

YAMATO-82162: A NEW KIND OF CI CARBONACEOUS CHONDRITE FOUND IN ANTARCTICA

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Abstract: A petrographic and mineralogical study of the Yamato-82162 (Y-82162) meteorite shows that it may be the first CI carbonaceous chondrite that has ever been found in Antarctica. Y-82162 consists largely of fine-grained, phyllosilicate-rich matrix and contains a large amount of Ni-bearing pyrrhotite and small amounts of framboidal, platy, spheroidal, and anhedral magnetite, Mg-Fe-rich carbonates, and Ca-phosphate. Isolated clusters of coarsely crystallized phyllosilicates are also present. The presence of these minerals supports the idea that Y-82162 is a CI carbonaceous chondrite. However, this meteorite shows several mineralogical features that apparently differ from non-Antarctic CI chondrites: it has much higher abundances of coarse phyllosilicates and pyrrhotite than non-Antarctic CI chondrites, and has no veins of sulfates and carbonates, suggesting that it was derived from different primary materials and has experienced a different aqueous alteration history from non-Antarctic CI chondrites. The Y-82162 matrix also contains abundant fine grains of olivine, which contrasts with non-Antarctic CI chondrites. The textures suggest that matrix phyllosilicates were dehydrated and altered to olivine by heating. Thus, this meteorite probably has been affected by mild thermal metamorphism. These results indicate that Y-82162 has experienced a distinct late history from the non-Antarctic CI chondrites, suggesting that it may have been derived from a different source from that of non-Antarctic CI chondrites.

1. Introduction

The CI carbonaceous chondrites are regarded as being the most primitive solar system material available for study, and thus are the subjects of broad, intense interest. Despite the vast number of meteorites recovered from Antarctica (nearly nine thousand meteorites), no CI chondrite has been reported. The Yamato-82162 (Y-82162) meteorite is composed largely of dark, fine-grained materials and is apparently free of chondrules and inclusions, resembling CI chondrites (YANAI and KOJIMA, 1987). In order to study this unusual meteorite, a research consortium was organized by the Antarctic Meteorite Research Committee of NIPR (Leader: Dr. Y. IKEDA). Currently available are oxygen isotopic (MAYEDA *et al.*, 1987) and preliminary compositional data (KALLEMEYN, 1988), and they support a CI classification for this meteorite. Thus Y-82162 may be the first CI chondrite found in Antarctica.

In this paper, we present results of petrographic, scanning electron microscope (SEM) and transmission electron microscope (TEM) studies of the Y-82162 chondrite.

Our goals are to provide detailed mineralogical and compositional characteristics of the constituent minerals and to compare them with those of non-Antarctic CI chondrites, particularly Orgueil. Our study indicates that, based on general petrography, texture, and mineral species, Y-82162 most closely resembles CI chondrites. However, details of mineralogy and relative abundances of minerals considerably differ, suggesting that Y-82162 has experienced a different formation history from non-Antarctic CI chondrites. In particular, the abundance of coarsely crystallized phyllosilicates and the lack of sulfate veins suggest that Y-82162 has been less affected by aqueous alteration than non-Antarctic CI chondrites. However, Y-82162 shows additional features indicative of mild thermal metamorphism. Evidence of such thermal effects has not been known from non-Antarctic CI chondrites. Thus, Y-82162 may potentially provide new insights into the formation history of the CI chondrites and the environments of their parent body (or bodies).

2. Material and Methods

Y-82162 consists of three fragmental pieces, weighing totally 41.73 g, that are of medium to dark gray color in the interior and are partly covered by black fusion crusts. The specimen apparently suffered little terrestrial weathering.

The sample available for study is a polished thin section of approximately 58 mm² area. We used an electron microprobe analyzer (JEOL 733 Superprobe), equipped with wave-dispersive X-ray spectrometers, and a scanning electron microscope (JEOL JSM-840) with an energy-dispersive X-ray spectrometer. Most analyses were performed using a focused electron beam, $\sim 2 \mu\text{m}$ in diameter. For the matrix analyses, we used a defocused electron beam, $\sim 10 \mu\text{m}$ in diameter. After petrographic characterization, particular regions in the thin section were removed, mounted on TEM grids, and thinned by argon-bombardment.

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

3. Mineralogy of Non-Matrix Minerals

Y-82162 is a breccia composed of millimeter to submillimeter clasts that consist almost entirely of fine-grained, optically opaque to translucent matrix. In an ultra-thin section, the color and darkness of matrix vary considerably from clast to clast, suggesting differences in matrix mineralogy between clasts (Fig. 1). Anhydrous silicates occur but are extremely rare. These features are common to most CI chondrites. Modal abundances of matrix and non-matrix minerals are listed in Table 1. "Matrix" is here defined as everything not optically recognizable as monomineralic grains ($< 1 \mu\text{m}$ in diameter). Results of a wet chemical analysis of the bulk meteorite by H. HARAMURA are shown in Table 2. Selected microprobe analyses of non-matrix minerals and an average of defocused-electron beam analyses of the matrix are given in Tables 3–5. In the following sections, mineralogy and com-

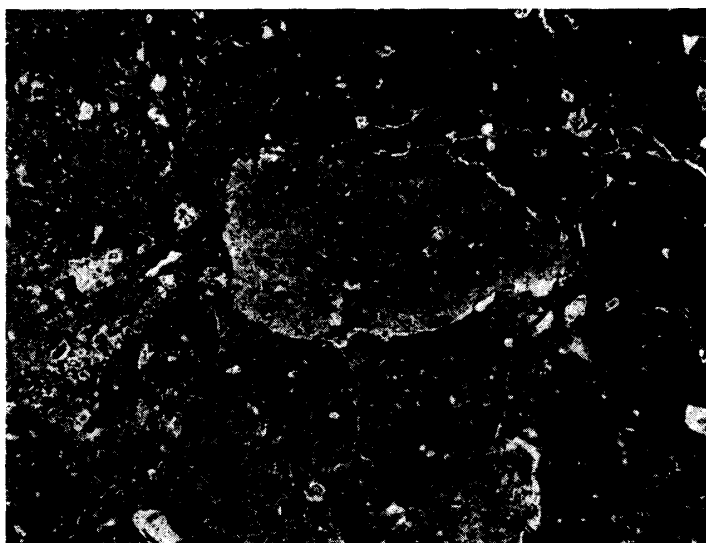


Fig. 1. An optical microscope photo of an ultra-thin section of Y-82162. The meteorite is composed largely of dark, fine-grained matrix. A clast that is bright in its matrix is seen in the center of this image. Field width=1 mm, plane polarized light.

Table 1. Modal analysis of the Y-82162 meteorite (volume percent from optical point counts).

Coarse phyllosilicates		4.0
Sulfides		
Euhedral grains		3.5
Anhedral grains	< 3 μm	2.2
	> 3 μm	5.4
Magnetite		
Irregularly-shaped grains		0.1
Framboids		0.3
Plaquettes		0.1
Spheroids		0.1
Carbonates		0.5
Phosphates		0.2
Matrix		83.6

Table 2. Wet chemical analysis of the Y-82162 meteorite*.

SiO ₂	26.99
TiO ₂	0.23
Al ₂ O ₃	2.26
Fe ₂ O ₃	2.32
FeO	10.85
MnO	0.31
MgO	20.19
CaO	2.04
Na ₂ O	0.87
K ₂ O	0.13
H ₂ O(-)	3.94#
H ₂ O(+)	8.01#
P ₂ O ₅	0.36
Cr ₂ O ₃	0.48
FeS	20.08
NiO	1.28
Co	0.039
Total	100.37

* Analyst, H. HARAMURA.

C content is included in these values.

positions of non-matrix minerals are discussed in detail and are compared to those of non-Antarctic CI chondrites.

3.1. "Coarse" phyllosilicates

Phyllosilicates that are relatively coarsely crystallized ("coarse phyllosilicates") (500 to 2000 Å in width) occur in isolated clusters ranging in size from 10 to 300 μm

Table 3. Selected electron microprobe analyses of "coarse" phyllosilicates (weight percent).

	1	2	3	4	5	6*
SiO ₂	45.64	43.91	47.17	48.37	51.07	40.22
TiO ₂	0.01	0.00	0.01	0.01	0.00	0.00
Al ₂ O ₃	4.54	3.66	4.88	4.28	5.51	4.05
FeO	8.39	10.89	7.64	9.89	6.83	27.32
MnO	0.04	0.10	0.00	0.00	0.00	0.23
MgO	24.26	28.27	22.05	27.75	24.87	20.84
CaO	0.10	0.26	0.15	0.14	0.03	0.01
Na ₂ O	2.52	1.43	3.02	2.31	4.56	1.98
K ₂ O	0.29	0.06	0.26	0.23	0.24	0.00
P ₂ O ₅	0.00	0.00	0.00	0.00	0.00	0.00
Cr ₂ O ₃	1.01	1.38	0.19	1.62	0.06	0.81
NiO	0.09	0.14	0.23	0.08	0.08	0.00
SO ₃	0.29	0.54	0.76	0.54	0.24	0.13
Total	87.18	90.64	86.36	95.22	93.49	95.59

* This analysis is from the matrix of the magnetite aggregate in Fig. 6.

Table 4. Selected electron microprobe analyses of sulfides (atomic percent).

	Pyrrhotite				Pentlandite	Cu-Fe-sulfide	
	1	2	3	4	5	6*	7*
Fe	49.18	48.45	47.86	47.32	27.60	29.77	30.01
Ni	0.00	0.36	1.15	2.10	22.63	0.44	0.11
Cu	—	—	—	—	—	19.28	19.41
Co	0.03	0.12	0.07	0.09	1.61	—	—
S	50.76	50.95	50.93	50.33	47.75	50.52	50.47
Si	0.00	0.00	0.00	0.02	0.03	—	—
Mg	0.01	0.12	0.00	0.11	0.02	—	—
Cr	0.01	0.00	0.00	0.05	0.00	—	—
Total	99.99	100.00	100.01	100.02	99.64	100.01	100.00

* These analyses are from the grains shown in Fig. 4.

Table 5. Selected electron microprobe analyses of some minerals and an average of matrix analyses (weight percent).

	Carbonates		Phosphates		Olivine	Mesostasis glass	Average of matrix analyses
	1	2	3	4	5	6	
SiO ₂	1.72	0.58	0.12	0.40	38.80	43.94	33.06
TiO ₂	0.00	0.08	0.00	0.04	0.01	0.52	0.05
Al ₂ O ₃	0.11	0.00	0.00	0.02	0.00	11.95	2.10
FeO	25.50*	18.24*	0.16	6.58	16.35	21.40	20.76
MnO	2.17	21.13	0.00	0.00	0.22	0.33	0.25
MgO	38.88	34.61	0.13	31.92	43.01	2.78	21.32
CaO	0.31	3.16	52.55	0.03	0.07	12.05	0.44
Na ₂ O	0.00	0.35	0.00	3.74	0.00	3.09	0.69
K ₂ O	0.00	0.03	0.00	0.08	0.03	0.13	0.18
P ₂ O ₅	0.07	0.12	42.47	57.10	—	—	—
Cr ₂ O ₃	0.00	0.06	0.07	0.00	0.38	0.18	0.45
NiO	0.00	0.07	0.28	0.25	0.00	0.02	1.39
S	3.13	1.10	0.23	0.18	—	—	3.41
Total	71.89	79.53	96.01	100.34	98.87	96.39	84.10

* Part of Fe is probably from intergrown Fe-oxide and/or -sulfide.

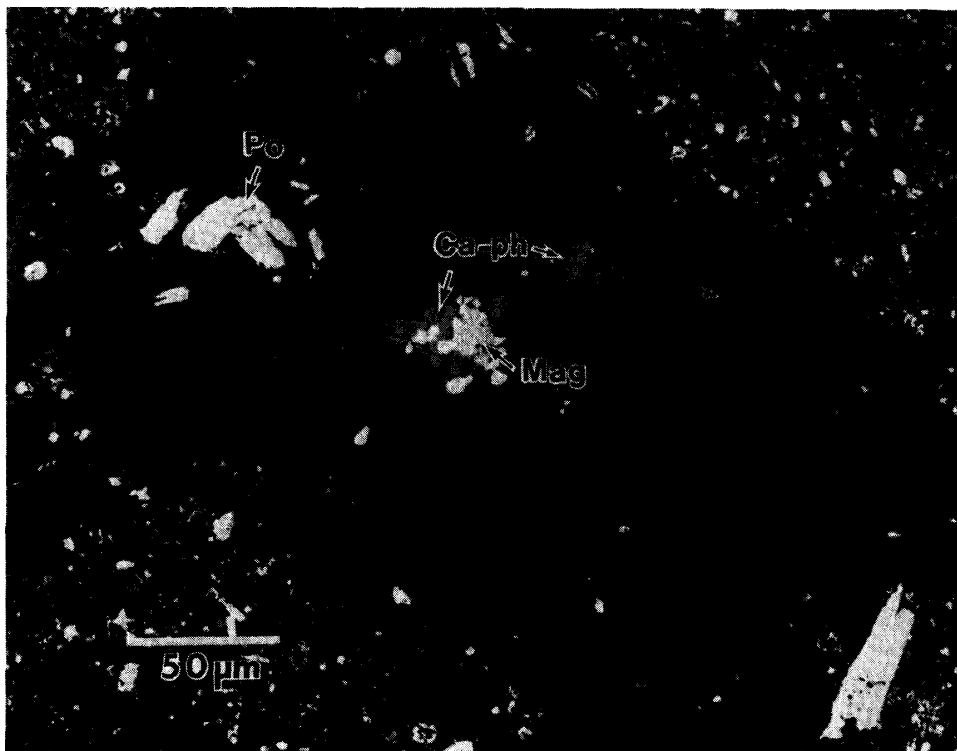


Fig. 2. A cluster of the coarse phyllosilicates (backscattered SEM image). Grains of pyrrhotite (Po), magnetite (Mag), and Ca-phosphate (Ca-ph) are enclosed within the cluster.

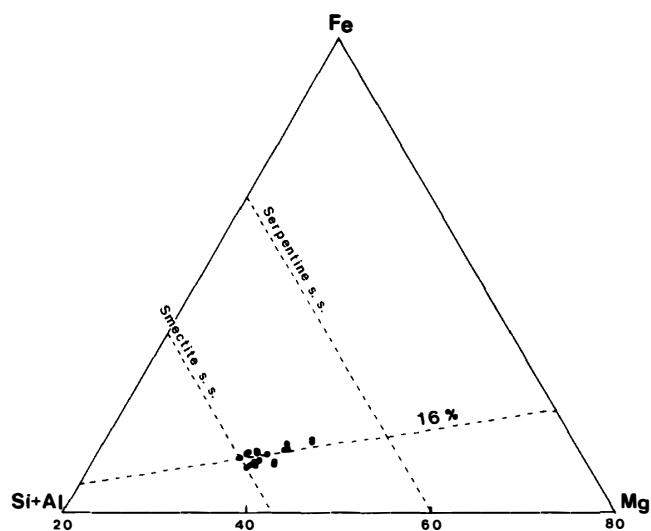


Fig. 3. Electron microprobe analyses of the coarse phyllosilicates in terms of atomic percents of Fe, Si+Al, and Mg. Also shown are the ideal Mg-Fe solid solution lines of serpentine and trioctahedral smectite. Most analyses lie near the line defined by $Fe/(Fe+Mg)=16$ atomic %.

(Fig. 2). They show brownish, translucent color in a transmitted light and can be recognized by an optical microscope. The coarse phyllosilicates are much more abundant and occur in much larger clusters than in Orgueil; in the latter, the coarse

phyllosilicate clusters are at most 30 μm in diameter (TOMEOKA and BUSECK, 1988). Some phyllosilicate clusters enclose grains of magnetite, pyrrhotite, and Ca-phosphate (Fig. 2).

Microprobe analyses of the coarse phyllosilicates are plotted in terms of Fe, Si+Al, and Mg (Fig. 3); their selected analyses are shown in Table 3. Most analyses fall between the serpentine and the trioctahedral smectite (or mica) solid solution lines (both are ideal solid solutions) and on a line of $\text{Fe}/(\text{Mg}+\text{Fe})=16\%$, similar to the phyllosilicates in Orgueil (*cf.* Fig. 10 in TOMEOKA and BUSECK, 1988). The analyses of the Orgueil phyllosilicates plot widely between smectite (saponite) and serpentine compositions, and on average, the smectite and serpentine occur in approximately equal molar proportions. However, the analyses of the Y-82162 phyllosilicates mostly concentrate near the smectite composition, and this suggests that a large proportion of the coarse phyllosilicates is a smectite-type phyllosilicate. However, the Y-82162 phyllosilicates show considerably higher Na contents (1.4 to 4.6 wt % as Na_2O) (Table 3) than terrestrial smectite. Thus, part of the phyllosilicates may be Na-rich trioctahedral mica such as Na-phlogopite (SCHREYER *et al.*, 1980). Another significant feature is that microprobe analyses of the Y-82162 phyllosilicates show consistently higher sums than the phyllosilicates in Orgueil (*cf.* Table 1 in TOMEOKA and BUSECK, 1988), suggesting that the phyllosilicates have suffered dehydration or are mixed with small anhydrous minerals. In order to obtain more detailed data, TEM investigation is necessary and is in progress; the results will be shown elsewhere.

3.2. Sulfides

Y-82162 has a significantly higher abundance of Fe-rich sulfides than non-Antarctic CI chondrites. Volumetrically, the sulfides constitute $\sim 11\%$ of the meteorite (Table 1). They are mostly non-stoichiometric, Fe-deficient pyrrhotite. Sulfides having closely similar compositions were reported from the Revelstoke and Orgueil meteorites, and they were confirmed as pyrrhotite by X-ray diffraction methods (FOLINSBEE *et al.*, 1967; BASS, 1970).

Pyrrhotite occurs in relatively large (10 to 50 μm in diameter) anhedral, euhedral (commonly hexagonal), and lath-like grains and also in small grains ranging in diameter from submicron to several microns; the latter are widely dispersed throughout the meteorite. Most pyrrhotites contain small but variable amounts of Ni (Table 4). Pentlandite occurs but is rare. Pyrrhotites in non-Antarctic CI chondrites are commonly replaced by limonite (BOSTRÖM and FREDRIKSSON, 1966; KERRIDGE, 1970a) or ferrihydrite (TOMEOKA and BUSECK, 1988), but those in Y-82162 are much less altered.

Several grains of Cu-Fe sulfide are identified in an aggregate, where they coexist with pyrrhotite (Fig. 4). The occurrence of such Cu-Fe sulfide is of particular significance because cubanite, CuFe_2S_3 , was reported to occur in non-Antarctic CI chondrites (MACDOUGALL and KERRIDGE, 1977). The sulfide in Y-82162 has an approximate chemical formula of $\text{Cu}_2\text{Fe}_3\text{S}_5$ (Table 4), and thus the stoichiometry does not correspond to cubanite but to an intermediate between chalcopyrite and cubanite.

In non-Antarctic CI chondrites, S also occurs in major amounts as Mg-, Ca-sulfates and elemental S (DUFRESNE and ANDERS, 1962; BOSTRÖM and FREDRIKSSON, 1966). However, neither sulfates nor elemental S were observed in Y-82162. The

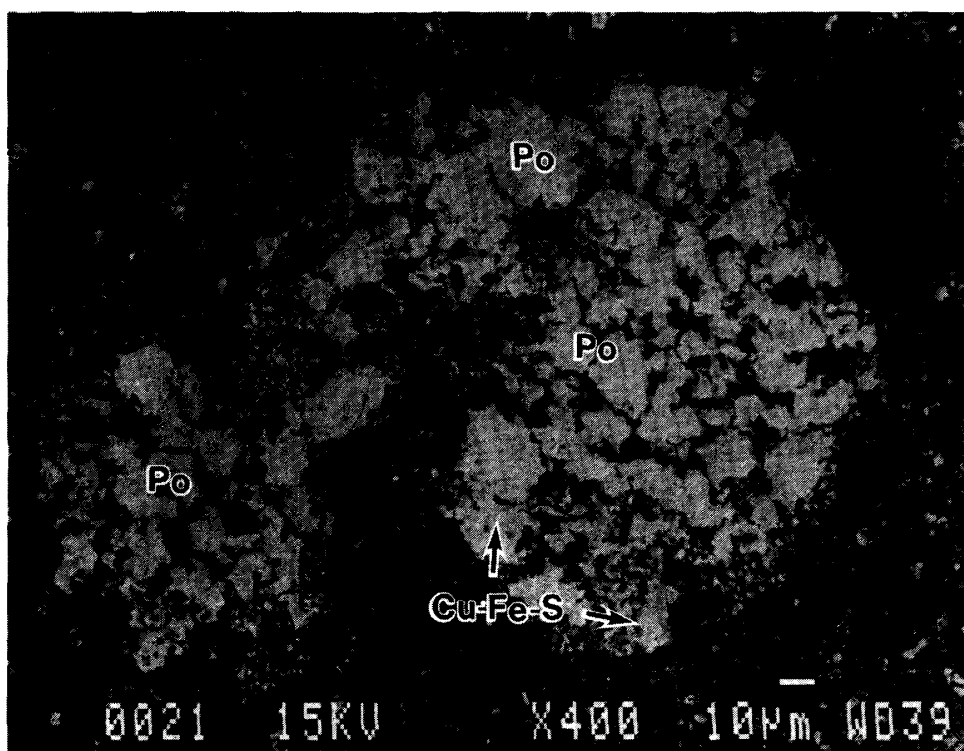


Fig. 4. An aggregate of Cu-Fe-sulfide (indicated by arrows) and pyrrhotite (Po) (backscattered SEM image). Because of little difference in brightness, it is difficult to distinguish between Cu-Fe-sulfide and pyrrhotite in the SEM image.

wet chemical analysis also confirms that most S in Y-82162 occurs as sulfides (Table 2).

3.3. Magnetite

Magnetite constitutes 0.6 modal % (Table 1), which is much lower than non-Antarctic CI chondrites. It occurs in small ($<10\ \mu\text{m}$ in diameter), irregular grains and also in a variety of forms; they are (1) framboidal aggregates (Fig. 5), (2) plaquettes (Fig. 6), and (3) spheroidal grains (or spherulites) (Fig. 7). These magnetite morphologies are characteristic of CI chondrites (JEDWAB, 1967, 1971; KERRIDGE, 1970b; KERRIDGE *et al.*, 1979). In the CI chondrites, polygonal to subrounded grains (from 0.2 to $2.0\ \mu\text{m}$ in diameter), which apparently resulted from disaggregation of the framboidal aggregates, are also dispersed throughout the meteorite. However, such magnetite grains are not abundant in Y-82162.

Figure 5 shows a framboidal aggregate containing magnetite grains of three different sizes as well as plaquettes and spheroids. The rounded external shape of the aggregate and the coexistence of framboids, plaquettes, and spheroids suggest that all the magnetite varieties formed together by replacing a rounded Fe-rich mineral grain or aggregate. Of particular interest is that part of the spheroidal grains consists of Fe-sulfide, while no other sulfide is present in other parts of the aggregate. Many other spheroidal grains in Y-82162 also contain Fe-sulfide. The evidence suggests that the spheroidal magnetite may have resulted from alteration of Fe-sulfide.

Figure 6 shows an unusual aggregate of magnetite plaquettes and minor pyrrhotite

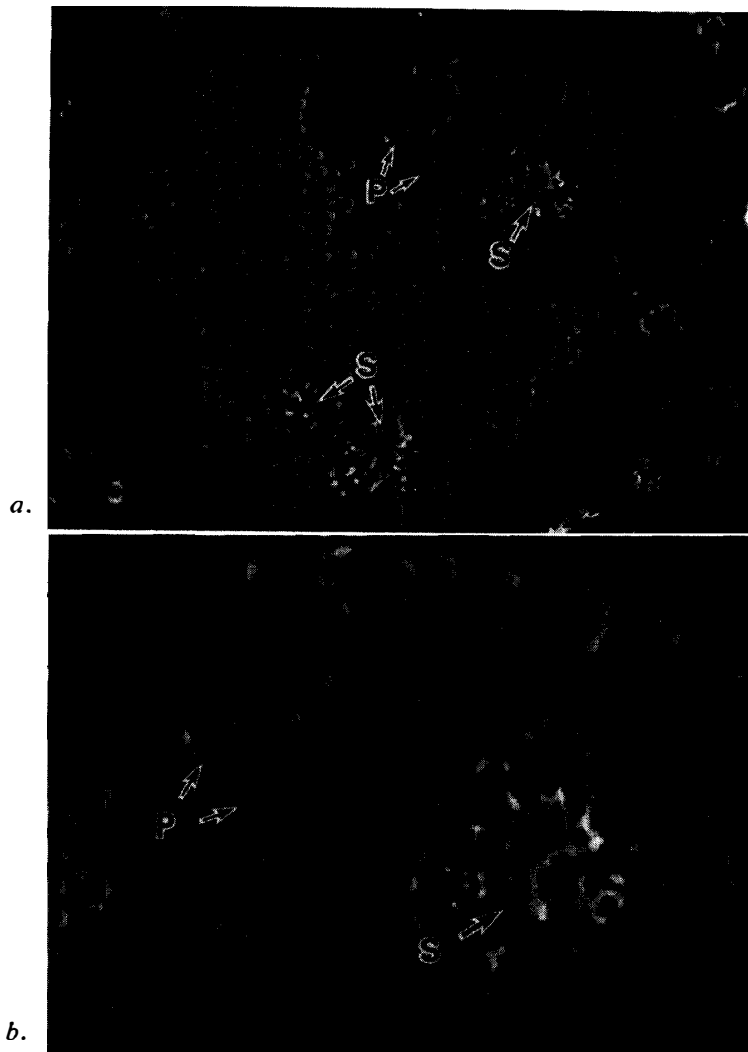


Fig. 5. (a) A framboidal aggregate of magnetite having particles of different sizes, spheroidal grains (S) and plaquettes (P) (secondary electron SEM image). (b) An enlarged image of the upper-right corner of the aggregate in (a).

and Ca-phosphate occurring within a phyllosilicate matrix. The phyllosilicate in the aggregate is distinctly more Fe-rich than the phyllosilicates in isolated clusters (Table 3). The coexistence of magnetite plaquettes with phyllosilicate suggests that they formed together presumably in a process of aqueous alteration. In non-Antarctic CI chondrites, magnetite is commonly enclosed within dolomite or Ca-rich carbonate, but such occurrence is rare in Y-82162.

3.4. Carbonates

Mg-Fe carbonates, primarily breunnerite occur in grains ranging up to 300 μm ; they also contain small, variable amounts of Mn and Ca (Table 5). Minute grains (1 to 5 μm in diameter) bearing variable amounts of Fe and S are sprinkled in the carbonates; they are presumably Fe-oxide and/or Fe-sulfide (Fig. 8). Microprobe analyses of the carbonates also show small variable amounts of Si, suggesting sub-micron mixtures with a silicate. The carbonates are heterogeneous on a submicron

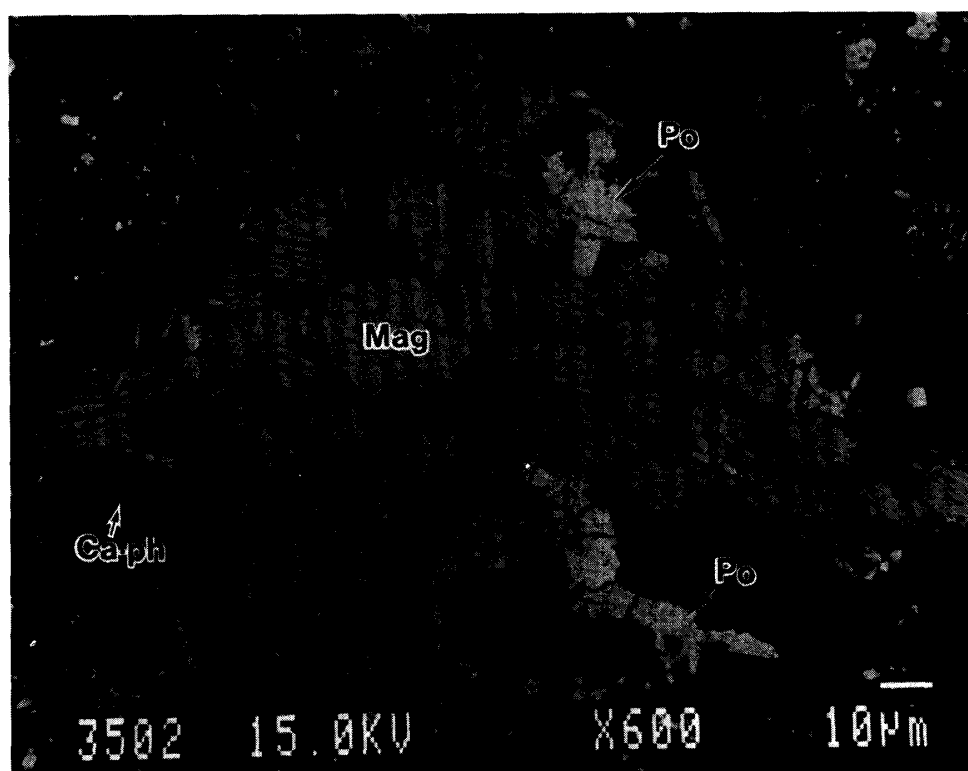


Fig. 6. An aggregate of magnetite plaquettes, pyrrhotite (Po) and Ca-phosphate (Ca-ph) (back-scattered SEM image). The light gray matrix in the aggregate consists of Fe-rich phyllosilicates, whose composition is shown in Analysis #6 in Table 3.

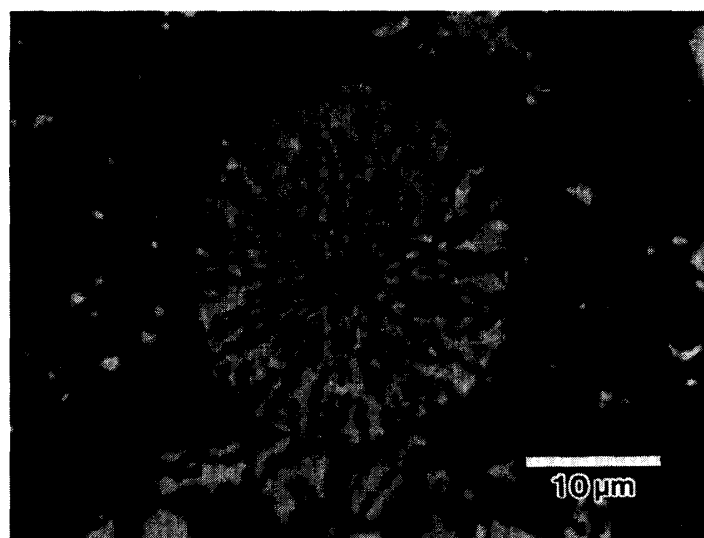


Fig. 7. A spheroidal magnetite grain (secondary electron SEM image). Part of the grain consists of Fe-sulfide.

scale, having patchy textures consisting of Mg-Fe-rich and Mn-Ca-rich regions (Fig. 9).

In non-Antarctic CI chondrites, dolomite is predominant, and Ca-carbonate, possibly aragonite, also occurs in significant amounts (RICHARDSON, 1978; FREDRIKSSON

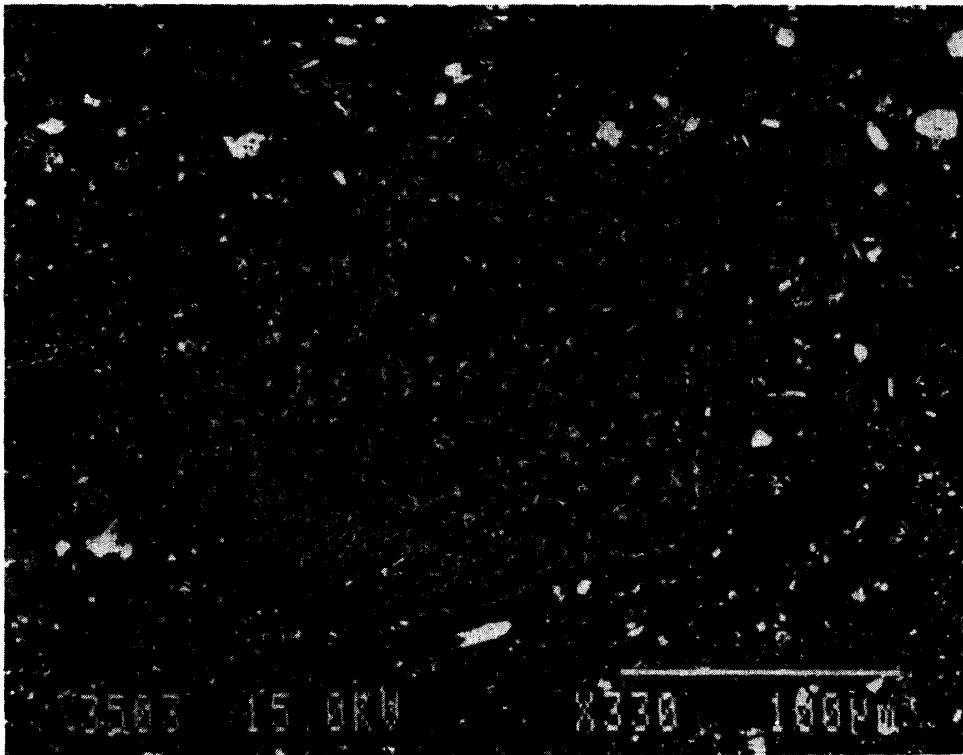


Fig. 8. Mg-Fe-rich carbonate containing minute grains of Fe- and S-bearing phases (bright specks), probably pyrrhotite and magnetite (backscattered SEM image).

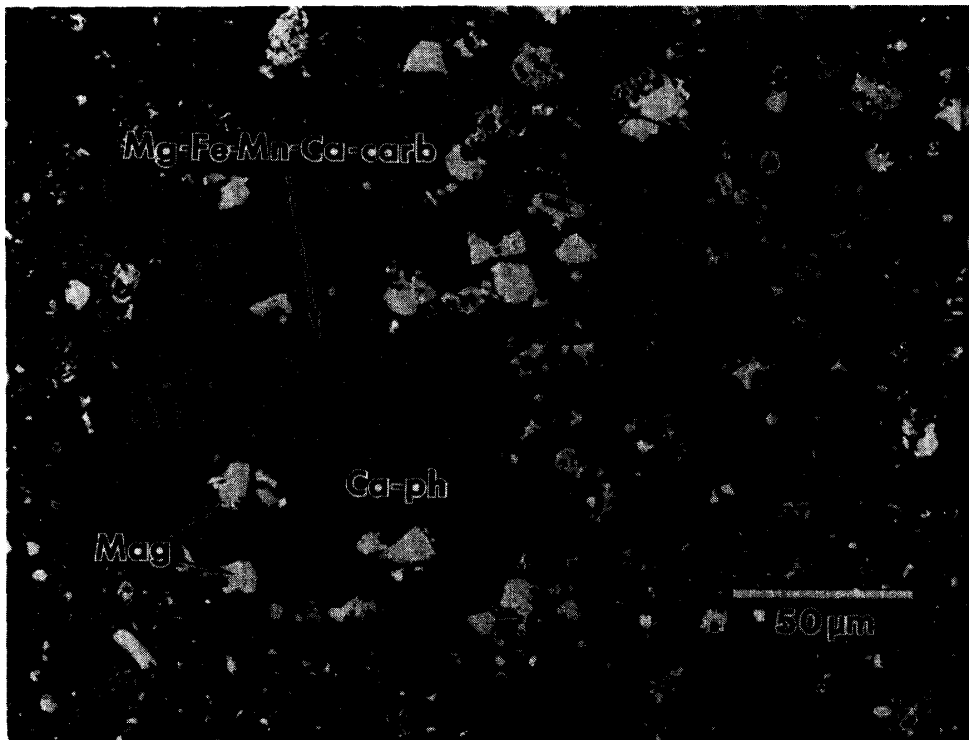


Fig. 9. An aggregate of Ca-phosphate (Ca-ph), Mg-Fe-Mn-Ca carbonate, and magnetite (backscattered SEM image). The carbonate has a patchy texture consisting of Mg-Fe-rich (dark) and Mn-Ca-rich (bright) regions.

and KERRIDGE, 1988). However, Y-82162 contains only trace amounts of dolomite and Ca-carbonate.

3.5. Phosphate

Ca-phosphate has been reported as an extremely minor mineral from Orgueil (NAGY and ANDERSEN, 1964; BOSTRÖM and FREDRIKSSON, 1966). In Y-82162, however, Ca-phosphate is apparently more abundant and occurs in relatively large grains ranging up to 200 μm in diameter (Fig. 9). Our microprobe analyses show no significant amounts of other cations, and the compositions appear to be consistent with apatite or whitlockite (Analysis 3 in Table 5). The Ca-phosphate commonly occurs together with the Mg-Fe carbonates and magnetite, suggesting some genetic link. We also found an aggregate (120 μm in diameter) of Na-bearing, Mg-Fe phosphate (Table 5), which may be related to sarcopside or farringtonite. Such Mg-Fe phosphates have not been known from carbonaceous chondrites.

3.6. Anhydrous silicates

As a rare case, we found an aggregate (120 μm in the largest dimension) consisting of angular grains (5 to 30 μm) of Fe-bearing olivine enclosed in a Ca-Al-Si-rich mesostasis glass (Fig. 10 and Table 5). The aggregate is apparently a broken fragment of a chondrule. The olivine grains have a range of compositions between Fo_{84} and Fo_{78} and are zoned with Fe-rich rims; some olivine grains also have Fe-rich cores. Although individual grains of olivine and pyroxene have been reported from Orgueil (REID *et al.*, 1970; KERRIDGE and MACDOUGALL, 1976), no chondrule has been reported. In some places, the mesostasis glass is in direct contact with the surrounding matrix but shows no indication of alteration. Considering that this

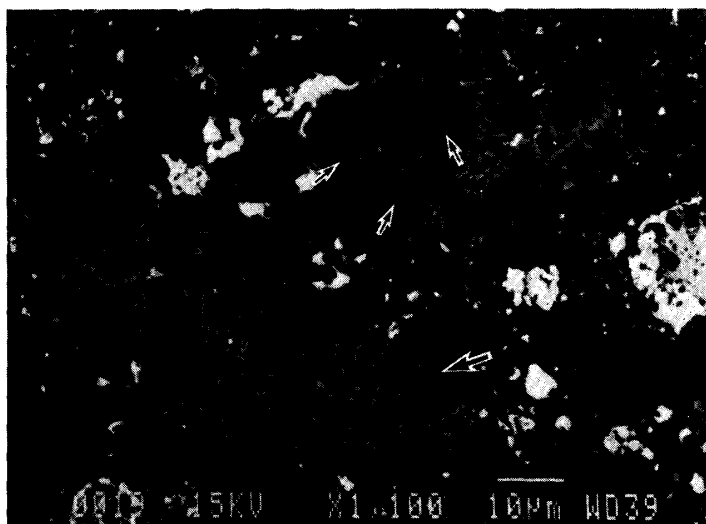


Fig. 10. A chondrule-like aggregate of Fe-rich olivine grains bounded by a Si-Al-Ca-Fe rich glass (backscattered SEM image). Selected microprobe analyses of the olivine and glass are shown in Table 5 (Analyses 5 and 6). Each olivine grain has a narrow Fe-rich rim, which appears bright in the image, and some grains show Fe-rich cores (e.g., the grains indicated by arrows). Indicated by a large arrow is a broken surface of an olivine grain, which is directly exposed to matrix; no Fe-rich rim is seen along the surface.

meteorite has experienced considerable aqueous alteration, this aggregate probably was mechanically mixed from another environment into the matrix after the aqueous alteration was completed; otherwise, the mesostasis glass would have been altered to a phyllosilicate, because glass is a very reactive precursor to phyllosilicate (RICHARDSON, 1981). REID *et al.* (1970) and KERRIDGE and MACDOUGALL (1976) reached the same conclusion for the individual olivine and pyroxene grains that they described from Orgueil. Where broken olivine surfaces are exposed to the matrix, there are no reaction rims (Fig. 10), indicating that the zoning of Fe was produced prior to emplacement of the aggregate into the meteorite.

4. Matrix Mineralogy

Microprobe analyses of the matrix show considerable variations in Fe. The Fe distributions differ among the clasts; some clasts are unusually enriched in Fe in their matrices and are distinctly bright in backscattered SEM images (Fig. 11). The texture is common to the matrix of Orgueil (*cf.* Fig. 3 in TOMEOKA and BUSECK, 1988).

TOMEOKA and BUSECK (1988) showed that the Orgueil matrix consists of a heterogeneous, submicron mixture of serpentine, saponite, and S-, Ni-bearing ferrihydrite ($5\text{Fe}_2\text{O}_3 \cdot 9\text{H}_2\text{O}$). The serpentine and saponite are coherently intergrown and occur in poorly crystallized platelets, in intimate association with the ferrihydrite. Because of the submicron mixture of those minerals, microprobe analyses of the Orgueil matrix show correlations between Fe, S, and Ni and also inverse correlations of these elements with Si, Mg, and Al (*cf.* Figs. 4 and 5 in TOMEOKA and BUSECK, 1988).

In order to see whether similar elemental correlations exist in the Y-82162 matrix, we plot our microprobe analyses in terms of Fe *vs.* S and Si *vs.* Fe (Figs. 12a and b). It is evident that the Y-82162 matrix shows no such obvious elemental correlations as in the Orgueil matrix, indicating that the matrix mineralogies of these meteorites are

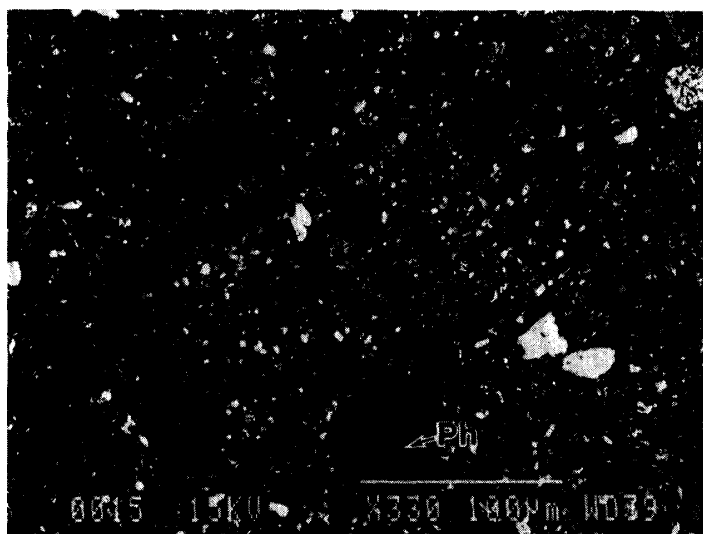


Fig. 11. A clast that is distinctly enriched in Fe in its matrix (backscattered SEM image). The bright small grains that are dispersed throughout the meteorite are mostly pyrrhotite. A phyllosilicate cluster (Ph) is also seen in this field.

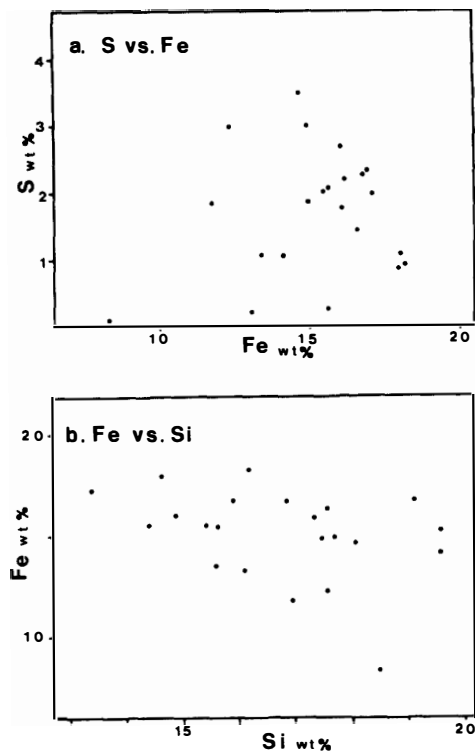


Fig. 12. (a) Plot of Fe vs. S from the Y-82162 matrix (microprobe analysis), (b) Plot of Fe vs. Si.

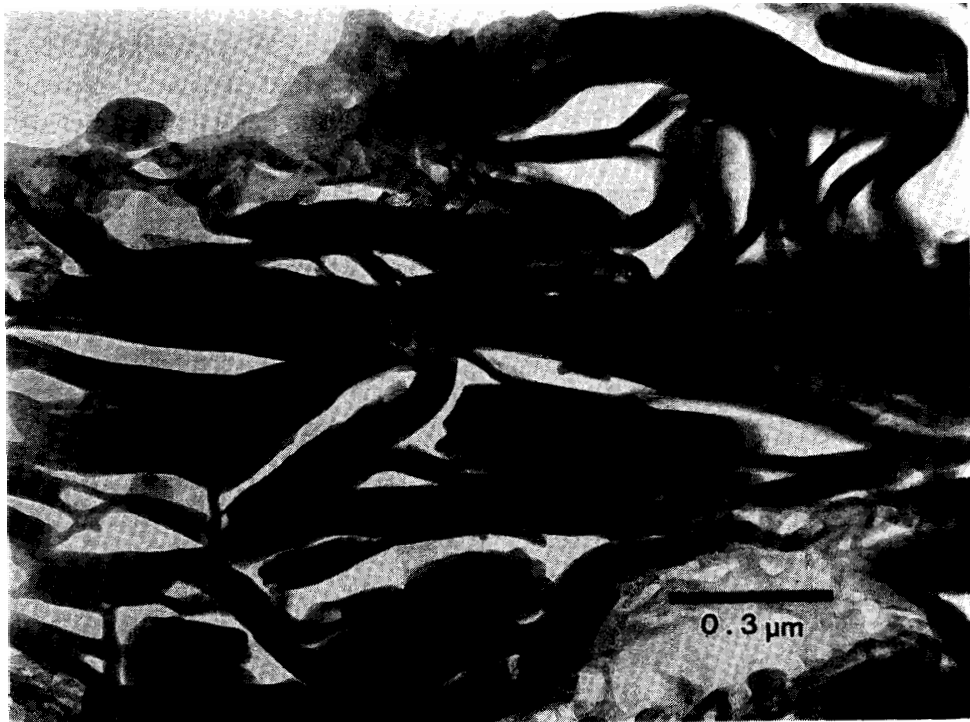


Fig. 13. A low-magnification TEM image of phyllosilicates in the matrix. Despite the relatively coarse grain sizes, they show only weak diffraction spots with broad powder rings, indicating their poor crystallinity.

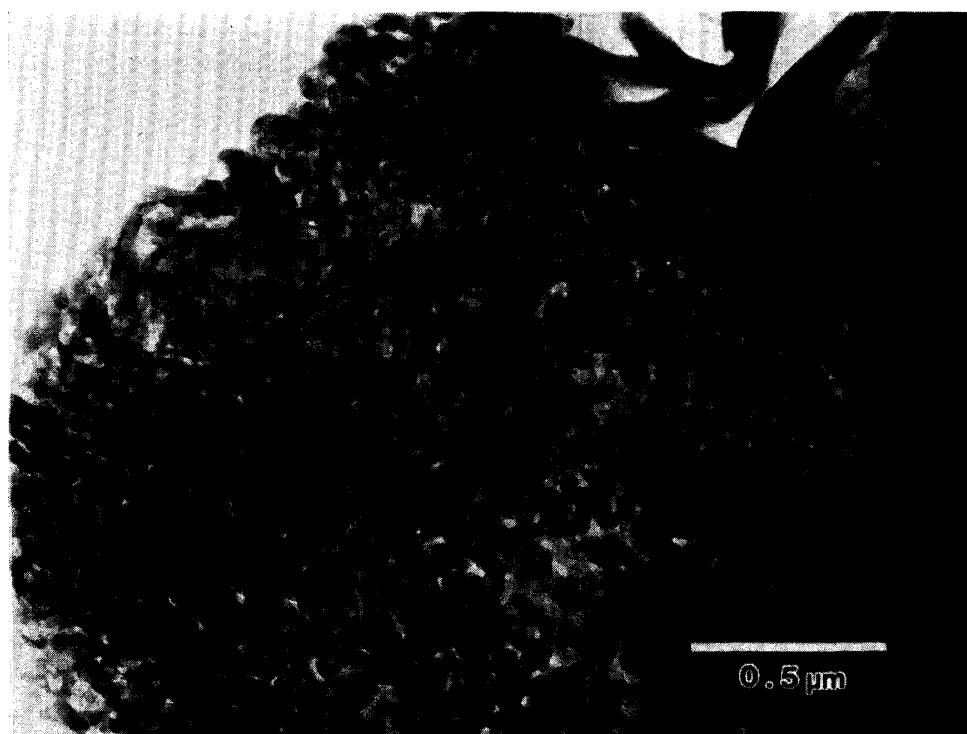


Fig. 14. Fine grains of Mg-Fe olivine in the matrix. The platy grains in the upper-right corner are phyllosilicates.

different.

Another difference in matrix composition is seen in the relative proportions of Fe^{2+} and Fe^{3+} . BOSTRÖM and FREDRIKSSON (1966) reported that Orgueil contains 5.6 wt% Fe^{2+} and 12.7 wt% Fe^{3+} . A large proportion of the Fe^{3+} in Orgueil is accounted for by the ferrihydrite (TOMEOKA and BUSECK, 1988). The wet chemical analysis of Y-82162 shows a much smaller proportion of Fe^{3+} (1.6 wt% Fe^{3+} vs. 8.4 wt% Fe^{2+}) and a lower H_2O content (Table 2), suggesting that its matrix has lower concentration of ferrihydrite than the Orgueil matrix.

Our preliminary TEM observations show that the matrix consists in large part of fine-grained phyllosilicates (Fig. 13). A striking difference from the Orgueil matrix is that the Y-82162 matrix contains abundant fine grains ($<1000 \text{ \AA}$ in diameter) of Mg-Fe silicates that are structurally different from phyllosilicates; they show diffraction rings consistent with olivine (Fig. 14). There are also pyrrhotite, pentlandite, and Mg-Fe carbonates. Those grains are closely associated with the fine phyllosilicates. The phyllosilicates generally have larger grain sizes than those in the Orgueil matrix. However, they commonly show poor crystallinity and exhibit only weak diffraction spots and broad powder rings. Ferrihydrite is not so abundant. The abundance of fine-grained olivine is reminiscent of the Y-86720 chondrite (TOMEOKA *et al.*, 1989).

5. Discussion

The petrography and mineralogy of Y-82162 indicate that it most resembles CI

chondrites. However, details of mineralogy, particularly of matrix mineralogy, and relative abundances of minerals in Y-82162 differ considerably from those in non-Antarctic CI chondrites.

5.1. Aqueous alteration

The CI and CM chondrites have experienced various degrees of aqueous alteration, probably by the activity of liquid water on their parent bodies (*e.g.*, MCSWEEN, 1979, 1987). The presence of complex network of veins of Mg-, Ca-sulfates in the CI chondrites provides strong evidence for such alteration (DUFRESNE and ANDERS, 1962; BOSTRÖM and FREDRIKSSON, 1966; RICHARDSON, 1978). Previous petrographic studies suggested that the aqueous alteration experienced by CI chondrites was a *multi*-stage process and that the sulfate veins formed in a very *late* stage, contemporaneous with the brecciation event on the meteorite parent body (BOSTRÖM and FREDRIKSSON, 1966; RICHARDSON, 1978; TOMEOKA and BUSECK, 1988). Sr isotopic measurements indicated that the sulfate veins could have been formed much later than the earlier alteration (MACDOUGALL *et al.*, 1984). The absence of sulfate veins in Y-82162 suggests that this meteorite has not experienced such late aqueous alteration.

The lack of the late aqueous alteration may be responsible for the abundance of large clusters of coarse phyllosilicates. In Orgueil, the matrix is largely a complex mixture of fine phyllosilicates and ferrihydrite, and coarse phyllosilicates are sparse and occur only in small clusters ($<30 \mu\text{m}$ in diameter). TOMEOKA and BUSECK (1988) showed evidence that the coarse phyllosilicates were attacked by Fe-rich aqueous solutions and were decomposed to the fine phyllosilicates, and the ferrihydrite precipitated from the solutions, thus resulting in the complex mixture of the fine phyllosilicates and ferrihydrite. They suggested that the alteration occurred simultaneously with the sulfate vein formation. Thus, the higher abundance of coarse phyllosilicates and the lower abundance of ferrihydrite in Y-82162 are consistent with the lack of sulfate vein formation process.

The matrices of Orgueil, Alais, and Ivuna are strongly depleted in Na, relative to the bulk meteorite contents (MCSWEEN and RICHARDSON, 1977; KERRIDGE, 1976). Na is one of the highly water-soluble elements, and its depletion probably resulted from leaching during aqueous alteration (RICHARDSON, 1978). In the non-Antarctic CI chondrites, Na-bearing sulfate, bloedite $(\text{Na}_2\text{Ni})(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$, occurs as fracture-filling veins (BOSTRÖM and FREDRIKSSON, 1966; FREDRIKSSON and KERRIDGE, 1988). In Y-82162, the phyllosilicates contain unusually large amounts of Na (1.43 to 4.56 wt% Na_2O), and the matrix is also enriched in Na (0.69 wt%) compared to other CI matrices (0.08 to 0.35 wt% except an Alais analysis) (Table 5; *cf.* MCSWEEN and RICHARDSON, 1977). Because no other visible grains bearing Na are present, most Na in Y-82162 probably occurs in the phyllosilicates. It is plausible that the phyllosilicates in the non-Antarctic CI chondrites were also previously enriched in Na like those in Y-82162, and the late aqueous alteration resulted in the depletion of Na in the matrix and the deposition of the bloedite veins.

TOMEOKA and BUSECK (1988) suggested that ferrihydrite in Orgueil resulted from alteration of magnetite and Fe-(Ni) sulfides as well as precipitation from Fe-rich

solutions, and thus more magnetite and Fe-(Ni) sulfides than are now present may have existed prior to the late aqueous alteration. The high abundance of Fe-(Ni) sulfides and the low abundance of ferrihydrite in Y-82162 may be explained by the lack of the late aqueous alteration.

All these observations suggest that Y-82162 escaped the alteration responsible for the veins of sulfates and carbonates in other CI chondrites, and thus it may retain the mineralogy prior to that alteration event.

5.2. *Thermal metamorphism*

Several mineralogical and chemical features are consistent with Y-82162 having been thermally metamorphosed after the aqueous alteration. The poor crystallinity of phyllosilicates and the presence of abundant fine-grained olivine in the matrix suggest that the phyllosilicates were dehydrated and transformed to olivine by heating. Recently, AKAI (1988) presented evidence that serpentines in the matrices of Yamato-793321 and Belgica-7904 were altered to olivine by heating. Some of the textures in those meteorite matrices closely resemble those in the Y-82162 matrix.

A major amount of Fe (mostly Fe^{3+}) in the Orgueil matrix is accounted for by ferrihydrite, and most S and Ni in the matrix are associated with the ferrihydrite, presumably in some forms of ions or compounds (TOMEOKA and BUSECK, 1988). By contrast, ferrihydrite is much less abundant in the Y-82162 matrix, and most S and Ni in the matrix occur as submicron grains of pyrrhotite and pentlandite in close association with the fine phyllosilicates and olivine. Such occurrence of pyrrhotite and pentlandite is not observed in the Orgueil matrix. A major portion of the sulfides, fine grains in particular, may have resulted from thermal metamorphism. It is possible that ferrihydrite bearing S and Ni existed before the aqueous alteration that produced the sulfate veins and that the fine-grained sulfides were produced by thermal decomposition of the S-Ni-bearing ferrihydrite.

Thermal metamorphism is also suggested by the results of wet chemical analysis (Table 2), which shows that Y-82162 has a distinctly lower H_2O content than other CI chondrites. This is consistent with the presence of considerable olivine and the lower concentration of ferrihydrite in the Y-82162 matrix. A preliminary elemental analysis of Y-82162 indicates significantly lower concentration of nitrogen than other CI chondrites (A. SHIMOYAMA, pers. commun.), which may have resulted from volatilization of some organic compounds by heating. The Y-793321 and B-7904 CM chondrites reportedly contain extremely small quantities of amino acids compared to other CM chondrites (SHIMOYAMA and HARADA, 1984).

If Ca-, Mg-sulfates existed as veins in Y-82162 and were decomposed to form other minerals by thermal metamorphism, there should be chemical and textural evidence for their presence and subsequent reactions. However, no such evidence is observed. If sulfates were thermally decomposed to form Fe-sulfides, part of the S must have been volatilized together with H_2O and organic materials. However, Y-82162 shows no significant depletion of S, assuming that it had the same concentration of S as other CI chondrites before thermal metamorphism. Most Mg in Y-82162 resides in the phyllosilicates and fine-grained olivine, whereas Ca resides in Ca-phosphate and -carbonates. It is apparently difficult to thermally decompose

Ca-, Mg-sulfates and relocate Mg, Ca, and S to produce the minerals as seen in the present meteorite. The thermal effects should be reflected in elemental abundance patterns. Compositional studies of this meteorite are ongoing and should shed further light on this matter.

5.3. Genetic relationship to non-Antarctic CI chondrites

TOMEOKA *et al.* (1989) found that the matrix of the Y-86720 carbonaceous chondrite contains fine grains of olivine that were probably produced by thermal metamorphism of phyllosilicates. AKAI (1988) studied two Antarctic CM chondrites, B-7904 and Y-793321, and showed evidence of similar thermal effects. Most CI and CM chondrites experienced various degrees of aqueous alteration. However, no evidence of significant thermal metamorphism has been reported from non-Antarctic CI and CM chondrites. Considering that the number of well-characterized non-Antarctic CI and CM chondrites is much larger than that of Antarctic counterparts, it is difficult to conceive that those four Antarctic carbonaceous chondrites accidentally show similar thermal effects; thermal effects cannot be related to Antarctic weathering process.

It has been pointed out that Antarctic eucrites are petrographically distinct from non-Antarctic eucrites (TAKEDA *et al.*, 1983). DENNISON *et al.* (1986) and DENNISON and LIPSCHUTZ (1987) suggested that apparent compositional differences exist between Antarctic and non-Antarctic populations of H or L chondrites. MCGARVIE *et al.* (1987) found differences in carbon isotopic profiles between Antarctic and non-Antarctic CI and CM chondrites. All these authors suggested the possibility that those differences are due to distinct extraterrestrial sources.

We suggest that the differences in thermal history between the four Antarctic chondrites and non-Antarctic CI, CM chondrites may reflect distinct meteorite sources. Most non-Antarctic carbonaceous chondrites are falls and less than 100 years old, and they may have been derived from a substantially different meteoroid flux from the much older Antarctic meteorites ($\sim 10^5$ years older; DENNISON *et al.*, 1986). Thus, Y-82162 may have come from a location distinct from other CI chondrites, *i.e.*, separated regions in a parent body or distinct parent bodies. Considering these possibilities, more extensive and detailed studies of Antarctic carbonaceous chondrites are of obvious importance and may provide new insights into the environments of their parent bodies.

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