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MINERALOGY AND PETROLOGY OF BELGICA-7904: A NEW KIND OF CARBONACEOUS CHONDRITE FROM ANTARCTICA

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Abstract: A mineralogical and petrological study of Belgica-7904 (B-7904) shows that it can be classified into the CM group. B-7904 has a variety of chondrules and aggregates, where pyroxenes and mesostasis glass are completely replaced by phyllosilicates, but olivine remains little altered. It has a high abundance of troilite; most occur in submicron to micron grains dispersed in the matrix. Minor taenite occurs, but magnetite is rare and tochilinite is absent. The phyllosilicates have relatively high Na contents and lower (Mg+Fe)/(Si+Al) ratios than serpentine; thus, they may be intergrowths of serpentine and a smectite-like phyllosilicate. Microprobe analyses of the phyllosilicates show high analytical totals relative to ordinary phyllosilicates, being consistent with the idea that they were dehydrated by heating. The fine troilite grains in the matrix may have been transformed from a thermally labile phase such as tochilinite during thermal metamorphism. The opaque mineral assemblage suggests that the thermal metamorphism occurred in a reduced condition.

B-7904 and Y-86720 are mineralogically similar, although the former is less affected by aqueous alteration than the latter. They were probably derived from similar precursors and experienced aqueous alteration and thermal metamorphism in a common environment. These meteorites and ordinary CM chondrites apparently experienced distinct alteration histories, suggesting that they came from different regions in a parent body or different parent bodies.

1. Introduction

Belgica-7904 (B-7904) is one of the unusual carbonaceous chondrites found in Antarctica and is now the subject of a consortium study organized by the Antarctic Meteorite Research Committee of NIPR. This meteorite has been studied by several workers (Kojima *et al.*, 1984; Skirius *et al.*, 1986; Akai, 1988; Paul and Lipschutz, 1989), and all of them agree that B-7904 is classified into the CM group. However, Mayeda *et al.* (1987) indicated that B-7904 has a CI-like oxygen isotopic signature. Yamato-82162 and -86720 (Y-82162 and -86720) are other two meteorites that show CI-like oxygen isotopic characteristics (Clayton and Mayeda, 1989). Previous mineralogical and chemical studies indicated that Y-82162 can be classified into the CI group and Y-86720 into the CM group (Tomeoka *et al.*, 1989a, b; Zolensky *et al.*, 1989; Paul and Lipschutz, 1989). However, details of their mineralogy are different from those of ordinary CI and CM chondrites. Of particular interest is that all these meteorites show evidence of thermal metamorphism (Kojima *et al.*, 1984; AKAI, 1988; TOMEOKA *et al.*, 1989a, b; PAUL and LIPSCHUTZ, 1989). These three meteorites propose new aspects of carbonaceous chondrite mineralogy and chemistry, and potentially provide new insights into the nature of the CI and CM parent bodies.

Despite earlier works, details of mineralogy and petrology of B-7904 are still poorly known. I present here the results of petrographic and scanning electron microscope (SEM) studies of B-7904. Our primary goals are to provide more detailed mineralogical characteristics of B-7904, to compare them with those of Y-82162, Y-86720, and other CI and CM chondrites, and to infer their genetical relationships. The present results support a CM classification for this meteorite. However, B-7904 has many features distinct from ordinary CM chondrites but similar to Y-86720.

2. Materials and Methods

The sample available for study is a polished thin section of $\sim 7.0\ mm^2$ area, which is specially made for our future TEM study and is different from the thin sections delivered to most consortium members for regular petrographic studies. It should be noted that our thin section is several times smaller in area than those studied by other consortium members. I 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. For most analyses, a focused beam $\sim 2\ \mu m$ in diameter was employed. For the matrix analyses, I used a defocused electron beam $\sim 10\ \mu m$ in diameter.

3. Petrography and Mineralogy

3.1. Chondrules, aggregates, and isolated silicate grains

B-7904 has a variety of olivine-rich chondrules and aggregates ranging in size from 100 μm to 1 mm (Fig. 1). Olivines are mostly forsteritic except the ones in a barred olivine chondrule (Fig. 2a), where olivine is zoned and has a range of compositions between Fo_{55} and Fo_{71} (Table 1). Despite the abundance of olivine in chondrules and aggregates, pyroxene is absent. Minor, submicron to micron grains of troilite are scattered in the replacement products. Only the barred olivine chondrule contains a large troilite grain measuring up to 60 μm.

Mesostasis and some phenocrysts in chondrules and aggregates are replaced by a brownish, translucent material, but most olivine grains remain little altered (Figs. 2 and 3). The replacement products contain major Si, Mg, Fe, and Al and minor Na (0.6 to 2.0 wt% Na_2O) and Cr (1.0 to 3.5 wt% Cr_2O_3) (Table 2). Based on texture and composition, they are probably a phyllosilicate (or phyllosilicates). The mesostasis shows a fibrous appearance in SEM images that is characteristic of phyllosilicates, whereas the replaced phenocrysts show relatively smooth surfaces (Fig. 3a, b). The mesostasis tends to be slightly higher in Mg contents and lower in Fe contents than the replaced phenocrysts.

The replacement products are apparently too enriched in Na to be serpentine. Their microprobe analyses are plotted in terms of Fe, Si+Al, and Mg as in a plot described in TOMEOKA *et al.* (1989b) (Fig. 4). Most analyses fall between the serpentine

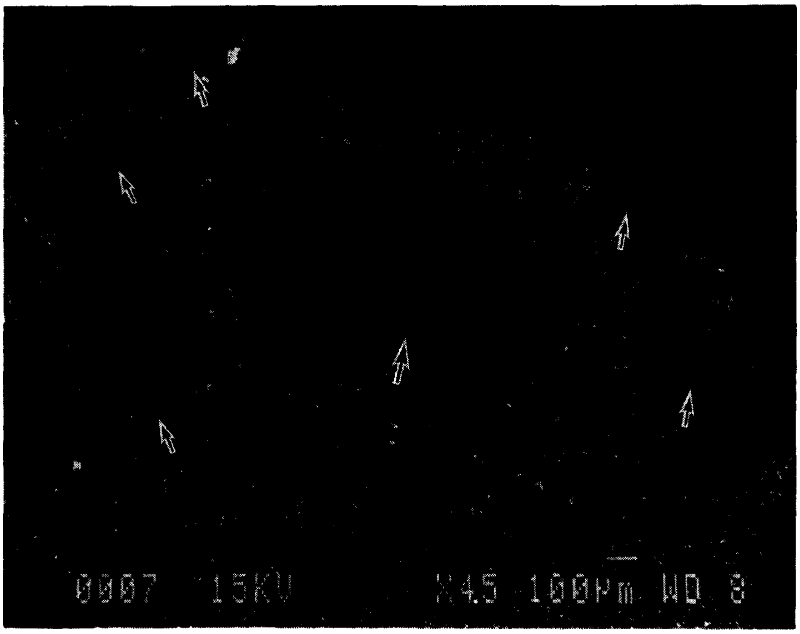


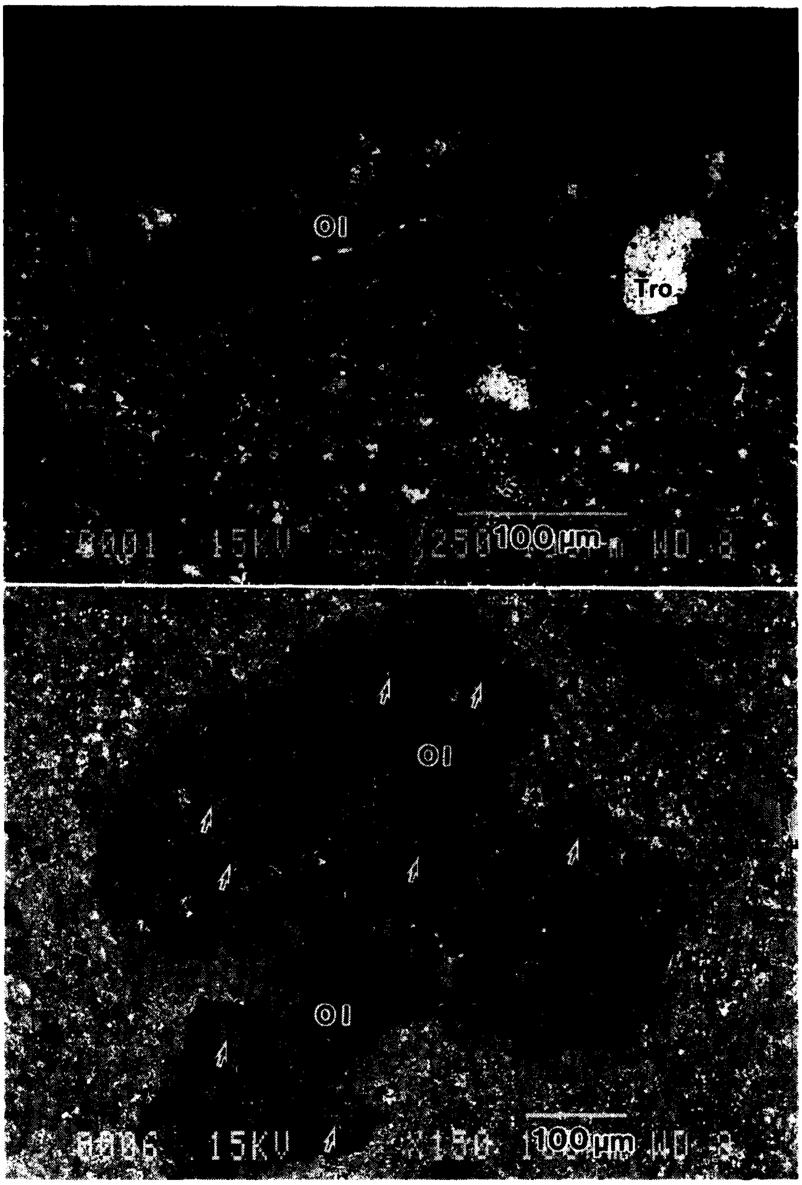
Fig. 1. A low-magnification, backscattered SEM image of B-7904. The meteorite contains a variety of olivine-rich chondrules and aggregates, some of which are indicated by arrows.

Table 1. Electron microprobe analyses of olivine and pyroxene (weight percent).

	Olivine							Pyroxene
	1	2	3	4	5	6	7	8
SiO_2	42.86	42.45	37.26	35.47	42.36	39.80	34.35	58.18
TiO_2	0.09	0.00	0.00	0.03	0.04	0.00	0.00	0.20
Al_2O_3	0.42	0.57	0.00	0.24	0.28	0.10	0.00	0.83
Cr_2O_3	0.00	0.38	0.55	0.28	0.25	0.58	0.53	0.83
FeO	0.31	0.81	25.85	38.67	0.17	14.95	41.78	1.88
MnO	0.22	0.06	0.19	0.49	0.00	0.18	0.37	0.23
MgO	56.28	55.35	35.70	26.21	55.80	44.77	22.47	36.70
CaO	0.18	0.20	0.15	0.36	0.38	0.17	0.16	0.30
Na_2O	0.08	0.22	0.00	0.22	0.00	0.00	0.00	0.00
K_2O	0.01	0.00	0.00	0.00	0.00	0.08	0.00	0.00
Total	100.45	100.04	99.70	101.97	99.28	100.63	99.66	99.15

Analyses Nos. 1–4: from chondrules and aggregates, 5–8: from isolated grains.
Analyses Nos. 3 and 4 are from a core and a rim in an olivine grain in the chondrule shown in Fig. 2 a.

and smectite solid solution lines. Thus, they may be a submicron intergrowth of these two phyllosilicates. Chondrules and aggregates in Y-86720 contain two compositionally different replacement products, which TOMEOKA *et al.* (1989b) called high-Al and low-Al phases. The replacement products in B-7904 have closely similar compositions to the low-Al phase (Fig. 4); an only difference is that the former show higher Cr contents than the latter. In our specimen, the material corresponding to the high-Al phase is not observed. Like the low-Al phase, the replacement products in B-7904 show consistently high analytical totals in their microprobe analyses (90.0 to 96.0



a.

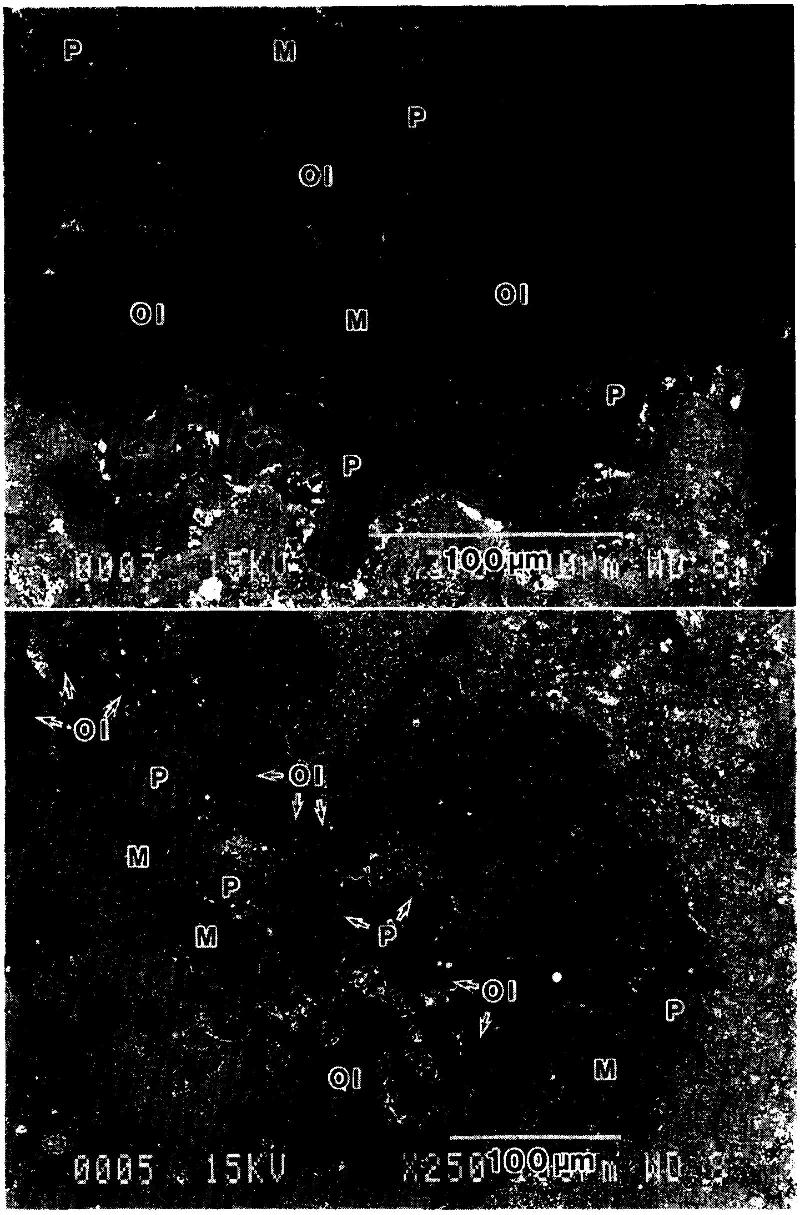
b.

Fig. 2. (a) A barred-olivine chondrule (backscattered SEM image). The olivine (Ol) grains are zoned with Fe-rich rims. The mesostasis is altered by the phyllosilicates. Bright grains are troilite (Tro). (b) A granular-olivine chondrule. Dark part consists mostly of Mg-rich olivine, whereas light grains, some of which are indicated by arrows, are the replacement products.

wt%) (Table 2).

Many chondrules and aggregates have characteristic rims that range in width from 10 to 50 μm. The rims are highly enriched in Fe and S (Table 3). High-magnification SEM images indicate that they contain extremely minute grains rich in Fe and S, possibly metal and/or sulfide, in high density.

An aggregate (~80 μm in the largest dimension) of spinel occurs (Fig. 5). It consists of small angular grains of spinel (<8 μm in diameter) that have nearly pure compositions ($MgAl_2O_4$). The aggregate is surrounded by a ~5 μm-thick rim of



a.

b.

Fig. 3. (a), (b) Chondrules consisting of olivine and replacement products (backscattered SEM image). There are two occurrences for the replacement products, i.e. mesostasis (M) and phenocrysts (P).

phyllosilicates.

Isolated grains of olivine ranging in diameter from several to 200 μm are scattered in the matrix. Small olivine grains (<20 μm in diameter) are particularly common; some of them have a characteristic angular morphology (Fig. 6). They have a relatively large range of Fe/Mg ratios (Fo_{100} to Fo_{49}; Table 1) compared to the olivines in chondrules and aggregates. Pyroxene is extremely rare; we observed only two grains of enstatite (15 and 40 μm in diameter) in the matrix (Table 1). Isolated phyllosilicate grains are also present.

Table 2. Electron microprobe analyses of replacement products in chondrules and aggregates (weight percent).

	1	2	3	4	5	6	7	8
SiO_2	48.72	40.97	42.15	41.40	42.32	41.26	38.34	40.16
TiO_2	0.08	0.14	0.18	0.16	0.11	0.07	0.33	0.18
Al_2O_3	5.64	7.38	7.51	7.10	8.21	5.33	9.90	5.42
Cr_2O_3	1.04	1.35	1.26	1.37	1.23	1.67	1.63	3.17
FeO	10.21	16.81	15.20	13.53	18.71	19.29	21.41	19.11
NiO	0.00	0.04	0.00	0.00	0.05	0.01	0.17	0.04
MnO	0.07	0.00	0.17	0.12	0.00	0.07	0.14	0.23
MgO	25.79	26.03	24.17	24.84	21.84	20.84	20.45	22.41
CaO	0.15	0.08	0.02	0.10	0.15	0.29	0.49	0.42
Na_2O	1.67	1.98	1.36	1.45	1.52	0.63	1.44	0.84
K_2O	0.25	0.21	0.23	0.20	0.42	0.42	0.26	0.30
P_2O_5	0.00	0.13	0.06	0.13	0.00	0.19	0.16	0.19
S	0.11	0.12	0.04	0.20	0.32	0.17	0.38	0.26
Total	93.73	95.24	92.35	90.60	94.88	90.24	95.10	92.73

Analyses Nos. 1–4: from mesostasis, Nos. 5–8: from replaced phenocrysts.

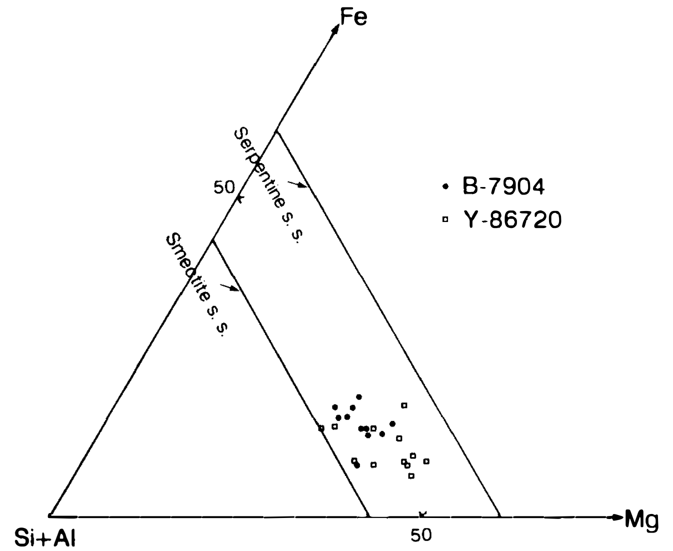


Fig. 4. Electron microprobe analyses of the replacement products in chondrules and aggregates in B-7904 and Y-86720 in terms of atomic percents of Fe, Si+Al, Mg. Also shown are the ideal Mg-Fe solid solution lines of serpentine and trioctahedral smectite.

3.2. Sulfide, metal, and some unusual material

This meteorite has a high abundance of Fe-sulfide, primarily troilite, which mostly occurs in small grains (<10 μm) dispersed in the matrix. The occurrence of the sulfide resembles those in Y-82162 and Y-86720. However, relatively large lath-like Fe-sulfide grains (100 to 500 μm in length) that are common in both Y-82162 and Y-86720 (TOMEOKA *et al.*, 1989a, b) are not observed in B-7904. Porous aggregates of small troilite grains are also common (Fig. 7). Minor Fe-Ni metal occurs in aggregates with troilite (Fig. 8). Most grains have compositions characteristic of taenite. Unlike ordinary CM chondrites, magnetite is rare, and PCP is absent.

Table 3. Electron microprobe analyses of chondrule rims and Si-Mg-Fe-S-rich material (weight percent).

	Chondrule rims				Si-Mg-Fe-S-rich material	
	1	2	3	4	5	6
SiO_2	29.97	31.25	33.03	31.78	34.04	24.87
TiO_2	0.07	0.28	0.18	0.29	0.16	0.17
Al_2O_3	2.58	2.96	2.57	2.52	2.75	2.01
Cr_2O_3	0.48	0.73	0.45	0.49	0.17	0.26
FeO	32.42	30.38	25.04	32.40	32.56	37.61
NiO	2.23	2.43	1.23	1.50	1.69	1.94
MnO	0.30	0.23	0.13	0.33	0.34	0.13
MgO	14.17	15.30	18.61	15.31	16.59	13.80
CaO	0.50	0.37	0.27	0.37	2.11	0.30
Na_2O	0.77	0.40	0.38	0.40	0.94	0.69
K_2O	0.09	0.15	0.12	0.06	0.09	0.05
P_2O_5	0.00	0.07	0.00	0.00	0.00	0.18
S	4.04	3.03	4.32	2.59	5.26	11.20
Total	87.62	87.58	86.33	88.04	96.70	93.21

Table 4. Electron microprobe analyses of B-7904 matrix (weight percent).

	1	2	3	4	5	6	7	Average*
SiO_2	31.96	36.54	36.66	31.96	29.99	31.73	32.05	32.43
TiO_2	0.07	0.16	0.31	0.16	0.13	0.00	0.01	0.12
Al_2O_3	2.08	2.86	3.43	2.63	2.56	3.03	2.57	2.83
Cr_2O_3	0.29	0.51	0.46	0.57	0.27	0.39	0.42	0.43
FeO	21.78	23.75	24.42	24.71	25.37	26.13	28.26	25.80
NiO	2.20	1.64	0.83	2.15	2.56	1.35	0.93	1.59
MnO	0.43	0.14	0.09	0.23	0.24	0.21	0.17	0.18
MgO	26.85	19.62	19.93	21.51	18.14	19.36	17.19	18.71
CaO	0.65	2.55	0.40	1.56	0.82	0.99	1.36	1.93
Na_2O	0.20	0.44	1.18	0.89	0.80	0.25	0.62	0.46
K_2O	0.06	0.10	0.09	0.09	0.10	0.04	0.07	0.08
P_2O_5	0.02	0.09	0.03	0.05	0.26	0.00	0.21	0.17
S	0.43	0.85	1.82	0.60	0.15	1.42	1.58	1.03
Total	87.02	89.25	89.65	87.11	81.39	84.90	85.44	85.76

* Average of 27 analyses.

Subrounded clusters (20 to 100 μm in diameter) having unusual compositions occur in the matrix (Fig. 9); they contain major Si, Mg, Fe, and S and minor Al and Ni (Table 3). As far as the compositions are concerned, they are reminiscent of PCP (FUCHS *et al.*, 1973). However, their textures are apparently different; the clusters in B-7904 appear to consist of numerous, extremely small particles rich in Fe and S, probably troilite and/or metal, and a phyllosilicate matrix. This material is compositionally and texturally similar to the chondrule rims described in Section 3.1.

Other minor materials include rounded aggregates rich in Ca, possibly Ca carbonate, and Mg-Al-bearing chromite.

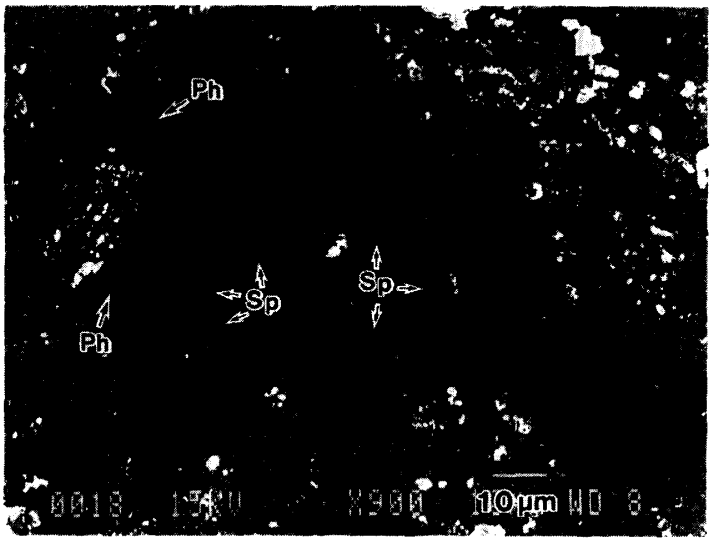


Fig. 5. An aggregate of spinel (Sp) grains coexisting with phyllosilicates (Ph) (backscattered SEM image).

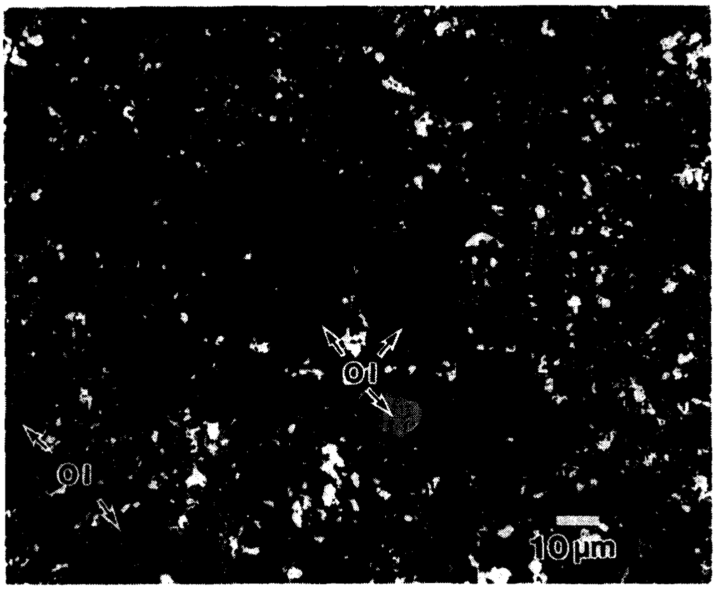


Fig. 6. Fe-rich olivine (Ol) grains in the matrix (backscattered SEM image). The brightness is roughly proportional to Fe contents.

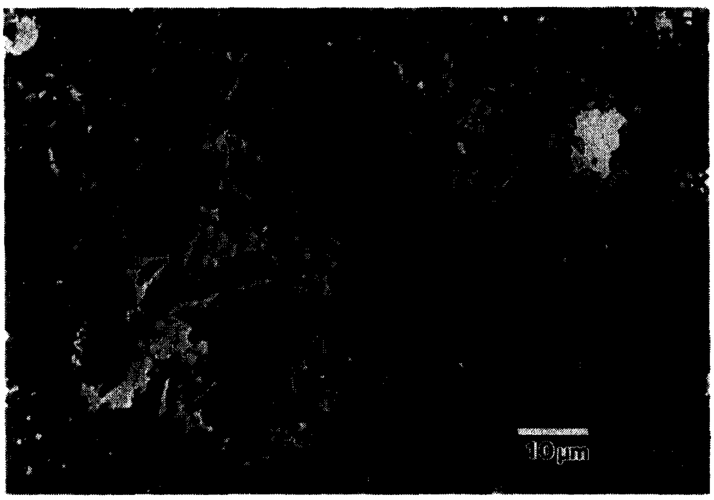


Fig. 7. Aggregates of troilite particles (backscattered SEM image). Dark part in the aggregates is a pore space.

Fig. 8. A troilite grain coexisting with Fe-Ni metal (backscattered SEM image).

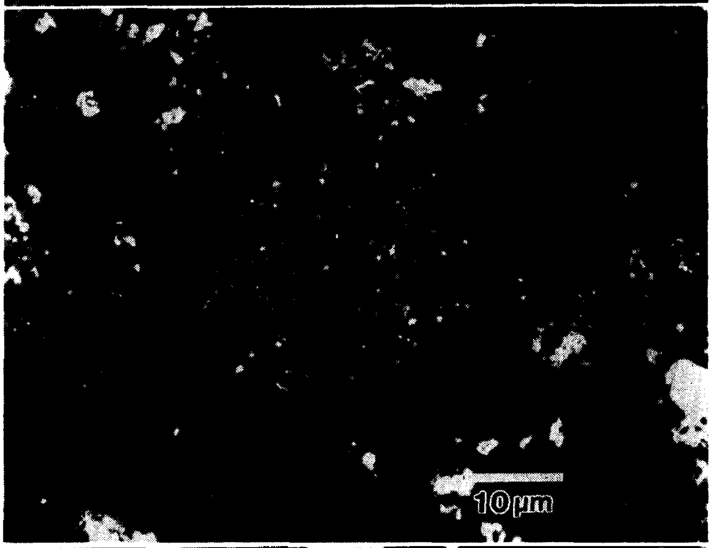


Fig. 9. A cluster rich in Si, Mg, Fe, and S (backscattered SEM image). It appears to contain numerous, submicron Fe-S-rich particles.

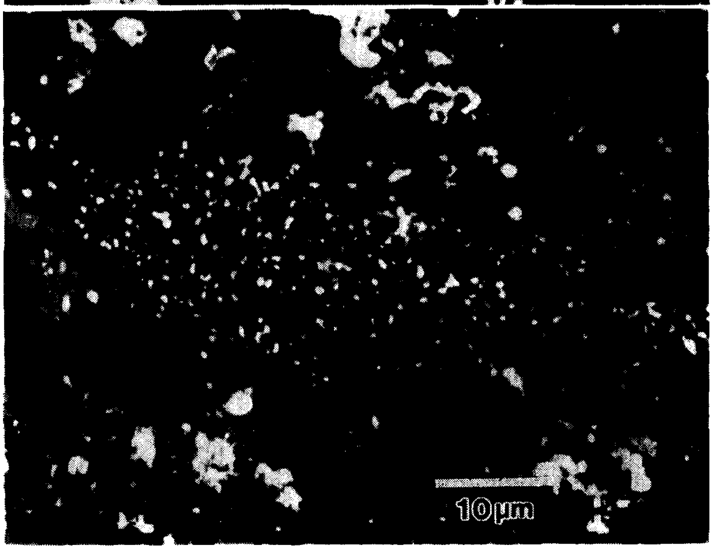


Fig. 10. Fe-Ni-rich particles in the matrix (backscattered SEM image).

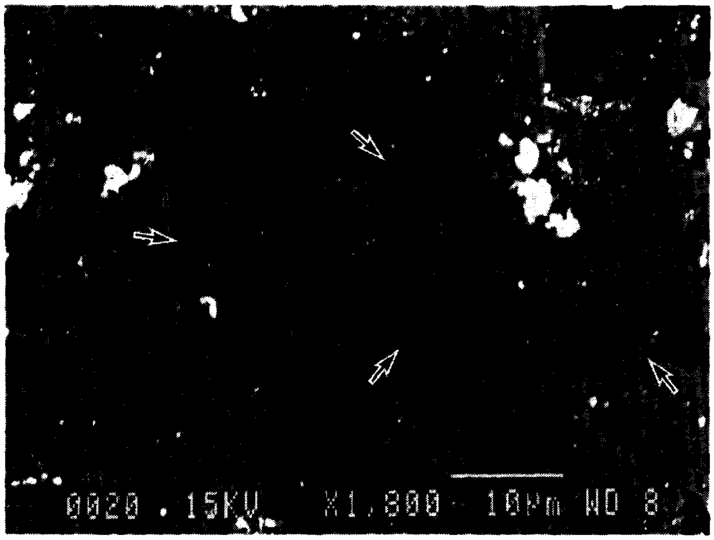


Fig. 11. Ca-rich veins (indicated by arrows) in the matrix (back-scattered SEM image).

3.3. *Matrix*

Broad-beam microprobe analyses indicate that the matrix shows large variations in Fe contents. In average, its Fe content is in the level of ordinary CM chondrites (Table 4; *cf.* McSween and Richardson, 1977). S is considerably depleted relative to other CM chondrites and appears to have positive correlations with Fe in their distributions. In the matrices of ordinary CM chondrites, most Ni occurs in tochilinite and pyrrhotite, thus exihibiting positive correlations with Fe and S. However, in the matrix of B-7904, Ni does not show obvious correlations with Fe and S, being similar to the matrix of Y-86720. Tomeoka *et al.* (1989b) found that submicron particles rich in Fe and Ni, probably Fe-Ni metal, are widespread in the Y-86720 matrix, and suggested that most Ni in the matrix resides in the Fe-Ni-rich particles. Similar Fe-Ni-rich particles are found in the B-7904 matrix (Fig. 10), and thus the major part of Ni in the B-7904 matrix may also be accounted for by those particles.

The analyses of B-7904 matrix show relatively high and variable Ca contents compared to ordinary CM chondrite matrices (1.93 *vs.* 0.56 CaO wt% on average; the latter is derived from ten CM chondrites; data from McSween and Richardson, 1977; Table 4). SEM observations of highly Ca-enriched areas reveal networks of narrow Ca-rich veins (<2 μm in width; Fig. 11). The narrow widths of the veins preclude identifying this phase; however, because no other major components than Ca are detected, it may be a Ca carbonate. Veins filled by Ca-Mg-rich carbonate were reported from CI chondrites (Richardson, 1978), but they are much larger in size and rarer than those in B-7904. Such veins are not known in CM chondrites.

4. Discussion

4.1. *Aqueous alteration*

The present mineralogical and petrographic study indicates that B-7904 can be classified into the conventional CM group and is similar to Y-86720. In CM chondrites, chondrules and aggregates are altered in various degrees to phyllosilicates (McSween, 1979, 1987; Ikeda, 1983; Tomeoka *et al.*, 1989c). In the chondrules and aggregates of B-7904, the mesostasis and some phenocrysts were replaced by the phyllosilicates, but olivine remains little altered (Figs. 2 and 3). On the other hand, the chondrules and aggregates in Y-86720 were completely replaced by the phyllosilicates (TOMEOKA *et al.*, 1989b). IKEDA (1983) found that mesostasis glass, pyroxene, and olivine in chondrules of CM chondrites were altered in this order with advancing alteration. Based on this criterion and the observed textures, I suggest that the phyllosilicates constituting the mesostasis in the B-7904 chondrules and aggregates probably resulted from alteration of glass, and those constituting the phenocrysts resulted from alteration of pyroxene. Even in the relatively mildly altered CM chondrites such as Murray and Murchison (MCSWEEN, 1979), olivine grains are replaced by phyllosilicates to some extent (*e.g.*, Fig. 1 in TOMEOKA *et al.*, 1989c). However, such textural evidence is not observed in the B-7904 olivines. Thus, the degree of aqueous alteration for B-7904 may be even lesser than those for Murray and Murchison.

The matrix of B-7904 shows unusually high, variable Ca contents, which are explained by the presence of narrow veins of the Ca-rich material. Ca is one of the elements particularly susceptible to aqueous alteration and tends to be leached at early stages of aqueous alteration (RICHARDSON, 1978; IKEDA, 1983); thus, in most CI and CM matrices, Ca is strongly depleted relative to the bulk compositions. In CI chondrites, the leached Ca was apparently deposited as Ca-sulfate and dolomite (FREDRIKSSON and KERRIDGE, 1988), and in CM chondrites, it was mostly deposited as calcite. The most probable sources for the Ca in the B-7904 matrix are Ca-clinopyroxenes (*e.g.*, diopside, fassaite, *etc.*) and mesostasis glass in chondrules and aggregates. Ca-Al-rich inclusions (CAIs) may also be a source, but CAIs are apparently rare in this meteorite. Because of a low degree of aqueous alteration, Ca probably remained relatively unleached in the B-7904 matrix.

Isolated grains of olivine having various Fe/Mg ratios are common in the matrix of B-7904. Many olivine grains have characteristic angular morphologies (Fig. 6). Such external shapes could not have survived if they were incorporated into the matrix before or during aqueous alteration. The olivine grains were probably disaggregated from chondrules and aggregates after completion of aqueous alteration. The abundance of such olivine grains may be explained by the early completion of aqueous alteration.

Although opaque minerals such as sulfides, metal, PCP, and magnetite are common in chondrules and aggregates in CM chondrites, only minor troilite occurs in chondrules and aggregates in B-7904. This characteristic was also recognized by TOMEOKA *et al.* (1989b) in Y-86720, and they suggested that this may be a consequence of advanced aqueous alteration. However, B-7904 was apparently affected by a lesser degree of alteration than Y-86720. The sparsity of opaque minerals, thus, may be ascribed to the original nature of the chondrules and aggregates of these meteorites.

4.2. *Thermal metamorphism*

B-7904 has unusually low H_2O and C contents (HARAMURA *et al.*, 1983; SHIMOYAMA and HARADA, 1984), which has been ascribed to thermal metamorphism (KOJIMA *et al.*, 1984). AKAI (1988) found that the matrix in B-7904 contains abundant submicron olivine grains and concluded that they were formed by thermal transformation of the phyllosilicates. TOMEOKA *et al.* (1989a, b) also found similar evidence from the matrices of Y-82162 and -86720. Trace element chemistry also supports the view that they were thermally metamorphosed (PAUL and LIPSCHUTZ, 1989). The relatively high analytical totals of the replacement products in the B-7904 chondrules and aggregates are probably explained by partial alteration of phyllosilicates to olivine by heating.

Based on heating experiments, previous workers have shown that transformation of serpentine to olivine occurs between 500 and 600°C (BRINDLEY and ZUSSMAN, 1957; BALL and TAYLOR, 1963; Souza SANTOS and YADA, 1979, 1983; AKAI, 1988). AKAI found that the phyllosilicate structure is completely absent in the B-7904 matrix, which he ascribed to a relatively high degree of thermal transformation. Phyllosilicates are also almost completely absent in Y-86720; however, some phyllosilicates remain in Y-82162 (TOMEOKA *et al.*, 1989a, b). Based on these observations, Y-82162 appears to have been affected by less thermal transformation than Y-86720 and B-7904, although it is not clear yet whether it means a higher degree of transformation temperature or a longer duration of heating.

One of the major mineralogical differences between B-7904 and ordinary CM chondrites is that PCP is absent in the former, while it is abundant in the latter. PCP is an intimate intergrowth of FESON (tochilinite) and cronstedtite (TOMEOKA and BUSECK, 1985), and tochilinite decomposes to troilite at 245°C (FUCHS *et al.*, 1973). TOMEOKA *et al.* (1989b) suggested that the small grains of troilite in the matrix presumably resulted from thermal transformation of the thermally labile tochilinite, thus resulting in the depletion of Fe and S in the Y-86720 matrix. We suggest that the troilite grains in the B-7904 matrix, small grains in particular, also have the same origin. The present study reveals that B-7904 matrix contains unusual clusters that apparently consist of intimate mixtures of Fe-sulfide particles and phyllosilicates (Fig. 9). Those clusters may be products of thermal alteration of Type II PCP (TOMEOKA and BUSECK, 1985). The porous aggregates of troilite particles (Fig. 7) also could have been formed by decomposition of some Fe-S-bearing material and loss of volatiles by heating.

B-7904 contains much troilite and minor Fe-Ni metal and little magnetite and pentlandite. The opaque mineral assemblage is similar to that in Y-86720 but differs from those in other CM chondrites. The presence of Fe-Ni metal and the sparsity of magnetite and Ni-rich sulfides suggest that the thermal metamorphism occurred in a relatively reduced condition (TOMEOKA *et al.*, 1989b).

4.3. A scheme for new carbonaceous chondrite classification

Since it has been recognized that Y-82162, Y-86720, and B-7904 have distinct mineralogical, chemical, and oxygen isotopic characteristics from those of ordinary CI and CM chondrites, there seems to have been considerable confusion about a classification of these chondrites. We now know that there are two separate sets of CI and CM (or Cl and C2) chondrites in the oxygen isotopic plot (CLAYTON and MAYEDA, 1989), which may reflect different precursors or different parent bodies.

I suggest that the carbonaceous chondrites should be first divided into the separate groups based on oxygen isotopic characteristics. Previous designations of chemical groups CI and CM can be redefined as oxygen isotopic groups. Then, each oxygen

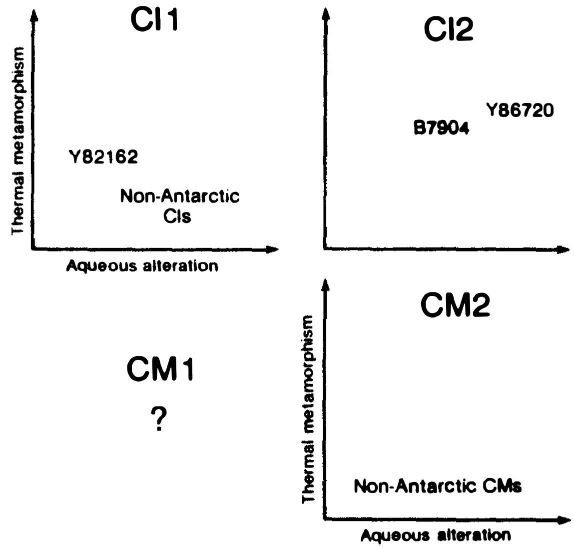


Fig. 12. Illustration indicating relative degrees of aqueous alteration (horizontal direction) and thermal metamorphism (vertical direction) experienced by the meteorites in the newly proposed classification. Arrows indicate increasing degrees of aqueous alteration and thermal metamorphism. Relative degrees of secondary effects are arbitrary. Meteorites that should be classified into the CM1 group have not been collected.

isotopic group can be subdivided based on petrographic, mineralogical, and chemical characteristics in a conventional manner, by using numerics *e.g.*, CI1, CI2, CM1, and CM2. According to such a scheme, Y-82162 is classified as a CI1 chondrite, and B-7904 and Y-86720 are classified as CI2 chondrites. The conventional CI (or C1) and CM (or C2) chondrites should be classified as CI1 and CM2, respectively. We have not yet collected meteorites that belong to CM1 group.

The classification does not include variations due to secondary effects. We now recognize that the CI and CM chondrites were affected by aqueous alteration and thermal metamorphism. Thus, we may need further subdivisions to indicate the degrees of such secondary effects. However, I am reluctant to incorporate them into the classification at present, because the degrees of the secondary effects are still ambiguous and thus their incorporation will cause more confusion. Figure 12 shows relative differences in the degrees of aqueous alteration and thermal metamorphism of B-7904, Y-82162, Y-86720, and non-Antarctic CI and CM chondrites in the newly proposed classification.

5. Conclusions

(1) B-7904 can be classified into the conventional CM group; its mineralogical and petrological characteristics are similar to Y-86720.

(2) It was affected by a lower degree of aqueous alteration than Y-86720. In chondrules and aggregates, mesostasis glass and pyroxene were completely replaced by phyllosilicates, but olivine remains little altered.

(3) Narrow veins of Ca-rich material, possibly carbonate, are widespread in the matrix; they probably explain the relatively high Ca content in the matrix. Ca was

presumably derived from Ca-clinopyroxene and mesostasis glass in chondrules and aggregates during aqueous alteration.

(4) The high analytical totals of EDS analyses of phyllosilicates are consistent with the idea that this meteorite has been affected by thermal metamorphism.

(5) Small grains of troilite are abundant in the matrix. Minor taenite occurs, but magnetite is rare and tochilinite is absent. The troilite grains, small grains in particular, may have been transformed from a thermally labile phase such as tochilinite during thermal metamorphism. The opaque mineral assemblage suggests that the thermal metamorphism occurred in a reduced condition.

(6) B-7904 and Y-86720 were probably derived from a common source. These meteorites and ordinary CM chondrites presumably experienced distinct aqueous alteration conditions and thermal histories, suggesting that they came from different sources.

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