, large mineral fragments and Fe-rich olivine aggregates (chondrule pseudomorphs). This DI has an especially unusual texture that comprises a network of arcuate bands, some crosscutting one another. Such a texture has not been reported from any other meteorite. Despite the rare and potentially important nature of this DI, its mineralogical and petrographic details have yet to be described. Here, we present the results of detailed scanning electron microscopic (SEM) observations of AMNH 2226-7. Our study has revealed that the arcuate bands closely resemble dish structures that form by the fluidization of silt- and sand-grade sediments on Earth. We will compare the textures of AMNH 2226-7 with possible terrestrial analogues and discuss potential formation processes of this DI.

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. In the thin section, AMNH 2226-7 is angular and irregular in shape and ~1.3 × 0.7 cm in size. It was examined with an optical microscope and a scanning electron microscope (JEOL JSM-5800) equipped with an energy dispersive x-ray spectrometer (EDS). For most observations, we used backscattered electron imaging. Analyses by EDS were obtained at 15 kV and 0.4 nA, with a focused electron beam ~2 μm in diameter. For the analysis of the fine-grained materials in the DI, a defocused electron beam ~10 μm in diameter was used. Wavelength dispersive x-ray spectrometer (WDS) analyses were obtained with a JEOL JXA-8900 electron microprobe (EPMA) operated at 15 kV and 12 nA with a focused electron beam ~2 μm in diameter. For both EDS and WDS analyses, well-characterized natural and synthetic minerals were used as standards.

RESULTS

General Features

Inclusion AMNH 2226-7 consists predominantly of fine grains of Fe-rich olivine (Fo_{49-57}) , most of which range in diameter from <1 to 5 μm. Minor mineral grains (<5 μm in diameter) include Ca-rich clinopyroxene, Fe-Ni metal, chromite and Fe-Ni sulfide. Most olivine grains are anhedral to granular in morphology. In their size and morphology, these olivine grains resemble those in the matrix of the host Vigarano meteorite and also those in the matrix of the other DIs in Vigarano (DC1 and DC2 in sample USNM#477) (Kojima *et al.*, 1993). These other DIs, which contain chondrule pseudomorphs, have probably experienced extensive aqueous alteration and subsequent dehydration. The EDS broad beam analysis indicates that the fine grains in AMNH 2226-7 resemble grains in the matrices of the other DIs in Vigarano (DC1 and DC2) (Kojima *et al.*, 1993), but they are distinctly more homogeneous in composition and lower in Fe/(Fe + Mg) ratio than those in the matrix of the host meteorite (Fig. 1, Table 1).

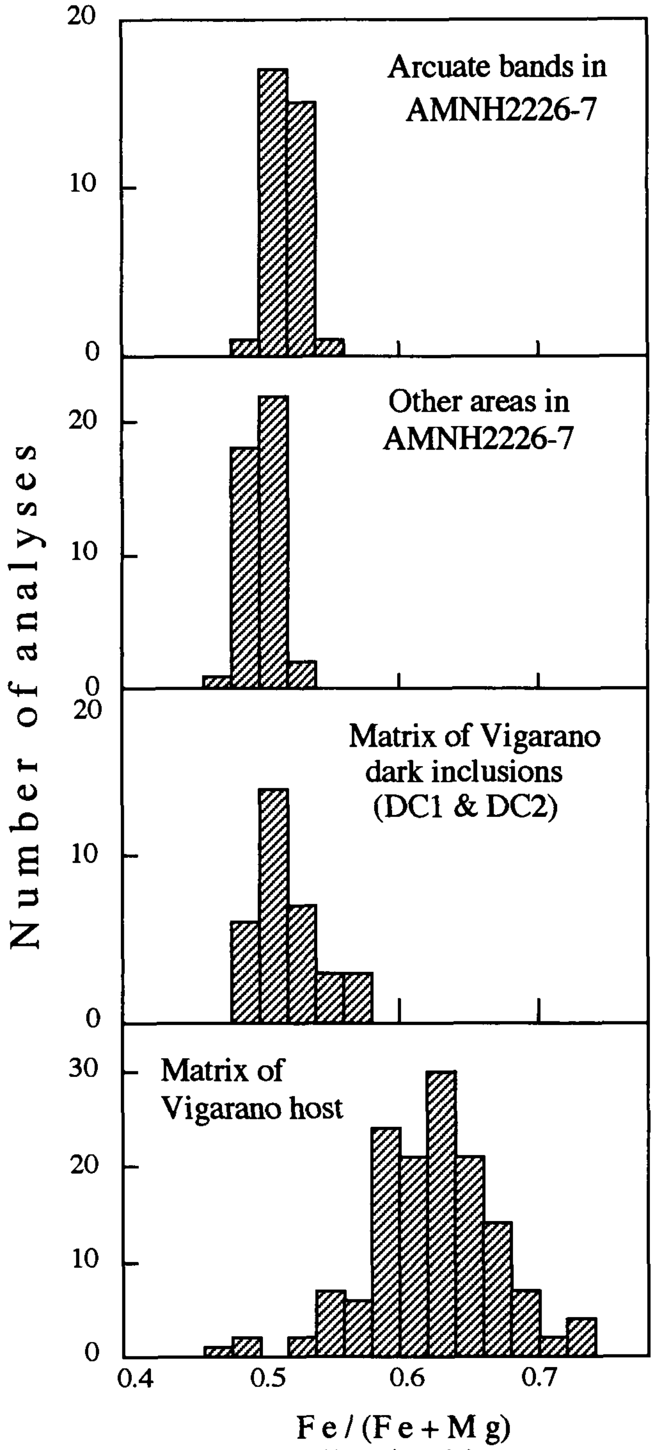

FIG. 1. The Fe/(Fe+Mg) ratios of arcuate bands and other areas in AMNH 2226-7, other Vigarano dark inclusions (DC1 and DC2; see Kojima *et al.*, 1993), and Vigarano host. Over 20 randomly selected points were analyzed using a defocused electron beam 10 μm in diameter.

Minor amounts of relatively coarse grains (10–60 μm in diameter) of Mg-rich olivine (Fo_{83-98}), Fe-rich olivine (Fo_{28-70}), Ca-rich clinopyroxene, enstatite, spinel, melilite and perovskite are dispersed throughout the DI (Fig. 2); compositions of some of these minerals are shown in Table 2. They are commonly angular in shape. There are also minor amounts of polymineralic aggregates (20–60 μm in diameter), such as enstatite enclosing forsterite or Fe-Ni metal, and spinel enclosed by thin rims of Ca-rich clinopyroxene (Fig. 3a,b). Many of the coarse grains of Mg-rich olivine, enstatite and spinel show Fe enrichment along grain edges and boundaries, which are similar to the grains in chondrules and CAIs in the host Vigarano and other CV3 chondrites (*e.g.*, Krot *et al.*, 1997). From texture and mineralogy, these coarse grains and aggregates are likely to be fragments of chondrules and CAIs, which suggests that AMNH 2226-7 has an origin related to the C3 chondrites, although it now contains neither chondrules nor CAIs. Calcite occurs in places as 2–5 μm wide fracture-filling veins that extend over a distance of ~1 mm.

Arcuate Bands

Low-magnification backscattered electron images show that the DI has a large-scale texture comprising arcuate bands. Arcuate bands appear bright in backscattered electron images (Fig. 4a,b). Most bands have approximately the same orientation. Two or more bands sometimes form sets of roughly parallel bands. Some of the bands crosscut one another. The bands typically range in apparent thickness from 0.05 to 0.3 mm and in length from 1.0 to 3.5 mm. Many of the bands are cut by the DI boundaries; so they must have been much longer originally. The boundary between a band and the matrix is sharp on the convex side of each arc; while it is commonly gradational on the concave side. The gradation is sometimes recognizable over a distance of 0.3–0.5 mm (Fig. 4c).

The bands are mainly composed of fine grains of Fe-rich olivine, which are similar in morphology to those in the interband areas. However, the bands contain slightly greater numbers of relatively small (<1 μm in diameter) grains that fill interstices between relatively larger (1–5 μm) grains, thus exhibiting a texture that is more densely packed than other areas of the DI (Fig. 5). The olivine grains are slightly more enriched in Fe than those in the interband areas (Fo_{49-54} *vs.* Fo_{51-57}) (also see Table 1). Small Fe-Ni-rich particles

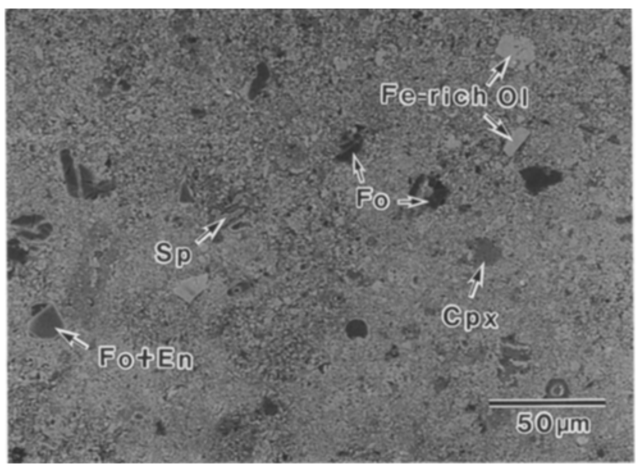

FIG. 2. A backscattered electron image of a portion of AMNH 2226-7. Relatively coarse (10–60 μm in diameter) grains of forsterite (Fo), Fe-rich olivine (Fe-rich Ol), enstatite (En), Ca-rich clinopyroxene (Cpx) and Fe-rich spinel (Sp) are dispersed in the matrix that consists mainly of fine grains of Fe-rich olivine.

TABLE 1. Bulk compositions of AMNH 2226-7, other Vigarano DIs and Vigarano host (wt%).

	AMNH 2226-7		Vigarano DIs (DC1 and DC2)		Vigarano host	
	Arcuate bands*	Other areas*	Matrix†	Bulk†	Matrix*	Bulk‡
SiO_2	28.3	28.9	31.0	31.7	27.8	29.7
Al_2O_3	2.78	3.24	2.73	2.61	3.63	2.99
TiO_2	n.d.	n.d.	0.07	0.09	n.d.	0.20
FeO	33.9	31.9	31.2	30.3	37.1	28.7
MnO	0.39	0.40	0.22	0.23	0.34	0.18
MgO	19.1	19.2	21.0	21.8	15.4	21.3
CaO	1.86	1.75	1.28	1.33	1.45	2.33
Na_2O	0.38	0.48	0.32	0.28	0.65	0.44
K_2O	n.d.	0.03	0.08	0.08	n.d.	0.05
Cr_2O_3	0.49	0.50	0.50	0.56	0.38	0.46
NiO	2.64	1.75	1.40	1.20	1.60	1.52
S	0.23	0.22	0.17	0.16	0.42	2.10
Total	90.1	88.4	90.0	90.3	88.8	90.0

*Averages of >40 analyses of randomly selected areas of 10 μm in diameter. Areas including grains of >3 μm in diameter were avoided.
†Kojima *et al.* (1993). Averages of 28 and 64 analyses for matrix and bulk, respectively.
‡Mason (1963). Normalized to total 90%.
n.d. = below detection limit.

TABLE 2. Selected electron microprobe analyses of relatively coarse mineral grains in AMNH 2226-7

	Ol	Ol	Ol	Ol	Px	Px	Px	Sp
SiO_2	42.4	42.1	40.7	35.2	59.4	58.0	55.1	n.d.
Al_2O_3	0.19	0.08	n.d.	0.07	0.08	0.95	1.31	71.4
TiO_2	n.d.	0.04	0.04	0.09	0.09	0.11	0.13	0.20
FeO	0.94	3.82	11.6	38.2	2.65	1.82	0.49	1.49
MnO	0.03	0.13	0.60	0.52	0.15	0.06	n.d.	n.d.
MgO	56.1	53.3	47.6	24.7	37.3	33.4	19.4	27.5
CaO	0.50	0.25	0.15	0.83	0.14	5.27	23.6	0.04
Na_2O	n.d.	n.d.	n.d.	0.04	0.02	0.11	0.03	n.d.
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n. d	n.d.	n.d.
Cr_2O_3	0.07	n.d.	n.d.	0.03	0.11	0.19	n.d.	0.08
NiO	n.d.	0.09	n.d.	0.35	n.d.	0.24	n.d.	n.d.
Total	100.2	99.8	100.7	100.0	99.9	100.2	100.1	100.7
Si	5.98	6.03	6.00	5.99	8.04	7.94	7.91	n.d.
Al	0.03	0.01	n.d.	0.01	0.06	0.15	0.22	12.0
Ti	n.d.	0.00	0.00	0.01	0.01	0.01	0.01	0.02
Fe	0.11	0.46	1.44	5.44	0.30	0.21	0.06	0.18
Mn	0.00	0.02	0.07	0.07	0.02	0.01	n.d.	n.d.
Mg	11.8	11.4	10.4	6.26	7.53	6.81	4.13	5.83
Ca	0.07	0.04	0.02	0.15	0.02	0.77	3.64	0.01
Na	n.d.	n.d.	n.d.	0.01	0.00	0.03	0.01	n.d.
K	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cr	0.01	n.d.	n.d.	0.00	0.01	0.02	n.d.	0.01
Ni	n.d.	0.01	n.d.	0.05	n.d.	0.03	n.d.	n.d.

Ol = olivine, Px = pyroxene, Sp = spinel. Atomic ratios are calculated as O = 24.
n.d. = below detection limit.

(~2 μm in diameter) are dispersed throughout the bands. The Fe enrichment of olivine and the denser packing of the grains are probably the main causes of the bright contrast when imaged using backscattered electrons. The gradation in grain size on the concave sides of the bands is due to a decrease in the abundance of the smaller grains of more Fe-rich olivine away from the contact. The EDS broad beam analysis shows no significant difference in major element concentrations between the bands and the interband areas, except for slight Fe and Ni enrichment in the bands (Table 1).

DISCUSSION

Relationship to Dish Structures

Johnson *et al.* (1990) pointed out that the crosscutting arcuate bands in AMNH 2226-7 resemble structures characteristic of terrestrial fluvial sedimentary deposits but did not mention any specific details that can be related to sedimentary processes. Zolensky *et al.* (1996) suggested that the bands are healed fractures formed by a reaction with an Fe-rich gas introduced through fractures. However, some of the textural characteristics described above, especially the gradation of the bands on the concave side of each arc, cannot be explained by such a fracture healing process.

In an extensive literature survey, we found the arcuate bands to be closely similar to the "dish structure" that is commonly observed in terrestrial siltstone and sandstone sedimentary rocks, especially turbidite sequences (Stauffer, 1967; Lowe and LoPiccolo, 1974) (Fig. 6a,b). Dish structures are defined, as seen in cross-sections oriented normal

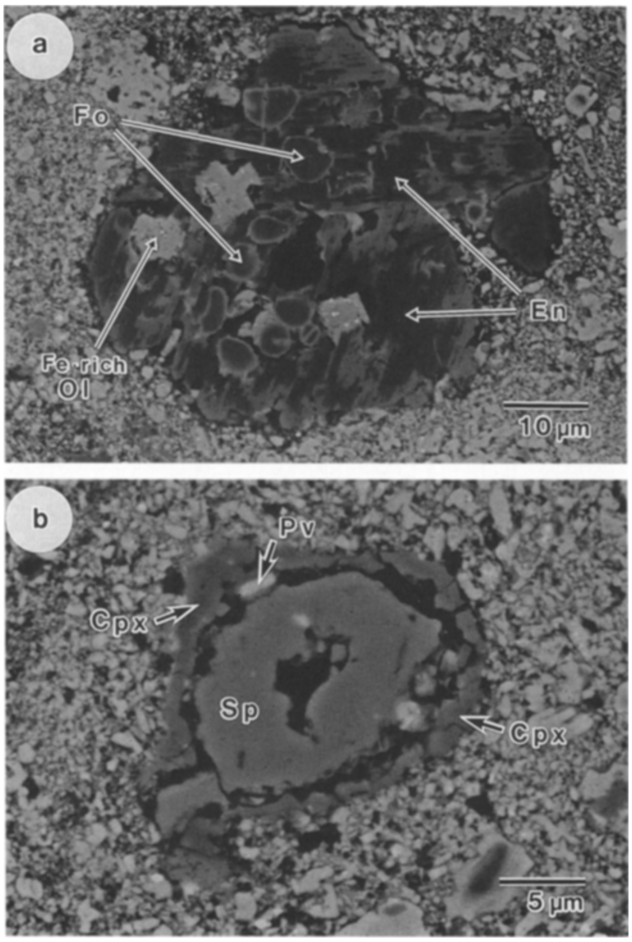

FIG. 3. Relatively large aggregates in AMNH 2226-7. (a) Enstatite (En) enclosing grains of forsterite (Fo) and Fe-rich olivine (Fe-rich Ol). Both enstatite and forsterite show Fe enrichment at grain edges and boundaries. (b) Spinel (Sp) enclosed by a thin rim of Ca-rich clinopyroxene (Cpx). Tiny grains of perovskite (Pv) are also contained.

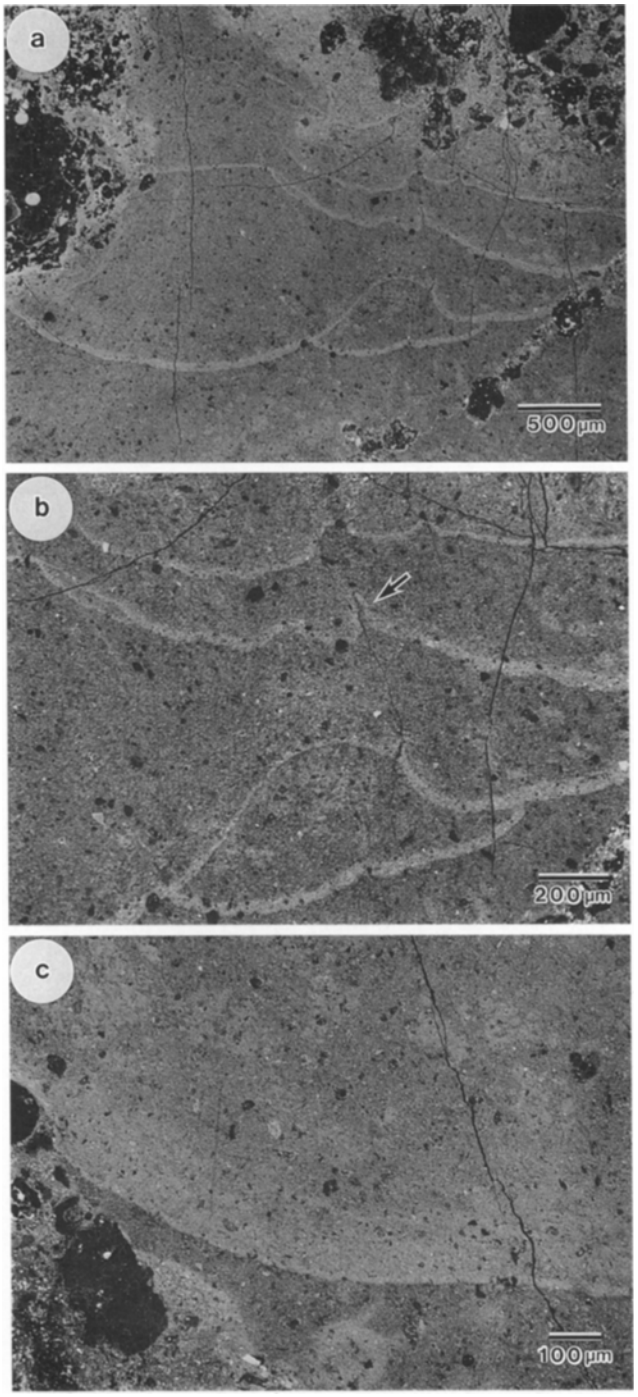

FIG. 4. (a) A backscattered electron image of dark inclusion AMNH 2226-7 including arcuate bands (bright bands). Part of the host meteorite (an assemblage of dark grains and bright matrix) is seen at top left, top right and bottom right (intrusion). (b) An enlarged image of the central portion in (a). Indicated by an arrow is a form similar to a pillar structure. (c) A band shows a sharp edge on the convex (downward) side of the arc; while it shows a broad gradational change on the concave (upward) side.

to bedding, by the presence of thin, dark-colored, subhorizontal, flat to concave-upward laminations that range in thickness from sharp lines <0.2 mm to diffuse zones up to 2 mm, and in width from <1 to >50 cm (Lowe and LoPiccolo, 1974). Dish structures are always

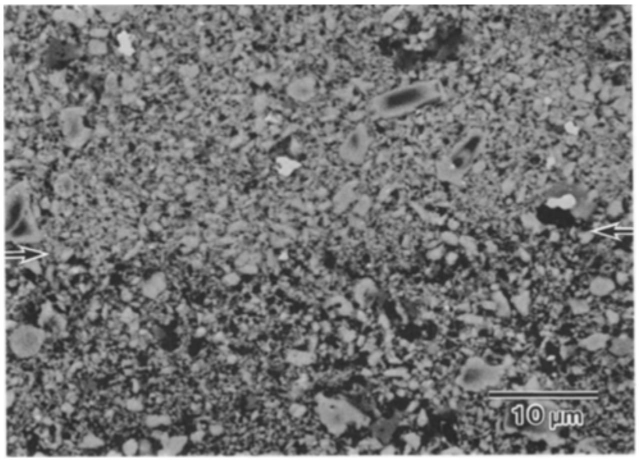

FIG. 5. A high-magnification BSE image of a boundary (arrows) between an arcuate band (top) and a matrix (bottom). The band is slightly higher in Fe content and contains a greater amount of relatively smaller (<1 μm) grains and, thus, has a more densely packed appearance than the matrix.

found in association with finer-grained clay or organics, and the dark lines are enriched in these materials. The grain size of sands slightly increases just above the dark clay-rich lines, and the amount of clay tends to decrease upward, exhibiting a distinct gradation (Lowe and LoPiccolo, 1974).

These textural characteristics in terrestrial sedimentary rocks closely resemble the arcuate bands in AMNH 2226-7, which suggests that a similar mechanism was involved in the formation of both textures. Dish structures have been studied by many investigators, but their origin has not been satisfactorily explained. It has been proposed that they result from: (1) disruption or deformation of laminations by differential loading and dewatering (Stauffer, 1967; Corbett, 1972), (2) gradual postdepositional escape of water (Lowe and LoPiccolo, 1974), (3) hydraulic injection of water into an existing sequence of unlithified beds (Allen, 1982), (4) collapse of water-filled cavities produced during dewatering (Tsuji and Miyata, 1987). (The term *dewatering* used here is different in meaning from dehydration; the former means the elimination of water from a rock during consolidation and any subsequent tectonic pressure; whereas the latter means the removal of a water constituent from a chemical compound.) Despite these differences in interpretation, most investigators agree that they are secondary structures formed during the consolidation of sediments and their fundamental mechanism of formation is related to fluidization of ganular aggregates. We use the term fluidization to describe the process that occurs when a fluid flowing vertically through a granular aggregate exerts drag forces on the grains to lift or suspend them momentarily against the force of gravity (Lowe, 1975). Various modification structures are known to form during fluidization, which include the direct rearrangement of sediment grains and the deformation of hydroplastic, liquefied or fluidized sediments in response to external stresses (Lowe, 1975). However, we point out that the fluidization defined here is a very local process without major disruption of the depositional fabrics.

Dish structures are commonly associated with vertical or nearly vertical columns of massive sand that are termed pillars (Lowe and LoPiccolo, 1974) (Fig. 6b). Pillars commonly occur between the upturned margins of adjacent dishes; they cut across the dishes or are crosscut by them. Pillars are thought to represent fluid escape channels (Lowe and LoPiccolo, 1974). Some of the arcuate bands

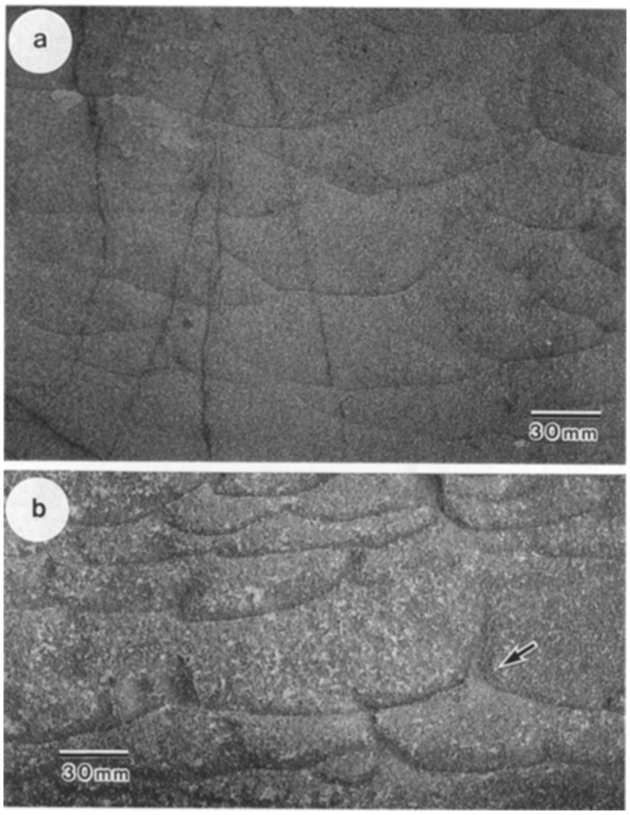

FIG. 6. (a) A photograph of a section normal to bedding of a fine-grained terrestrial sandstone with dish structure. (b) A pillar (arrow) in a sandstone with dish structure. Both photos from the Tertiary Nichinan Group (see Tsuji and Miyata, 1987, for details).

in AMNH 2226-7 do indeed show a form similar to the pillar structure (Fig. 1b).

Despite the textural similarities between AMNH 2226-7 and terrestrial sedimentary rocks, significant differences exist in the size of the grains and the dishes. The most easily fluidized sediments on Earth are thought to be those having grain diameters between 0.1 and 0.5 mm (Lowe, 1975); while most grains in AMNH 2226-7 range from 0.5 to 5 μm. (Grains larger than typical silt- and sand-size are highly permeable and, thus, do not become fluidized; while smaller grains show significant intergranular cohesive forces and are relatively impermeable and, thus, tend to resist fluidization.) The size (diameter) of dishes in terrestrial rocks is typically between 1 and 50 cm; while the dishes in AMNH 2226-7 range from 1 to 3.5 mm in diameter. In the absence of experimental studies on dish-structure formation, it is difficult to provide quantitative explanation for these differences. However, we believe that these differences are probably related to the difference in gravity between a very small planetesimal, where this DI was formed, and Earth as discussed below; the gravity on the former is probably lower by factors of 10^2–10^3 than that on the latter.

Fluidization takes place when the fluid velocity exceeds a critical value at which the downward gravity force on the grains is balanced by the upward fluid drag. This critical velocity, called minimum fluidization velocity, is known to be proportional to the square of grain diameter and also to the acceleration due to gravity.

According to Lowe (1975) in the absence of intergranular cohesive forces and if grain framework is free to expand, the minimum fluidization velocity, U_0, for a bed of uniformly sized spheres can be approximated by the equation:

$$U_0 = 0.00081(\rho_s - \rho_f)d^2g/\mu$$

where g is the acceleration due to gravity, d is the grain diameter, ρ_s and ρ_f are the densities of the solid and fluid phases, respectively, and μ is the dynamic viscosity of the fluid.

Thus with decreasing grain size and gravity, the minimum fluidization velocity becomes drastically smaller. This means that in a planetesimal that consists of micrometer-size grains, fluidization could occur at extremely low flow rates relative to those in terrestiral sediments. On Earth, however, cohesive forces between grains become important as grain size becomes smaller. Terrestrial sediments of grain size below 0.05 mm exhibit significant cohesive resistance to fluidization that increases with decreasing grain size and increasing degree of compaction (Lowe, 1975). However, under the much lower gravity in a planetesimal, the degree of compaction is much less and the effect of such cohesive resistance would be extremely small. In terrestrial sediments, their high clay content would also increase the cohesiveness, but no clay is contained in AMNH 2226-7. Therefore, we envision that in the planetesimal where the DI was formed, fluidization could affect grains much smaller than the silt- and sand-size.

Because dish structures result from postdepositional movement of grains due to permeable fluid flow, the size of dishes is probably related to the intensity of the pore-fluid pressure gradient under which the fluidization occurs. The presumed extremely slow pore-fluid movement in fine-grained sediments in a planetesimal, as mentioned above, should allow very local, low pore-fluid pressure gradients, thus, probably producing very small-size dishes. Lowe and LoPiccolo (1974) reported, based on their observations of terrestrial sedimentary rocks, that smaller, better-defined dishes generally occur in finer-grained rocks; while larger, more diffuse dishes occur in coarser-grained deposits. Because in finer-grained sediments, fluidization is considered to occur at a lower fluid velocity than in coarser-grained sediments, their observations appear to support our interpretation.

Relationship to Chondrule-bearing Dark Inclusions

Many mineralogical and textural features of AMNH 2226-7 are distinct from the major group of DIs that contain chondrules and/or chondrule pseudomorphs (Kojima *et al.*, 1993; Kojima and Tomeoka, 1996; Krot *et al.*, 1997), which indicates that the formation of this DI cannot be explained by direct replacement of a precursor chondrite. Thus, the question arises as to whether this DI has an origin related to the major group of DIs or not.

Assuming our interpretation for the sedimentary process is valid, an important question that should be addressed is what is the source of the fine-grained constituents of AMNH 2226-7. Importantly, the fine-grained components in AMNH 2226-7 are very similar in composition, size and morphology to those in the matrix of the other Vigarano DIs (DC1 and DC2) (Kojima *et al.*, 1993); while they are distinctly different in composition from those in the matrix of the host Vigarano meteorite (Fig. 1). The Vigarano DIs (DC1 and DC2) contain chondrule-pseudomorphs and probably formed by direct replacement of a precursor chondrite. These suggest that the fine grains in AMNH 2226-7 are genetically related to the matrix of the other DIs in Vigarano but not, at least directly, to the matrix of the host meteorite. Another important feature is the occurrence of tiny fragments of chondrules and CAIs dispersed throughout AMNH 2226-7. This suggests that there was a significant degree of brecciation and comminution of a chondritic precursor. From these observations and evidence, it is likely that the fine grains in AMNH 2226-7 resulted from disaggregation and destruction of a DI that had contained chondrules and CAIs; the fine grains may have been derived, therefore, from an aqueously altered and dehydrated portion of the Vigarano meteorite. The disaggregation and destruction may have been caused by extensive brecciation and comminution that occurred in the regolith of the parent body.

Another important feature of AMNH 2226-7 is the almost uniformly small size of constituent grains (<5 μm in diameter); such an aggregation of fine grains has not been previously reported from a CV3 chondrite. The texture suggests that grains now comprising AMNH 2226-7 experienced a form of size-sorting process after the brecciation and comminution. If our interpretation that the arcuate bands in AMNH 2226-7 were produced during fluidization is correct, we suggest that the size-sorting could also have occurred during activity of liquid water on the meteorite parent body. Such processes may be analogous to size-sorting that accompanies fluidization of terrestrial sediments deposited in fluvial environments. Recently, Huang *et al.* (1996) proposed that size- and density-sorting could have occurred in thick dust layers on the surfaces of the chondrite parent bodies that were fluidized by extensive degassing from their interiors. Although they mainly consider the activity of gaseous water as a driving force for fluidization and the details of their model are different from ours, a common mechanism may be responsible for these size-sorting processes.

Sedimentary Environments Implied by this Dark Inclusion

If the proposal that there was extensive aqueous activity in some CV chondrites (Kojima and Tomeoka, 1996; Krot *et al.*, 1997) is correct, the CV parent body can be regarded as having accreted as a mixture of silicate-rich particles and ice, as modelled for the CI and CM parent bodies (Grimm and McSween, 1989). In such primitive bodies, most of stony materials would have been composed initially of unconsolidated, loosely packed aggregates of fine grains. As the parent body grew and was heated, a large redistribution of water would have occurred in the interior of the parent body. With sufficient heating, intergranular water would have become gravitationally unstable; and if there is a sufficient thermal gradient in the interior of the parent body, it would have undergone hydrothermal convection (Grimm and McSween, 1989). Compaction due to impacts on the surface of the parent body may also have caused water migration. On Earth, a major source of fluidizing water is subjacent unconsolidated deposits; and the upward-directed water flow is driven by subsequent depositional events, which are commonly rapid and violent (Lowe, 1975). Many authors suggested that a major cause for such depositional events is earthquakes (*e.g.*, Lowe, 1975; Tsuji and Miyata, 1987). Similar effects could have been triggered by impacts on the surface of the meteorite parent body. In such an environment, fine grains may have been fluidized and various sedimentary processes would have taken place in response to permeable water flow. The present study provides the first evidence suggesting that such processes did indeed occur within at least one carbonaceous chondrite parent body.

In chondrites, various textures and petrofabrics indicative of mechanical modifications such as relocation of grains and fragmentation and deformation of materials are commonly interpreted to have resulted from brecciation and compaction due to impacts on the surfaces of the parent bodies. No major role of permeating water has been suggested in previous work. Even in the CI and CM chondrites, which have experienced extensive aqueous alteration, it is generally perceived that there was no major relocation and deformation of materials due to the activity of permeating water, except for the formation of fracture-filling veins (Richardson, 1978; Tomeoka, 1990; Lee, 1993). However, the present study suggests that permeating water in addition to impacts could have played a significant role in the modification of primary materials and could have been responsible for various textures and petrofabrics in the carbonaceous chondrites. We finally suggest that the fluidization of fine grains due to water migration may have been an important physical process in early planetesimals, and it may become necessary to reevaluate the evolution of carbonaceous chondrites in the context of such aqueous activity.

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REFERENCES

ALLEN J. R. L. (1982) *Sedimentary Structures* Vol. II. Elsevier Scientific Publishing Co., Amsterdam, Holland. 663 pp.

BREARLEY A. J. (1997) Disordered biopyriboles, amphiboles, and talc in the Allende meteorite: Products of nebular or parent body aqueous alteration? *Science* **276**, 1103–1105.

CORBETT K. D. (1972) Features of thick-bedded sandstones in a proximal flysch sequence, Upper Cambrian, southwest Tasmania. *Sedimentology* **19**, 99–114.

GRIMM R. E. AND MCSWEEN H. Y., JR. (1989) Water and the thermal evolution of carbonaceous chondrite parent bodies. *Icarus* **82**, 244–280.

HUANG S., AKRIDGE G. AND SEARS D. W. G. (1996) Metal-silicate fractionation in the surface dust layers of accreting planetesimals: Implications for the formation of ordinary chondrites and the nature of asteroid surfaces. *J. Geophys. Res.* **101**, 29 373–29 385.

JOHNSON C. A., PRINZ M., WEISBERG M. K., CLAYTON R. N. AND MAYEDA T. K. (1990) Dark inclusions in Allende, Leoville, and Vigarano: Evidence for nebular oxidation of CV3 constituents. *Geochim. Cosmochim. Acta* **54**, 819–830.

KELLER L. P. AND BUSECK P. R. (1990) Aqueous alteration in the Kaba CV3 carbonaceous chondrite. *Geochim. Cosmochim. Acta* **54**, 2113–2120.

KELLER L. P., THOMAS K. L., CLAYTON R. N., MAYEDA T. K., DEHART J. M. AND MCKAY D. S. (1994) Aqueous alteration of the Bali CV3 chondrite: Evidence from mineralogy, mineral chemistry, and oxygen isotopic compositions. *Geochim. Cosmochim. Acta* **58**, 5589–5598.

KOJIMA T. AND TOMEOKA K. (1996) Indicators of aqueous alteration and thermal metamorphism on the CV parent body: Microtextures of a dark inclusion from Allende. *Geochim. Cosmochim. Acta* **60**, 2651–2666.

KOJIMA T., TOMEOKA K. AND TAKEDA H. (1993) Unusual dark clasts in the Vigarano CV3 carbonaceous chondrite: Record of parent body process. *Meteoritics* **28**, 649–658.

KROT A. N., SCOTT E. R. D. AND ZOLENSKY M. E. (1995) Mineralogical and chemical modification of components in CV3 chondrites: Nebular or asteroidal processing? *Meteoritics* **30**, 748–775.

KROT A. N., SCOTT E. R. D. AND ZOLENSKY M. E. (1997) Origin of fayalitic rims and lath-shaped matrix olivine in the CV3 chondrite Allende and its dark inclusions. *Meteorit. Planet. Sci.* **32**, 31–49.

LEE M. R. (1993) The petrography, mineralogy and origins of calcium sulphate within the Cold Bokkeveld CM carbonaceous chondrite. *Meteoritics* **28**, 53–62.

LEE M. R., HUTCHISON R. AND GRAHAM A. L. (1996) Aqueous alteration in the matrix of the Vigarano (CV3) carbonaceous chondrite. *Meteorit. Planet. Sci.* **31**, 477–483.

LOWE D. R. (1975) Water escape structures in coarse-grained sediments. *Sedimentology* **22**, 157–204.

LOWE D. R. AND LOPICCOLO R. D. (1974) The characteristics and origins of dish and pillar structures. *J. Sedim. Petrol.* **44**, 484–501.

MASON B. (1963) The carbonaceous chondrites. *Space Sci. Rev.* **1,** 621–646.
MCSWEEN H. Y., JR. (1979) Are carbonaceous chondrites primitive or processed? A review. *Rev. Geophys. Space Phys.* **17,** 1059–1078.
RICHARDSON S. M. (1978) Vein formation in the C1 carbonaceous chondrites. *Meteoritics* **13,** 141–159.
STAUFFER P. H. (1967) Grain-flow deposits and their implications, Santa Ynez Mountains, California. *J. Sedim. Petrol.* **37,** 487–508.
TOMEOKA K. (1990) Phyllosilicate veins in a CI meteorite: Evidence for aqueous alteration on the parent body. *Nature* **345,** 138–140.
TOMEOKA K. AND BUSECK P. R. (1990) Phyllosilicates in the Mokoia CV carbonaceous chondrite: Evidence for aqueous alteration in an oxidizing environment. *Geochim. Cosmochim. Acta* **54,** 1745–1754.
TSUJI T. AND MIYATA Y. (1987) Fluidization and liquefaction of sand beds: Experimental study and examples from Nichinan Group. *J. Geol. Soc. Japan* **93,** 791–808.
ZOLENSKY M. E., KROT A. N., WEISBERG M. K., BUCHANAN P. C. AND PRINZ, M. (1996) Fine-grained inclusions in type 3 ordinary and carbonaceous chondrites (abstract). *Lunar Planet. Sci.* **27,** 1507–1508.