YAMATO-86720: A CM CARBONACEOUS CHONDRITE HAVING EXPERIENCED EXTENSIVE AQUEOUS ALTERATION AND THERMAL METAMORPHISM

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Abstract: A petrographic and mineralogical study of Yamato-86720 (Y-86720) shows that it may be a CM carbonaceous chondrite that has experienced a considerably different alteration history from most CM chondrites. Y-86720 has an unusually high abundance of troilite ($\sim$9 vol%); most troilite occurs in submicron to micron grains dispersed throughout the meteorite. Ca-Mg carbonates and minor Fe-Ni metal, mostly taenite, are present, but magnetite and PCP are absent. This meteorite contains chondrules and aggregates that were completely replaced by optically translucent materials, presumably phyllosilicates. Thus Y-86720 was probably extensively affected by aqueous alteration; the degree of alteration may be the highest of the CM chondrites.

Matrix consists largely of fine grains of Mg-Fe olivine, a nearly amorphous Si-Mg-Fe-rich material, and an Fe-rich material; the latter may be ferrihydrite. Phyllosilicates are rare. The textures suggest that the olivine and the Si-Mg-Fe-rich material were produced by alteration of phyllosilicates by heating. The replacement products of chondrules and aggregates show lower $(Mg+Fe)/(Si+Al)$ ratios than serpentine and relatively high Na contents (up to 2.0 wt% as Na_2O), suggesting the presence of not only serpentine but another type of phyllosilicate. However, the replacement products show consistently high analytical totals; thus they may have been dehydrated and partially altered to anhydrous phases. These results suggest that Y-86720 has experienced mild thermal metamorphism after the aqueous alteration; it appears to have been heated above 500°C in a reduced condition. Most fine-grained troilite probably segregated from matrix during the metamorphic process. Many of the troilites are replaced by a ferrihydrite-like material; thus, Y-86720 may have been affected by additional mild aqueous alteration after the thermal metamorphism.

1. Introduction

Yamato-86720 (Y-86720) is an Antarctic carbonaceous chondrite that consists largely of dark, fine-grained materials and appears to be free of chondrules and inclusions. The preliminary observations, thus, led to the suggestion that it is possibly a CI carbonaceous chondrite (YANAI and KOJIMA, 1987). In order to provide a more complete description of this unusual meteorite, a research consortium was organized by the Antarctic Meteorite Research Committee of NIPR (Leader, Dr. Y.

IKEDA). Thus far available are only preliminary compositional data, which indicate that Y-86720 stands somewhat intermediate between the CI and CM chondrite groups (KALLEMEYN, 1988).

In this paper, we present the results of our petrographic, scanning electron microscope (SEM), and transmission electron microscope (TEM) studies of the Y-86720 chondrite. We will compare mineralogy and petrology of Y-86720 with those of CI and CM chondrites and infer the genetical relationships among those chondrites. Our observations indicate that Y-86720 is petrographically closer to CM chondrites than to CI chondrites. However, it shows many mineralogical features distinct from CM chondrites. The mineralogy and textures suggest that this meteorite probably has experienced more extensive aqueous alteration than any other CM chondrites and also considerable thermal metamorphism after the aqueous alteration. The effect of thermal metamorphism has been also reported from two Antarctic CM chondrites (AKAI, 1988). The apparent differences in secondary history may indicate that Y-86720 was derived from a different environment than those from which other CM chondrites were derived.

2. Material and Methods

The specimen recovered from Antarctica, weighing 858.71 g, is subrounded and appears to be an unfragmented, whole meteorite. A dull black fusion crust covers approximately 60% of the whole surface. The exposed interior is dark gray in color and almost fresh with little weathered material. Numerous voids are dispersed in the meteorite.

Two polished thin sections were available for the present study. We used an electron microprobe analyzer (JEOL 733 Superprobe), equipped with wave-dispersive X-ray spectrometers, and a scanning electron microscope (JEOL JSM-840), equipped with an energy dispersive X-ray spectrometer. For most analyses, a focussed electron beam of $\sim 2\ \mu$m in diameter was employed. For the matrix analyses, we used a $\sim 10\ \mu$m defocussed electron beam and selected the regions where the surfaces are smooth and free of visible mineral grains. After petrographic characterization, areas of interest were removed from one of the thin sections for investigation by TEMs.

Imaging and electron diffraction were preformed with a JEOL 2000FX TEM, operated at 200 kV. Chemical analyses were carried out using an energy dispersive X-ray spectrometer with the 2000FX TEM. Details of our procedures for structural identification are the same as described by TOMEOKA and BUSECK (1985).

3. Petrography and Mineralogy

In an ultra-thin section, Y-86720 consists in major part of dark brownish to black, fine-grained matrix, but there are also considerable amounts of non-matrix, translucent objects, most of which are replaced chondrules and aggregates (Fig. 1). Thus, the modal proportion of real matrix ($\sim 80\%$) is apparently lower than CI chondrites and is in the range of CM chondrites (McSWEEN, 1979). "Matrix" is defined
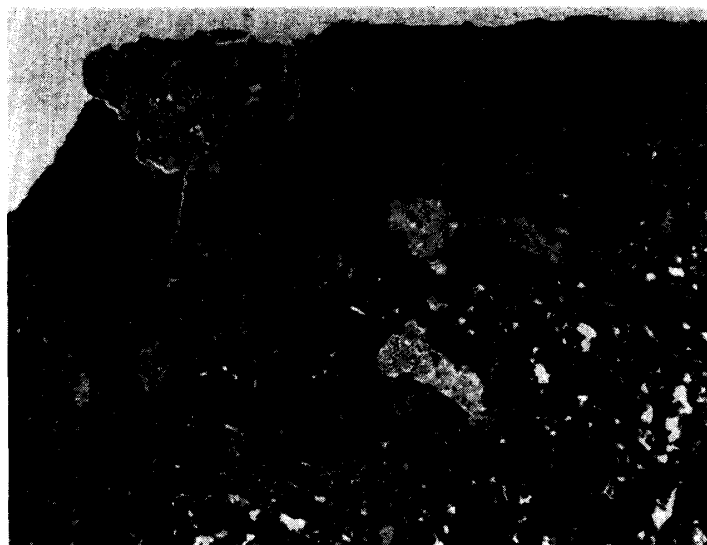
Fig. 1. An optical microscope photo of an ultra-thin section of Y-86720. The field consists mainly of dark, dense matrix with a few replaced chondrules and aggregates. White specks distributed in the lower-right region of the image are mostly voids. Field width=2 mm, plane polarized light.

Table 1. Modal analysis of the Y-86720 meteorite (volume percent from optical point counts).

Replaced chondrules and aggregates		10.6
Sulfides		
Lath-like grains		1.4
Anhedral grains	<3 μm	2.4[1]
	>3 μm	5.0
Metal		0.3
Matrix[2]		80.3

[1] Submicron grains are not optically detectable. Thus, the abundance of small troilites could be higher than this value.

[2] Because of low reflectivity and fine-grained nature, the Ca-Mg carbonate could not be well distinguished by optical microscopy. Thus, the carbonate is included in the matrix.

here as everything not optically recognizable as monomineralic grains and replaced chondrules and aggregates. Modal abundances of matrix and non-matrix minerals are listed in Table 1. Selected microprobe analyses of non-matrix minerals and matrix are shown in Tables 2, 3, and 4. Results of a wet chemical analysis of the bulk meteorite by H. HARAMURA are shown in Table 5.

3.1. Replaced chondrules and aggregates

Chondrules, aggregates, and their fragments ranging in size from 100 μm to 1.2 mm are completely replaced by brownish, translucent material. Many of the chondrules and aggregates preserve their original shapes and textures (Fig. 2a–d) including porphyritic and barred textures. No olivines, pyroxenes and glass of

Table 2. Selected electron microprobe analyses of replaced chondrules, aggregates, and inclusions (weight percent).

	HA-phase			LA-phase			
	1	2	3	4	5	6	7
SiO_2	39.19	33.82	33.95	43.43	45.88	43.96	38.56
TiO_2	0.08	0.13	0.09	0.05	0.09	0.35	0.13
Al_2O_3	19.75	25.17	21.46	2.43	2.41	4.30	4.76
FeO	19.48	17.37	16.20	15.89	13.32	13.53	15.24
MnO	0.12	0.18	0.04	0.06	0.00	0.00	0.25
MgO	20.98	20.72	23.90	26.26	30.31	29.66	22.07
CaO	0.04	0.48	0.46	0.07	0.05	0.15	0.13
Na_2O	1.22	1.31	1.52	0.41	0.43	0.61	1.02
K_2O	0.00	0.00	0.16	0.00	0.00	0.21	0.15
P_2O_5	0.22	0.77	1.05	0.04	0.00	0.12	0.34
Cr_2O_3	0.36	0.11	0.29	0.38	0.86	0.38	1.94
NiO	0.00	0.00	0.24	0.28	0.09	0.00	0.13
S	0.20	0.07	0.15	0.11	0.06	0.63	0.09
Total	101.64	100.13	99.51	89.41	93.50	93.90	84.81

Table 3. Selected electron microprobe analyses of troilite and metal (atomic percent).

	Troilite				Metal			
	1	2	3	4	5	6	7	8
Fe	49.27	48.68	49.33	46.45	95.06	57.19	55.57	44.45
Ni	0.06	0.24	0.02	3.29	4.46	42.06	42.11	54.75
Co	0.07	0.12	0.06	0.21	0.28	0.52	1.76	0.42
S	50.61	50.29	50.55	50.01	0.08	0.11	0.15	0.19
Si	0.00	0.67	0.01	0.05	0.10	0.08	0.18	0.20
Cr	0.00	0.00	0.04	0.00	0.02	0.05	0.24	0.00
Total	100.01	100.00	100.01	100.01	100.00	100.01	100.01	100.01

Table 4. Selected electron microprobe analyses of Y-86720 matrix (weight percent).

	1	2	3	4	5	6*	7*	Average
SiO_2	38.15	37.60	35.59	35.64	34.64	30.58	17.81	33.83
TiO_2	0.11	0.14	0.08	0.10	0.03	0.10	0.02	0.08
Al_2O_3	2.58	3.29	2.66	2.78	2.33	2.46	1.10	2.59
FeO	16.88	17.01	19.72	21.53	24.05	35.43	53.96	19.75
MnO	0.13	0.17	0.09	0.12	0.13	0.16	0.12	0.14
MgO	24.96	25.13	21.88	24.31	23.59	17.00	14.43	23.54
CaO	0.30	0.67	0.34	0.31	0.29	0.25	0.47	0.49
Na_2O	0.95	0.69	0.81	0.90	0.69	0.74	0.13	0.76
K_2O	0.12	0.18	0.16	0.21	0.14	0.09	0.05	0.13
Cr_2O_3	0.65	0.39	0.67	0.49	0.40	0.32	0.19	0.47
NiO	1.86	1.63	1.29	1.86	1.70	0.77	1.00	1.92
S	0.27	0.40	0.26	0.23	0.33	1.01	0.39	0.52
Total	86.96	87.30	83.55	88.48	88.32	88.91	89.67	84.22

* Fe-rich regions.

Table 5.   Wet chemical analysis of the Y-86720 meteorite*.

SiO_2	30.69
TiO_2	0.09
Al_2O_3	3.83
FeO	15.34
MnO	0.18
MgO	22.72
CaO	2.02
Na_2O	0.66
K_2O	0.04
$H_2O(-)$	1.7#
$H_2O(+)$	4.6#
P_2O_5	0.19
Cr_2O_3	0.45
FeS	13.22
Fe	2.84
NiO	1.16
Co	0.053
Total	99.78

* Analyst, H. HARAMURA.
# C content is included in these values.

optically visible sizes are observed.   Troilite occurs in minor amounts (Fig. 2d), but other common opaque phases like metal, magnetite, and PCP are absent.

The replacement products are rich in Si, Mg, Fe, and Al and contain minor Na. They show large variations in the elemental ratios but can be mainly divided into two types.   One type is characterized by high Al contents, and the other type by low Al contents (Table 2); they will be called "High-Al phase (HA-phase)" and "Low-Al phase (LA-phase)", respectively.   The HA-phase tends to be brighter, probably because of its higher Fe contents, and smoother in SEM images than the LA-phase (Fig. 2c).   The HA-phase commonly replaces the phenocrysts, whereas the LA-phase replaces the groundmass, although the distinction is unclear in some chondrules.

Microprobe analyses of the LA-phase are plotted in terms of Fe, Si+Al, and Mg (Fig. 3).   Most analyses fall between the serpentine and the trioctahedral smectite (or mica) solid solution lines; here all Al is assumed to occupy tetrahedral sites in substitution for Si, because Al has a tendency to reside in smectite rather than in serpentine and to occupy its tetrahedral sites (TOMEOKA and BUSECK, 1988).   The HA-phase contains much higher amounts of Al than the LA-phase, and thus part of Al would occupy the octahedral sites.   The (Mg+Fe+Al)/(Si+Al) ratios of the HA-phase calculated on the basis of 22 oxygen atoms are in the range between 0.8 and 1.0, considerably higher than the ratio for trioctahedral smectite (0.75).   These compositional features suggest that the HA- and LA-phases may be a mixture of smectite- and serpentine-type phyllosilicates.   However, their analytical totals tend to be higher than normal phyllosilicates; in particular, those of HA-phase reach 100% (Table 2), suggesting that they were dehydrated and partially altered to anhydrous phases.   In order to identify the HA- and LA-phases, TEM investigation
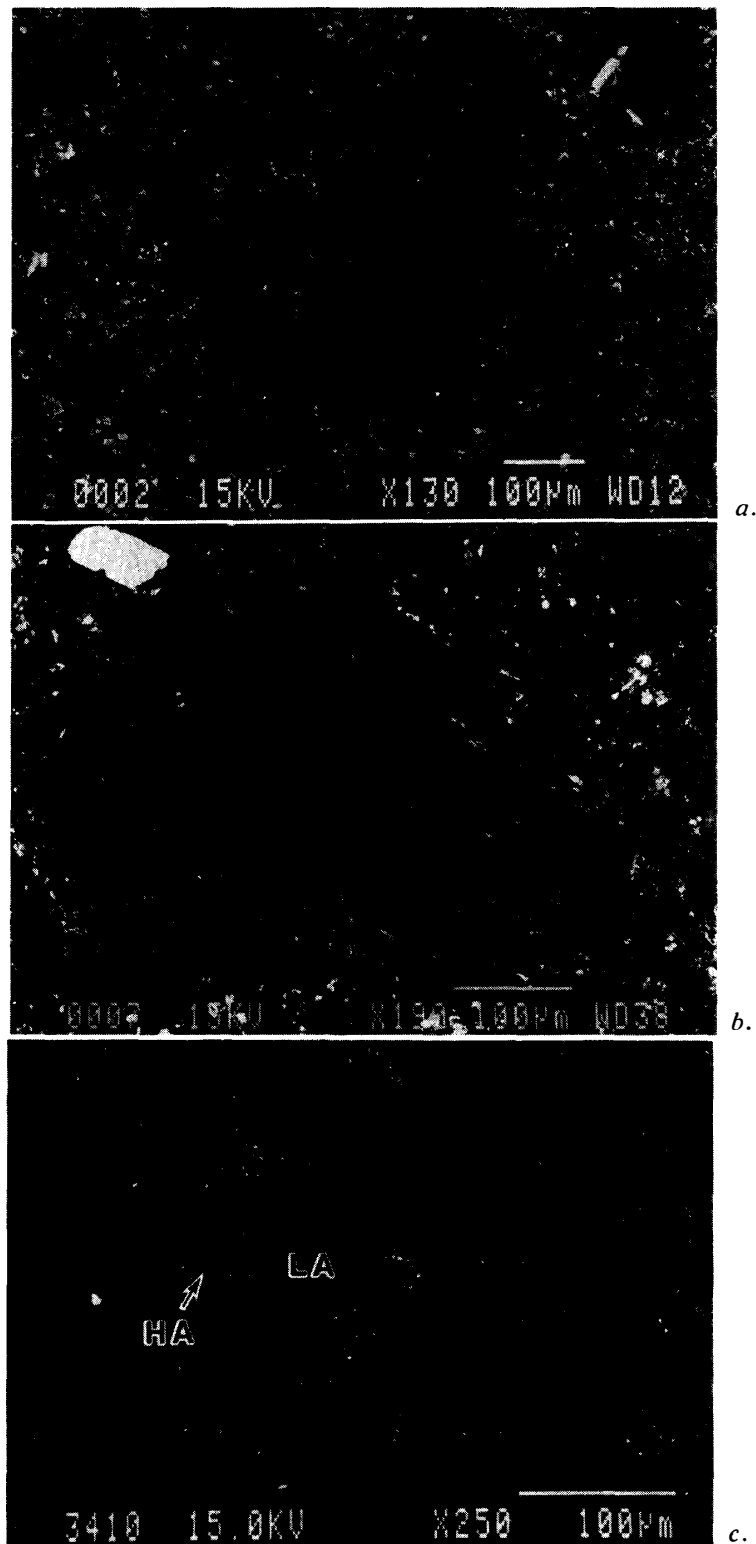
Fig. 2. (a) *A spherical, replaced chondrule preserving a porphyritic-like texture (backscattered SEM image).* (b) *A replaced chondrule with a well-preserved barred texture.* (c) *A portion of a chondrule consisting of the HA-phase (HA, bright part) and the LA-phase (LA, dark background). The HA- and LA-phases appear to have replaced the phenocrysts and the mesostasis glass in the chondrule, respectively. In next page: (d) A portion of a chondrule having a vein-like region containing small troilite grains (white).*

d.
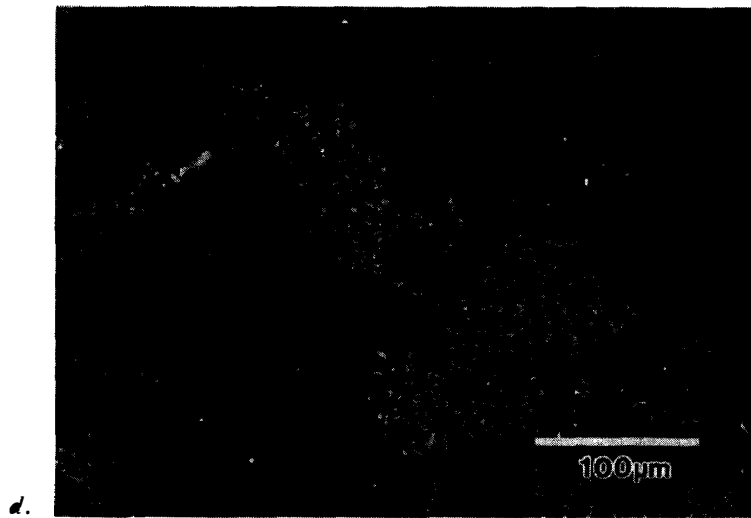
Fig. 2. (*continued*).
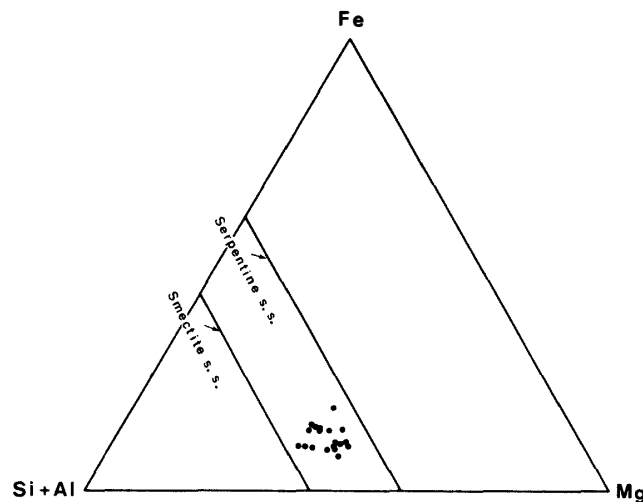
Fig. 3. *Electron microprobe analyses of the LA-phase in chondrules and aggregates in terms of atomic percents of Fe, Si+Al, Mg.   Also shown are the ideal Mg-Fe solid solution lines of serpentine and trioctahedral smectite.*

is necessary and is now in progress; the results will be presented elsewhere.

We found an inclusion ($\sim$ 600 μm in diameter) that is unusually rich in Al and Ti (Fig. 4).   It consists of a heterogeneous mixture of HA-phase, LA-phase, Fe-Ti-rich phase (probably ilmenite), and Ti-rich phase (probably Ti-oxide).   The abundance of high-Al and -Ti materials suggests that the inclusion is a pseudomorphic alteration product of a Ca- and Al-rich refractory inclusion (CAI).   CAIs occur in CM chondrites but are much less common than in CV and CO chondrites.   Ca tends to be leached more readily than Al during alteration (RICHARDSON, 1978).   Ilmenite also has been reported from aqueously altered CAIs as a product of replacing Ti-rich fassaite in Mokoia and Allende CV chondrites (TOMEOKA and BUSECK, 1986; HASHIMOTO and GROSSMAN, 1987).
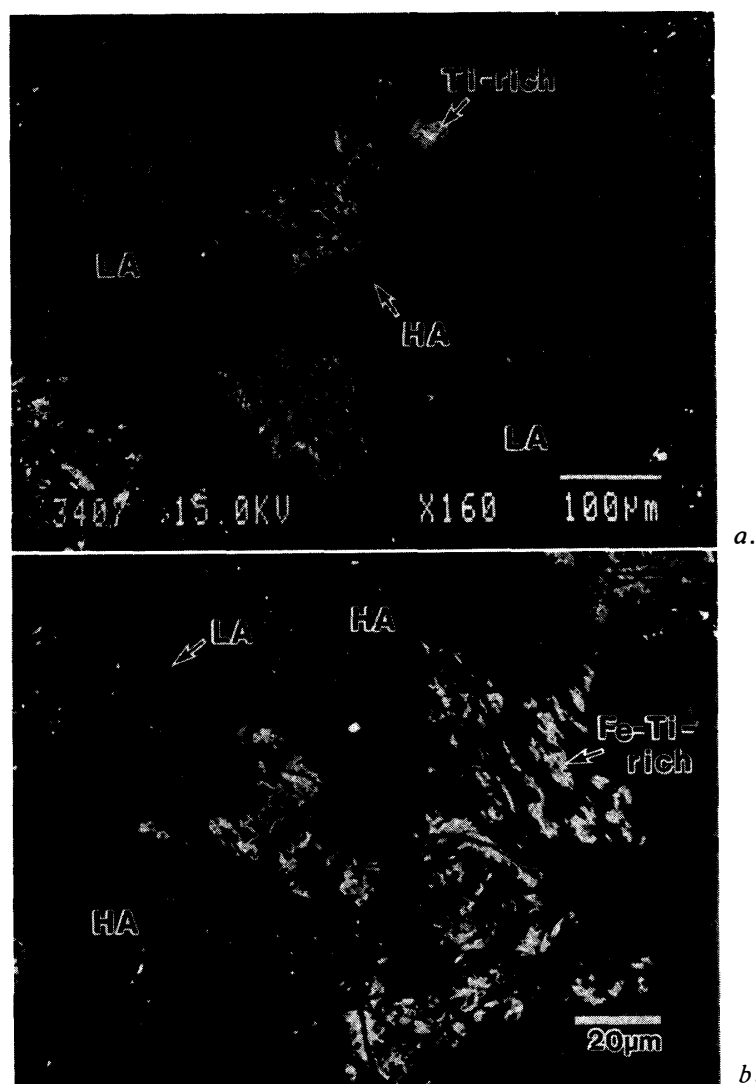
Fig. 4.   (a) A replaced inclusion rich in Al and Ti (backscattered SEM image).   The bright central regions consist largely of the HA-phase (HA), whereas the dark outer regions consist of the LA-phase (LA).   White small grains are an Fe-Ti-rich phase (probably ilmenite) and a Ti-rich phase.   (b) An enlarged image of the central area in (a), where the HA-phase and small Fe-Ti-rich grains (white) are concentrated.

3.2.   Fe-sulfide and Fe-Ni metal

Y-86720 has an unusually high abundance of Fe-sulfides (nearly 9 vol% of the meteorite).   They are primarily troilite but tend to be slightly metal deficient and contain minor Ni (Table 3).   Troilite occurs in irregularly shaped small grains (<1 to 20 μm in diameter) that are dispersed in high density throughout the meteorite (Fig. 5).   Of particular interest is the abundance of relatively large troilite grains having a characteristic lath-like morphology (10 to 50 μm in width and 50 to 200 μm in length) (Fig. 5).   Such Fe-sulfide laths occur in some CI chondrites, although less commonly (KERRIDGE, 1970; TOMEOKA et al., 1989a), but they are rare in CM chondrites.

A minor amount of Fe-Ni metal occurs in small grains (<10 μm in diameter)
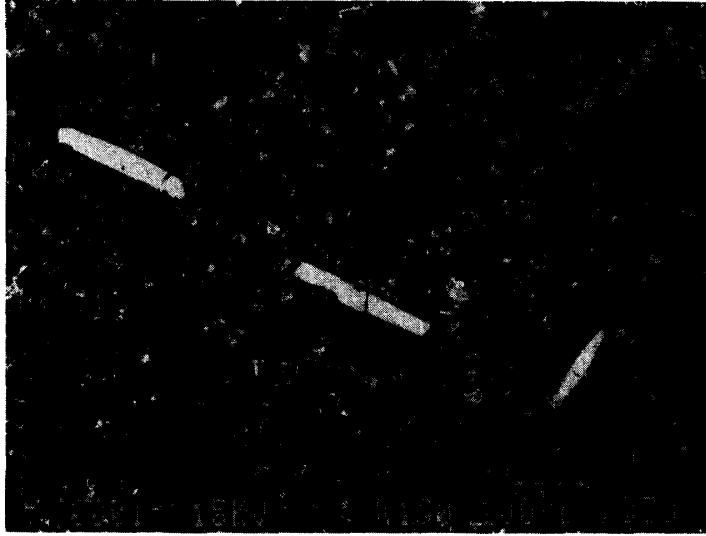
Fig. 5. Troilite grains having a lath-like morphology. Small troilite grains (white) are also dispersed in the matrix (backscattered SEM image).
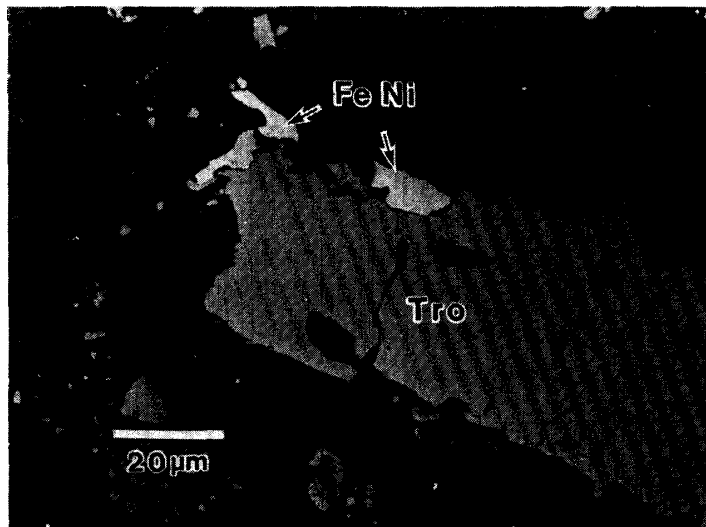

Fig. 6. A portion of a troilite lath containing Fe-Ni metal (bright grains indicated by arrows).

commonly together with troilite (Fig. 6). Most grains are taenite having a range of compositions ($Fe_{58}Ni_{42}$ to $Fe_{45}Ni_{55}$), but there is also kamacite ($Fe_{95}Ni_5$) (Table 3).

The fine-grained troilites are commonly replaced by a material containing a large amount of Fe and less, variable amounts of S, Si, and Mg (Fig. 7). The Fe-rich material is low in the analytical totals (<90 wt% as oxides); thus, it may have been hydrated. It shows extremely fine-grained, fibrous textures and is commonly intermixed with the surrounding matrix. From these characteristics, the Fe-rich material appears to be ferrihydrite, which is an X-ray amorphous ferric hydroxide that occurs as extremely small particles (<100 Å in diameter) (CHUKHROV *et al.*, 1973). Ferrihydrite has recently been reported to occur in a major amount in the Orgueil CI chondrite (TOMEOKA and BUSECK, 1988).
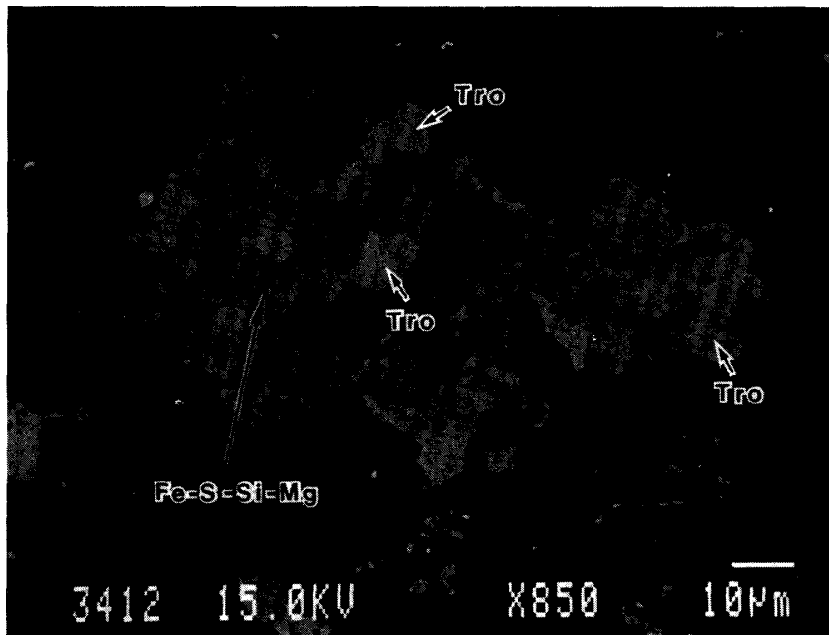
Fig. 7.   Troilite grains being partly replaced by an Fe-rich, S-Si-Mg-bearing material, probably ferrihydrite.

Ferrihydrite is a common terrestrial weathering product, and thus we need to consider that possibility for the origin of the Fe-rich material.   In this regard, of particular interest is that most metals in Y-86720 remain unaltered, while troilite occurring next to the metal is replaced by the Fe-rich material.   Considering that metal is one of the common precursors to ferrihydrite or Fe-hydroxides, this evidence suggests that the alteration occurred in an environment distinct from the Earth.   Future isotopic study would be useful to verify whether terrestrial alteration occurred in Y-86720.

3.3.   Matrix

Microprobe analyses of the Y-86720 matrix using a defocussed electron beam show that it is highly depleted in Fe and S relative to other CM matrices (cf. McSween and Richardson, 1977) (Table 6).   The matrix shows large variations in Fe contents (from 10 to 50 wt% as FeO) with lesser variations in Mg/(Si+Al) ratios (Fig. 8 and Table 4).   In the Fe-rich regions, troilite grains are extensively altered by the ferrihydrite-like material and have Fe-rich halos in the surrounding matrix.   Thus, it is evident that the Fe-rich regions in the matrix resulted from diffusion of the ferrihydrite-like particles that were produced by replacing troilite.

The matrix of CM chondrites consists mainly of Mg-Fe-serpentines, cronstedtite, and the Fe-Ni-S-O phase (tochilinite) (Tomeoka et al., 1989a).   Relative proportions of these phases vary in a broad range within a meteorite matrix and between meteorites (McSween, 1987).   Thus, in the microprobe analyses of the CM matrices, S is roughly correlated with Ni, and they are inversely correlated with Si and Mg (Tomeoka and Buseck, 1985).   However, such elemental correlations are not pronounced in the Y-86720 matrix (Table 4), suggesting that the matrix components are different from those in other CM chondrites.

Table 6. Comparison of elemental abundances in Y-86720 matrix and CM matrices (weight ratios).

	Element/Si		Y-86720 matrix/CM matrix
	Y-86720	Average of CM matrices* (range)	
Na	0.036	0.031 (0.004-0.078)	1.16
Mg	0.897	0.828 (0.742-0.900)	1.08
Al	0.087	0.116 (0.071-0.191)	0.75
S	0.033	0.221 (0.146-0.328)	0.15
K	0.007	0.006 (0.003-0.010)	1.17
Ca	0.022	0.041 (0.019-0.077)	0.54
Ti	0.003	0.004 (0.002-0.006)	0.75
Cr	0.020	0.018 (0.015-0.021)	1.11
Mn	0.007	0.012 (0.010-0.014)	0.58
Fe	0.970	1.859 (1.442-2.493)	0.52
Ni	0.095	0.120 (0.095-0.155)	0.79

* Data from McSween and Richardson (1977).
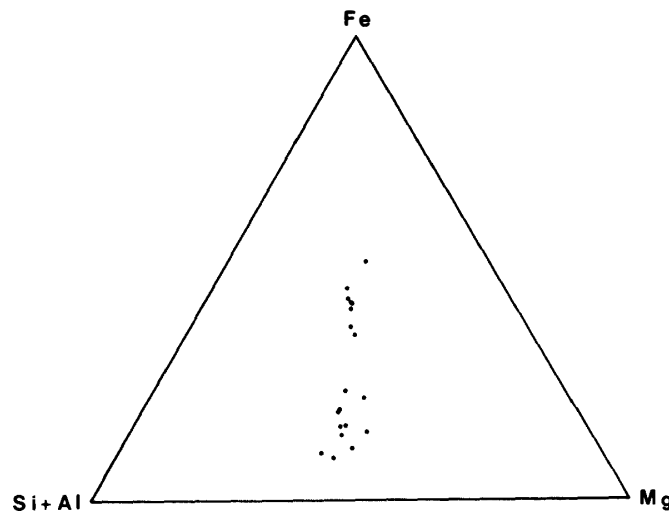
Fig. 8. Electron microprobe analyses of Y-86720 matrix in terms of atomic percents of Fe, Si + Al, Mg.

Preliminary TEM observations show that the matrix consists of extremely fine-grained materials rich in Si, Mg, and Fe. In low magnification TEM images, they show fibrous textures that are reminiscent of phyllosilicates (Fig. 9a). However, most show diffraction rings corresponding to olivine with broad powder diffraction halos, indicating the presence of randomly oriented, fine olivine grains and a nearly amorphous material. Even in high-resolution TEM images, fringes corresponding to phyllosilicate structures are rarely observed. These results suggest that the olivine and the nearly amorphous material were formed by dehydration and alteration of phyllosilicates.

In many places, irregularly-shaped grains (500 to 2000 Å in diameter) of olivine with various Mg/Fe ratios are aggregated, and an amorphous-like, Fe-rich material fills interstices between the olivine grains (Fig. 9b). The Fe-rich material contains
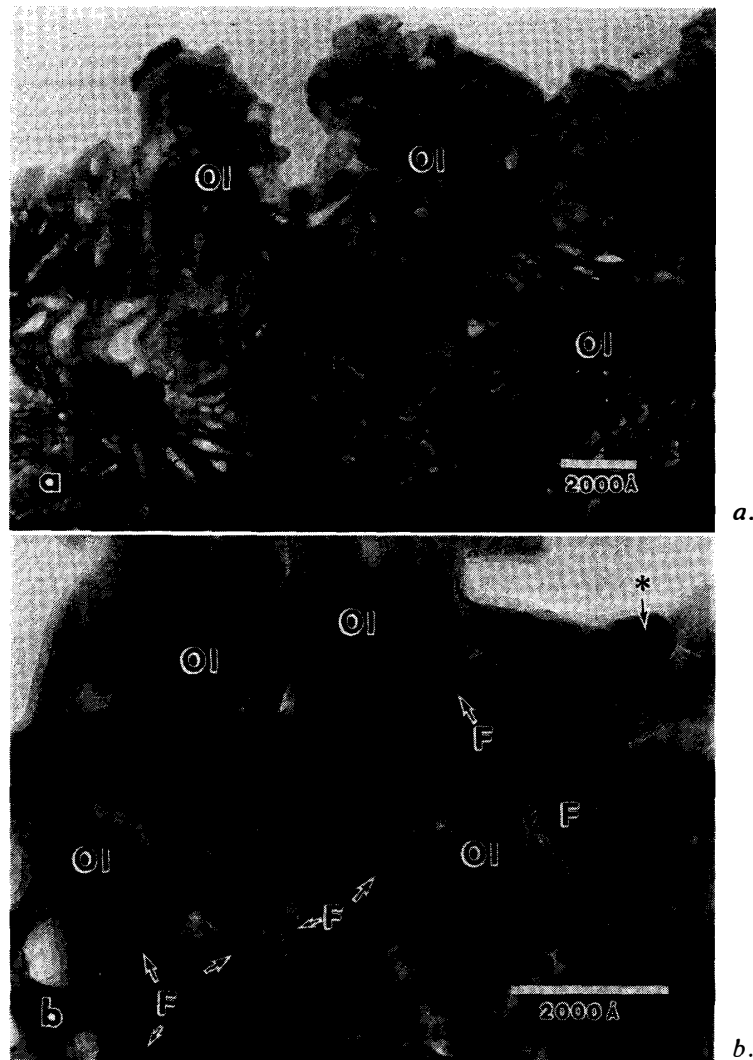
Fig. 9. (a) *A low-magnification TEM image of the matrix material showing a texture similar to phyllosilicates. The dark, irregularly shaped grains are olivine (Ol).* (b) *A higher-magnification TEM image of the matrix olivine (Ol) grains that are associated with an amorphous-like, Fe-rich material (F). Indicated by * is a grain rich in Al and Mg, possibly spinel.*

minor, variable amounts of Ni. It commonly has weak lattice fringes exhibiting curved structures, suggesting it has a weak tendency to form a layered structure. The Fe-rich and poorly crystallized nature suggests that it may be ferrihydrite (CHUKHROV et al., 1973).

Small particles (300 Å to 1 μm in diameter) of an Fe-Ni-rich phase are dispersed in the matrix (Fig. 10). They may be an Fe-Ni-metal or -oxide; their small grain size and three-dimensionally equal morphology make it difficult to obtain their diffraction patterns. Some particles show euhedral morphologies, resembling the magnetite particles occurring as framboidal aggregates in CI chondrites (KERRIDGE, 1970; JEDWAB, 1971). A peculiar occurrence is that they form a narrow rim surrounding a replaced chondrule (Fig. 11).

Fig. 10. A region of matrix having a high density of Fe-Ni-rich particles (backscattered SEM image).
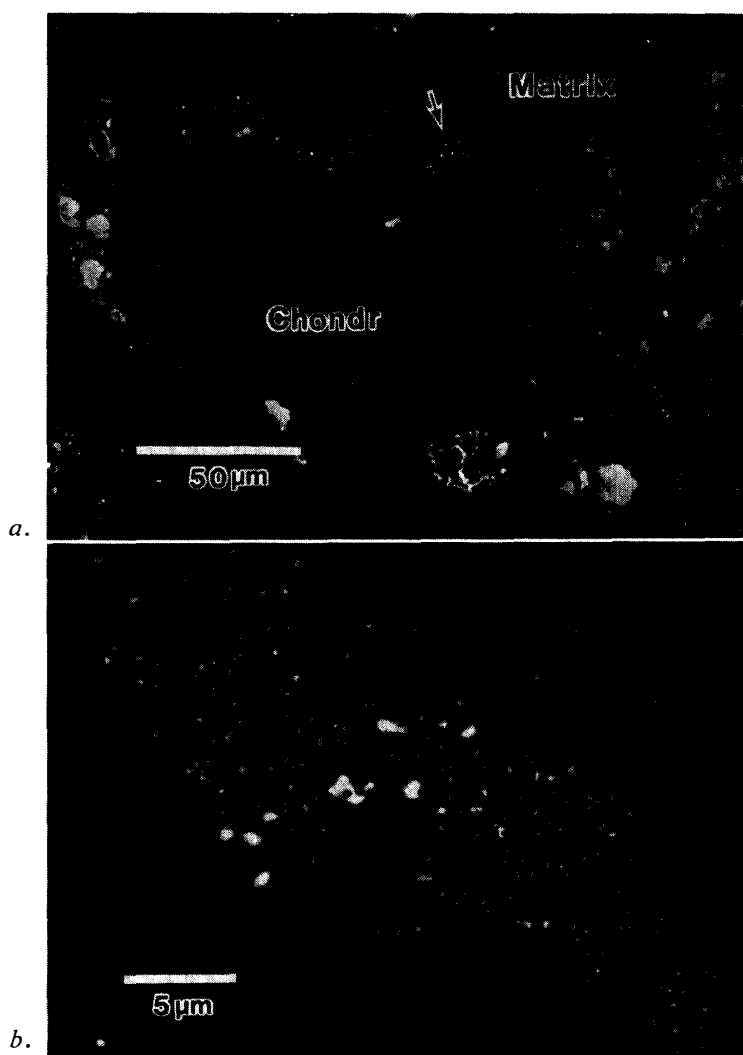
a.

b.

Fig. 11. (a) A portion of a chondrule with a rim (a narrow bright band indicated by an arrow); in the rim, the Fe-Ni-rich particles (white) are concentrated (backscattered SEM image). (b) An enlarged image of the area indicated by an arrow in (a).
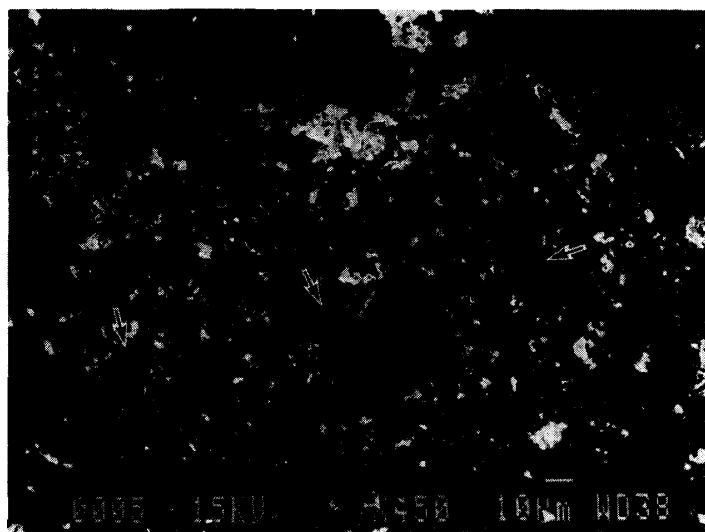
Fig. 12. A Ca-Mg-rich aggregate, probably carbonate (backscattered SEM image).   Small, white
grains are Fe-S-rich phase, probably troilite.   Silicate veins are indicated by arrows.

3.4. Ca-Mg carbonates?

Rounded, chondrule-like, Ca-Mg-rich aggregates ranging in diameter from 10 to 100 μm are scattered widely in the meteorite.   They are fine-grained and intermixed with silicate veins and small troilite grains (Fig. 12); thus it is difficult to obtain analyses of the pure Ca-Mg-rich phase.   From microprobe analyses and appearance, they are probably Ca-Mg-rich carbonate.   The intermixing with silicate veins suggests that they were subjected to considerable aqueous alteration.

4. Discussion

4.1. Aqueous alteration

CM chondrites experienced various degrees of aqueous alteration, probably on the regolith of their parent bodies (e.g., DuFRESNE and ANDERS, 1962; McSWEEN, 1979; BUNCH and CHANG, 1980).   The olivines, pyroxenes, and mesostasis glass in their chondrules and aggregates were altered by phyllosilicates to various extents (RICHARDSON, 1981; IKEDA, 1983; KOJIMA et al., 1984).   Some of the phyllosilicates show a characteristic green to brown color in a transmitted light, and thus they were described as "spinach" by FUCHS et al. (1973).   The chondrules and aggregates in Y-86720 were completely replaced by the brownish, phyllosilicate-like material.   This fact makes Y-86720 bear a resemblance to CM chondrites and suggests that the degree of alteration experienced by Y-86720 is probably the highest of the known CM chondrites.

Alteration of Mg-rich olivine and pyroxene in chondrules and aggregates resulted in addition of phyllosilicates with higher Mg/Fe ratios to matrix.   Part of the Fe was also probably deposited as magnetite and sulfides and was separated from matrix with advancing alteration (McSWEEN, 1979; TOMEOKA and BUSECK, 1985).   Thus, Fe contents of CM matrices decreased relative to Si and Mg contents with increasing degree of aqueous alteration (McSWEEN, 1979, 1987).   In the Fe-Si-Mg
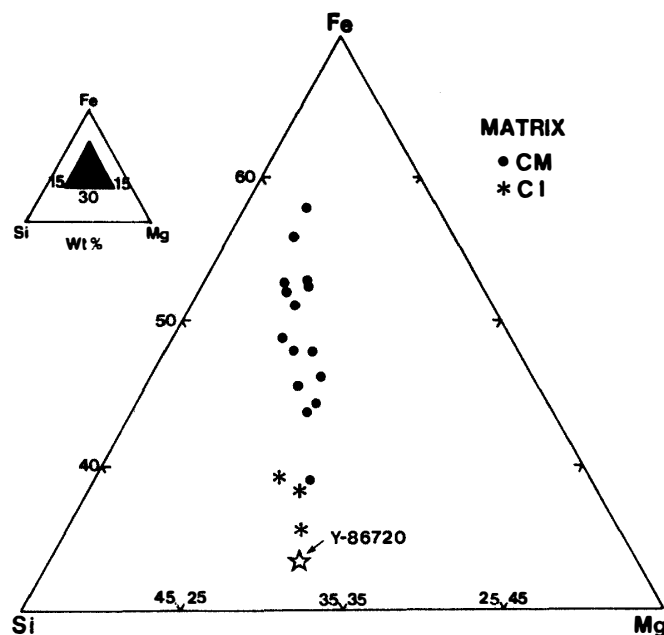
Fig. 13.   A comparison of matrix compositions of CM and CI chondrites in terms of weight pro-
portions of Fe, Si, and Mg (modified from MCSWEEN, 1979; data from MCSWEEN and
RICHARDSON, 1977).

ternary diagram, an average of microprobe analyses of the Y-86720 matrix plots
lower than any CM chondrite matrices (Fig. 13), which is consistent with the ob-
servation that Y-86720 has been more highly altered than other CM chondrites.
However, the Y-86720 matrix plots even below the CI area, which is unusual for a
CM chondrite.   We think that the strong Fe depletion is related to the S depletion
(Table 6) and should be ascribed to the separation of troilite by thermal metamorphism
rather than to aqueous alteration, as will be discussed below.

Advanced alteration is also suggested by the scarcity of opaque phases in the re-
placed chondrules and aggregates in Y-86720.   Most chondrules and aggregates in
CM chondrites contain a variety of Fe-rich opaque phases such as metal, sulfides,
magnetite, and PCP.   However, the Y-86720 chondrules and aggregates contain only
minor amounts of small troilite grains that are sprinkled mostly in phyllosilicate-rich
veins (Fig. 2d).   The observation suggests that the Fe-rich opaque phases once existed
in chondrules and aggregates but were subjected to extensive alteration, during which
most of their components migrated out to matrix.

Despite the petrographic similarity to CM chondrites, Y-86720 shows apparent
differences in phyllosilicate mineralogy from most CM chondrites.   The phyllo-
silicates in CM chondrites are predominantly Fe-Mg serpentines that show broad
compositional variations, from nearly pure Mg-rich serpentine to Fe-rich cronstedtite
(MACKINNON and BUSECK, 1979; AKAI, 1980; BARBER, 1981; TOMEOKA and BUSECK,
1985).   In contrast, the replacement products of Y-86720 chondrules and aggregates
have approximate compositions falling intermediate between serpentine and smectite
(or mica) (Fig. 3).   The compositions suggest that they are intergrowths of serpentine
and smectite-type phyllosilicates, although they may have been thermally altered to

anhydrous phases. These features as well as the Na enrichment indicate that the HA- and LA-phases are compositionally similar to those of phyllosilicates in CI chondrites (Tomeoka and Buseck, 1988; Tomeoka et al., 1989b). These results suggest that the primary components of chondrules and aggregates prior to alteration as well as aqueous alteration conditions themselves were different between Y-86720 and other CM chondrites.

4.2. Thermal metamorphism

Y-86720 shows several mineralogical and chemical features indicative of thermal metamorphism. The most pronounced feature is the abundance of olivine grains associated with an amorphous-like material in the matrix. The textures suggest that the phyllosilicates were dehydrated and altered to olivine. This is consistent with the relatively low H_2O content of this meteorite (Table 5). Similar material and textures have recently been reported from two Antarctic CM chondrites, Begica-7904 and Yamato-793321 that appear to have also experienced heating events (Akai, 1988). Based on heating experiments, Akai interpreted that the olivine in these chondrite matrices was produced by alteration of serpentine by heating. Transformation of serpentine to forsterite is known to commence in the range between 500 and 600°C in air (Brindley and Zussman, 1957; Ball and Taylor, 1963; Souza Santos and Yada, 1979, 1983; Akai, 1988). Thus, the minimum metamorphic temperature experienced by these meteorites may have been in that range.

Y-86720 contains little or no magnetite and pentlandite but contains much troilite and minor taenite. The opaque mineral assemblage is unusual for CM chondrites. The widely distributed, fine-grained troilite probably segregated from matrix during thermal metamorphism, resulting in the strong depletion of Fe and S in the matrix (Table 6). The presence of taenite and the absence of magnetite and Ni-rich sulfides suggest that the thermal metamorphism occurred in a reduced condition. Ni is siderophile, and thus, if metal is present, it migrates from sulfides to metal with increasing temperature (McSween, 1977). If our interpretation is correct, the environment which Y-86720 was derived from was unique in terms of redox condition, because most CM chondrites were oxidized.

Despite the depletion of Fe and S, the Y-86720 matrix does not show significant depletion of Ni compared to CM matrices (Table 6) (cf. McSween and Richardson, 1977). In CM chondrites, Ni usually exists in sulfides (pyrrhotite and pentlandite) and tochilinite and reacts concomitantly with S during alteration. However, our microprobe analyses show that Ni in the Y-86720 matrix does not show correlations with S, suggesting that Ni exists in a different form from sulfides and tochilinite. Our SEM and TEM observations reveal that submicron particles of an Fe-Ni-rich phase are dispersed in the matrix and probably account for the major part of Ni in the matrix. If the S in the matrix segregated as troilite during thermal metamorphism, the Fe-Ni-rich phase likely formed during the metamorphic stage. A possibility is that the Fe-Ni-rich phase is metal, and Ni migrated into them, as in the case of the metal-troilite aggregates.

The effect of heating is also suggested by the absence of PCP in this meteorite; PCP is a major constituent of CM chondrite matrices (Fuchs et al., 1973; Bunch

and CHANG, 1980) and was found to be an intergrowth of the Fe-Ni-S-O phase (FESON) and cronstedtite (TOMEOKA and BUSECK, 1983). The FESON is probably equivalent to an Fe-Ni-rich member of terrestrial tochilinite (MACKINNON and ZOLENSKY, 1984). FUCHS et al. (1973) conducted a heating experiment of the Murchison CM chondrite and showed that the "fibrous PCP" (tochilinite) decomposes at 245°C to troilite, apparently before the decomposition of coexisting serpentines. TOMEOKA and BUSECK (1985) also confirmed that FESON (tochilinite) transforms to polycrystalline troilite by exposure to the electron beam. The fine troilite grains that are dispersed throughout the Y-86720 meteorite may have been produced by thermal decomposition of tochilinite.

The matrix has numerous voids (see Fig. 1); they are particularly common near troilite grains and carbonates. They may have resulted from heating of some volatile components. In backscattered SEM images, those voids commonly have bright Fe-rich halos like troilite grains being replaced by ferrihydrite, suggesting that there was some Fe-rich mineral in the voids, and some Fe diffused out before the mineral grains were removed.

The effects of thermal metamorphism should be reflected in elemental abundance patterns including minor and trace elements, but no such data is currently available. A preliminary elemental analysis of Y-86720 indicates significantly lower concentration of C and N relative to other CM chondrites (A. SHIMOYAMA, pers. commun.), which may have resulted from volatilization of some organic compounds by heating. The future compositional study should shed further light on this matter.

After the thermal metamorphism, this meteorite may have been affected by additional aqueous alteration. Many troilite grains, fine grains in particular, are replaced by the ferrihydrite-like material, and it diffuses widely into matrix. Ferrihydrite converts to hematite on heating between 300 and 400°C (CHUKHROV et al., 1973), although adsorption of silica and C may raise the transition temperature up to ~600°C (CARLSON and SCHWERTMANN, 1981). Considering that this meteorite appears to have been heated above 500°C and was under the metamorphic event for by far extended duration, it is reasonable to assume that the alteration occurred after the thermal metamorphism was completed; otherwise, the ferrihydrite would not have survived.

TOMEOKA et al. (1989b) recently studied another Antarctic carbonaceous chondrite, Yamato-82162, and found that its mineralogy closely resembles that of Y-86720, although the former probably belongs to the CI group. For example, Y-82162 has a high abundance of fine-grained Fe-sulfides, and its phyllosilicates show evidence of dehydration and alteration to olivine. These characteristics appear to have also resulted from thermal metamorphism. A mineralogical comparison shows that the degree of thermal metamorphism is higher in Y-86720 than in Y-82162. The Belgica-7904 and Yamato-793321 CM chondrites are also described to have been affected by heating (AKAI, 1988). Thus, these four Antarctic carbonaceous chondrites contrast with other CI and CM carbonaceous chondrites; the latter show no or little evidence of thermal metamorphic effects.

The significance of petrological, chemical and isotopic differences between non-

Antarctic and Antarctic meteorites has been recognized by several workers (*e.g.*, TAKEDA *et al.*, 1983; DENNISON *et al.*, 1986; McGARVIE *et al.*, 1987). All of the workers suggested that those differences could have resulted from a difference in meteoroid flux between contemporary falls and substantially older Antarctic meteorites, thus implying distinct genetic histories. As discussed by TOMEOKA *et al.* (1989b), the apparent differences in thermal history between the Antarctic and non-Antarctic carbonaceous chondrites also may reflect distinct meteorite sources.

5. Summary

The mineralogy and petrography of Y-86720 suggest that it is a CM chondrite that has experienced extensive aqueous alteration and mild thermal metamorphism after accretion to the meteorite parent body. The thermal metamorphism probably occurred at $>500°C$ in a reduced condition. It shows many differences in mineralogy and chemistry from the known CM chondrites, and some characteristics rather resemble those of CI chondrites. These results suggest that Y-86720 may have been derived from considerably different "primary" materials and has experienced a distinct history from those of other CM chondrites.

Acknowledgments

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