THE ALTERATION OF CHONDRULES AND MATRICES IN NEW ANTARCTIC CARBONACEOUS CHONDRITES

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Abstract: Seven carbonaceous chondrites, Yamato-791717(CO3), -74135(CO3), -793321(CM), -791198(CM), -790003(CM), Belgica-7904(CM) and Y-791824(CM) have been studied petrographically and petrologically to characterize their state of alteration. The degree of alteration of these specimens varies widely, from unaltered Y-791717 to intensely altered Y-791824. Petrographical criteria and chemical compositions, especially the Si-Mg-Fe ratios of chondrules and matrices, can be used to define the degree of alteration of CM chondrites. The degree of alteration is classified into four stages, as follows: (1) Unaltered stage, (2) Weakly-altered stage, (3) Moderately altered stage and (4) Intensely altered stage. No CM chondrite belonging to stage 1 has been found. Y-793321 and -791198 are altered to stage 2. Y-790003 belongs to stage 3, and the alteration degree of Y-791824 lies between stage 3 and 4. B-7904 appears to have suffered thermal metamorphism after being intensely altered.

1. Introduction

Antarctic meteorites in the Japanese collection include over 30 carbonaceous chondrites. Many of these have suffered various degrees of alteration. The chondrules and matrices in some carbonaceous chondrites remain fresh, but those in other carbonaceous chondrites have been intensely altered to aggregates of hydrous materials.

In general, the hydrous materials included in chondrules and matrices in carbonaceous chondrites are considered to have been formed by the alteration in nebula or parent bodies (MCSWEEN and RICHARDSON, 1977; BUNCH and CHANG, 1978; DESNOYERS, 1980; RICHARDSON, 1981; IKEDA, 1983). MCSWEEN (1979) briefly classified CM chondrites into three categories, based on the state of their matrices: partly altered, altered and highly altered. But the detailed process and criteria for the degree of alteration of carbonaceous chondrites have not yet been clarified systematically.

In thie paper, the alteration which took place in nebula or parent bodies of carbonaceous chondrites Yamato-74135, -790003, -791198, -791717, -791824, -793321 and Belgica-7904 is studied, and the degree of their alteration is discussed.

2. Analytical Methods

One to three polished thin sections of each of the seven carbonaceous chondrites studied were prepared. Analyses were performed with a JCXA-733 superprobe microanalyzer, operated at an accelerating voltage of 15 kV and 1.0×10^{-8} A with a take-off angle of 40°. A defocussed beam ranging from 10 to 40 μm in diameter was used to obtain the chemical compositions of groundmasses and matrices. The correction method was according to BENCE and ALBEE (1968), with the revised correction factors of NAKAMURA and KUSHIRO (1970).

3. Descriptions

"Groundmass" is defined here as the mesostasis of chondrules, material filling the interstitial spaces between pyroxenes, olivines, and opaque minerals in the chondrules. In fresh chondrules which have suffered no alteration, the groundmasses consist of clean glass or a devitrified glass, whereas in the altered chondrules they consist of aggregates of phyllosilicates. "Matrix" was defined to be the aggregates of materials finer than micron size which occur between chondrules, CAI's, AOI's, and mineral fragments in the chondrites (McSWEEN and RICHARDSON, 1977; IKEDA, 1983).

3.1. Yamato-791717

This chondrite consists of chondrules, calcium-alminium inclusions (CAI's), amoeboid olivine inclusions (AOI's), mineral fragments and matrix. A variety of chondrule types are present, the main types being olivine-pyroxene porphyritic and olivine porphyritic. Minor radial pyroxene, barred-olivine and opaque chondrules also occur. The groundmasses of most olivine chondrules and olivine-pyroxene chondrules are clear transparent glasses (Fig. 1a), but some are brown devitrified glass. Chondrule minerals seem to have suffered no alteration. The chondrules are less than 1 mm in diameter. Many of the chondrules contain spherical and irregular-shaped grains of Ni-Fe metal and troilite. Irregular-shaped grains of Fe-Ni metal and troilite also occur in the matrix. According to WASSON's criteria (1974), this chondrite is classified as a CO3.

3.2. Yamato-74135

This chondrite consists of chondrules, CAI's, AOI's, mineral fragments, devitrified

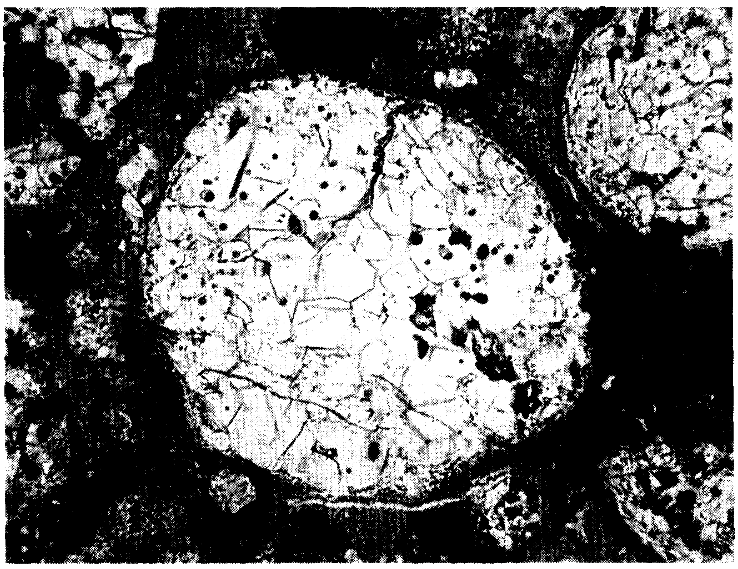


Fig. 1a. Clean transparent glass in the chondrule of Y-791717 (alteration stage I). Plain light. Long dimension of image, 0.6 mm.

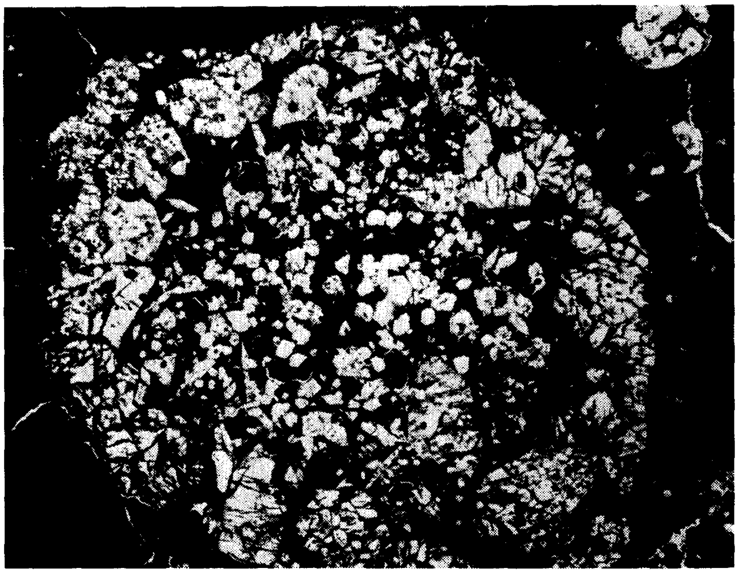


Fig. 1b. Groundmass phyllosilicates of alteration stage II in the chondrule of Y-793321. Plain light. Long dimension of image, 1.2 mm.

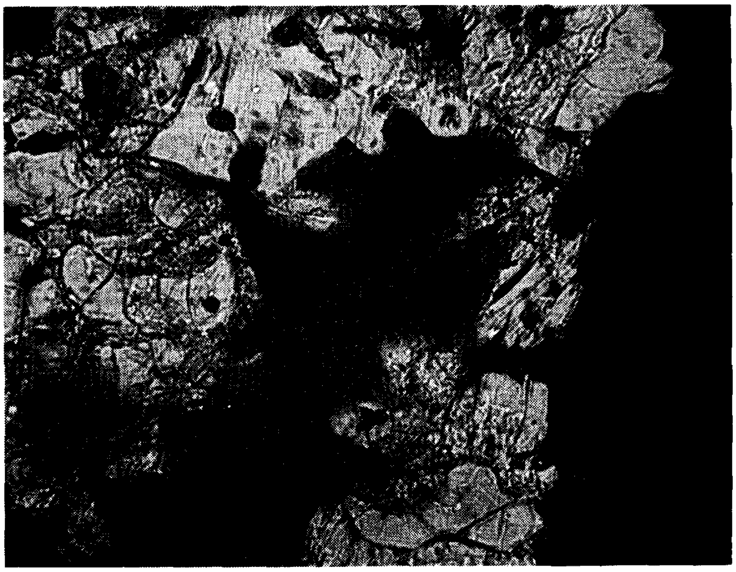


Fig. 1c. Groundmass phyllosilicates of alteration stage III with partially relic pyroxene and olivines in the chondrule of Y-791198. Plain light. Long dimension of image, 0.3 mm.

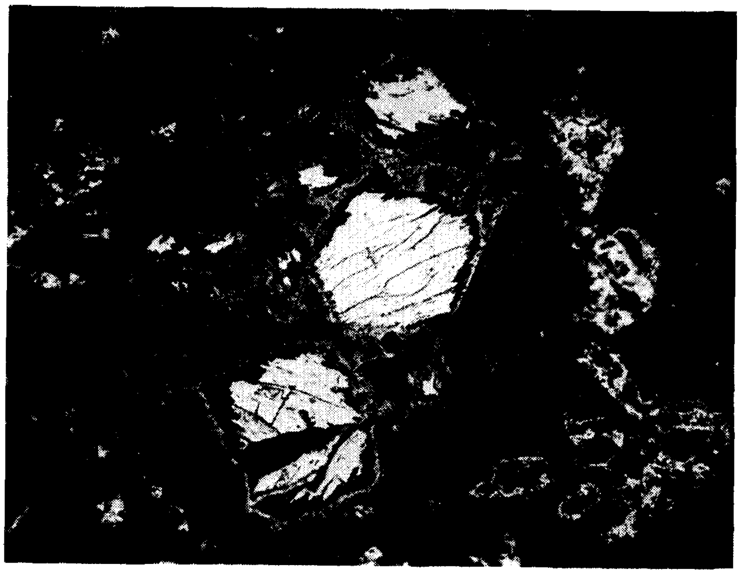


Fig. 1d. Groundmass phyllosilicates of alteration stage IV in the chondrule of Y-791824. Rims of olivine grains have suffered alteration. Plain light. Long dimension of image, 0.5 mm.

glass fragments and matrix. AOI's and CAI's are abundantly observed in this chondrite. Two melilite-bearing inclusions, about 50 and 400 μm in size, are set in the matrix. The chemical composition of the melilite is: $SiO_2=26.12$, $Al_2O_3=30.11$, $MgO=2.82$, $CaO=40.23$. A variety of chondrules are observed, including olivine-pyroxene porphyritic chondrules, olivine porphyritic chondrules, radial pyroxene chondrules, and barred-olivine chondrules. However, the latter two types are rare. The groundmasses of chondrules are pale brown transparent or devitrified brown glass. The chondrules are less than 700 μm in diameter. Spherical or irregular-shaped grains of Fe-Ni metal and troilite occur commonly in the chondrules. Irregular-shaped grains of Fe-Ni metal and troilite also occur in the matrix. Some metal grains partly altered to magnetite are observed.

This chondrite contains only 20–30 volume % matrix, substantially less than that of the Y-791717 chondrite. This chondrite is classified as a CO3.

3.3. Yamato-793321

This chondrite consists of chondrules, CAI's, AOI's, mineral fragments (silicates, opaques and calcite), devitrified glass fragments and matrix; and also clasts of CM chondrite material which have been altered to varying degrees. Most of the chondrules are olivine-pyroxene porphyritic types; minor barred olivine and olivine porphyritic chondrules also occur. These are mostly less than 1 mm in diameter; only two chondrules of about 2 mm diameter were found in two polished thin sections (1.5×1 cm) of this meteorite. Many calcite fragments occur in the matrix; their diameters are less than 0.1 mm. Spherical and irregular opaque minerals are common in the chondrules and the inclusions. Many of these are altered oxide or hydrous minerals, or sulfide minerals, but some are unaltered Fe-Ni metal grains. In the chondrules and the inclusions that include no altered metal, the other constituent minerals are also fresh. It is difficult to find metal grains less than about ten microns in size in the matrix. In a few cases, metal grains were not totally altered and remain as cores surrounded by thick oxide halos.

The chondrules and the inclusions of this chondrite suffered various degrees of alteration, ranging from the I to IIIb stages of IKEDA's classification (1983). The groundmasses of almost all the chondrules have been altered to dark brown, brown and yellowish-brown materials (Fig. 1b). Low-Ca pyroxenes showing polysynthetic twinning in chondrules and fragments also have suffered some degree of alteration. Many contain dark brown altered materials along the twinning and cleavage planes of the low-Ca pyroxene.

3.4. Yamato-791198

This chondrite consists of chondrules, CAI's, AOI's, and mineral fragments, including silicates, opaque and calcite, as well as devitrified glass fragments, opaque clots and matrix. The matrix is abundant, occupying the area more than 50% by volume. Chondrule types are limited to olivine-pyroxene porphyritic and olivine porphyritic varieties. No barred olivine and radial pyroxene types were observed. The chondrules and inclusions are less than 1 mm across, most by smaller than 0.5 mm.

Minor spherical and irregular-shaped grains of opaque minerals occur in chondrules, inclusions and the matrix. These consist of Fe-Ni metal, troilite and oxide or hydrous minerals. The troilite grains are less than 50 μm across, and metal grains are less than 10 μm across. The Fe-Ni metal grains occur directly set in the matrix, and also as inclusions in olivine crystals. Metal grains of the former occurrence are larger than those of the latter.

This chondrite has suffered moderate alteration. The groundmasses of chondrules and inclusions are altered to brownish-yellow, yellow and green materials. Low-Ca pyroxenes showing polysynthetic twinning are altered to various degrees (Fig. 1c), but no olivine has suffered alteration. This chondrite belongs to the CM type.

3.5. Yamato-790003

This chondrite consists of chondrules, AOI's, silicate and opaque mineral fragments, opaque clots, altered glass fragments and matrix. The matrix occupies more than 70–75% of its volume. Chondrules are less abundant than the matrix, and are limited to olivine-pyroxene porphyritic and olivine porphyritic types. Chondrules and inclusions are less than 1.2 mm in diameter, mostly less than 0.5 mm. The groundmasses of all the chondrules and inclusions are altered to yellowish-brown hydrous minerals. All low-Ca polysynthetically-twinned pyroxenes are altered in moderate to intense degrees, the same as the groundmasses. Some olivines in the chondrules and the inclusions are partly altered to dark gray to black materials.

The opaque minerals consist mainly of troilite and oxide or hydrous minerals, with minor Fe-Ni metals. The Fe-Ni metals are observed only as inclusions in relic olivine grains. They are in spherical grains, less than 3 μm in diameter. This chondrite is classified as a CM type, by the criteria of Meteorites News (NATIONAL INSTITUTE OF POLAR RESEARCH, 1982).

3.6. Belgica-7904

This chondrite consists of chondrules, AOI's, silicate and opaque mineral fragments, opaque clots and matrix. It has a foliated texture. Most of the chondrules and inclusions are less than 1 mm in size. Only two chondrules over 1.5 mm diameter were found in three polished thin sections. The matrix is abundant, occupying over 70% by volume. Rounded chondrules are rare. Most chondrules and chondrule fragments are olivine porphyritic and olivine-pyroxene porphyritic types, with minor examples of the barred olivine type. This chondrite has suffered intense alteration. The groundmasses of all chondrules are altered to brownish-gray to gray materials. Low-Ca pyroxenes showing polysynthetic twinning are also altered. However, low-Ca pyroxenes in a few chondrules and chondrule fragments are partially preserved as relic minerals. Many of the olivine grains in chondrules are altered. The alteration occurs at the rims and in the cracks of the olivine grains.

Opaque minerals are abundant in the matrix, but are minor constituents in the chondrules and the inclusions. Opaque minerals in the matrix consist of Fe-Ni metal and troilite. Troilites are more abundant than Fe-Ni metal grains. They are irregular in shape. These opaque grains are less than several tens of microns in size. Numerous opaque grains smaller than micron size are also visible in the matrix. The metal grains occur set directly in the matrix. Opaque minerals in chondrules and inclusions consist of metal, troilite and oxide or hydrous minerals. Here they are not as abundant as occurring in the matrix. There are two modes of occurrence of metal grains: as spherical inclusions in the olivines, and as irregular grains set directly in the matrix.

3.7. Yamato-791824

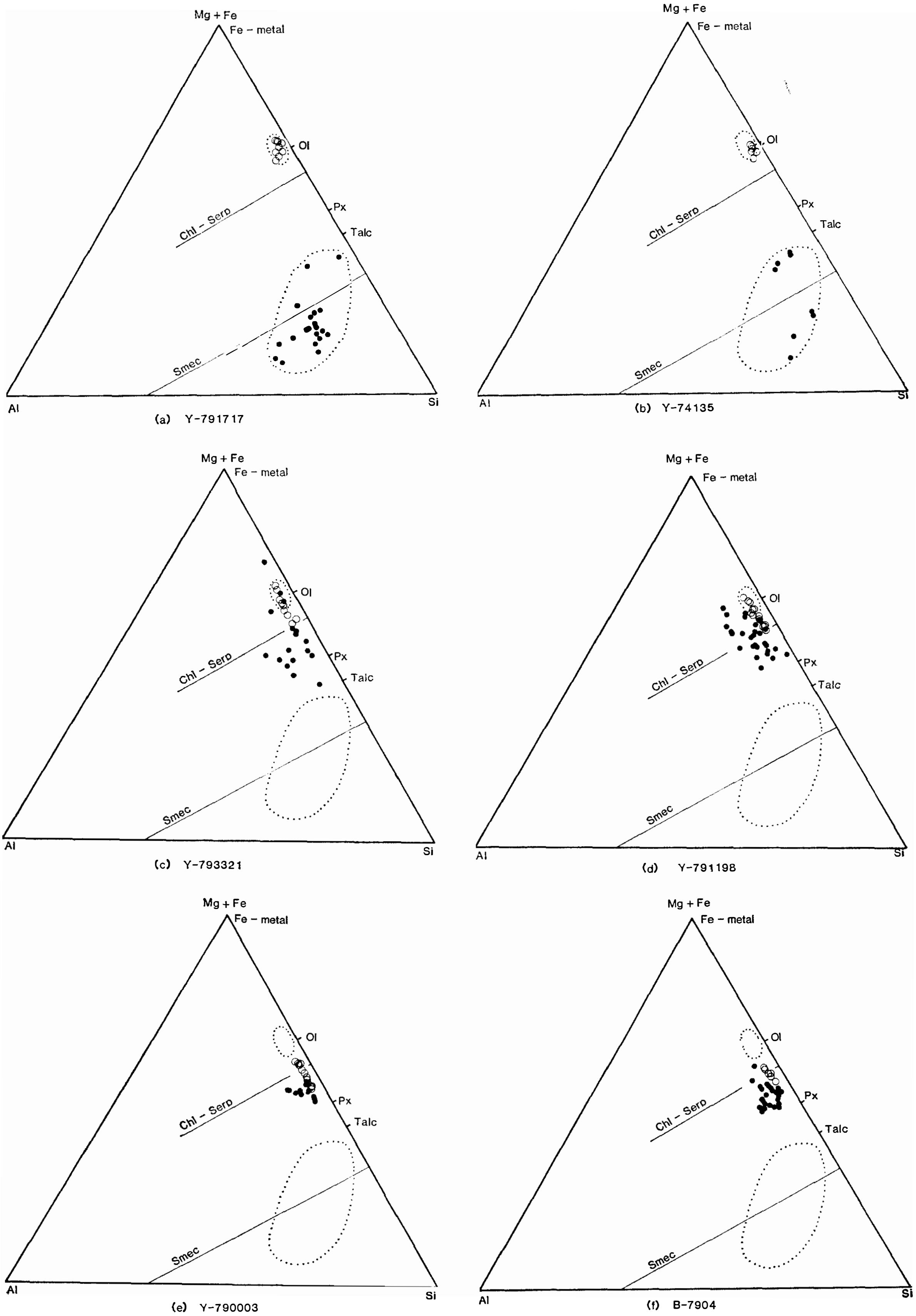
This chondrite consists of chondrules, CAI's, AOI's, silicate and opaque mineral fragments, opaque clots and matrix. The chondrules and inclusions are less than 0.7 mm in size. The matrix occupies about 70% by volume. only porphyritic chondrules are present. The alteration of this chondrite is the most intense of all the specimens studied. It shows *in situ* alteration. No metal grains are seen in the matrix and groundmasses, but several small spherules of Ni-Fe metals remain in relic olivine grains. The groundmasses of chondrules and inclusions are altered to green and gray materials. Low-Ca pyroxenes showing polysynthetic twinning have suffered intense alteration. In less-altered chondrules low-Ca pyroxenes have been altered along twinning planes, and only small relic crystals parallel to the polysynthetic twin planes remain. Olivines have also suffered alteration to various degrees (Fig. 1d). Where olivine grains are altered completely, their shape can still be recognized as a pseudomorph.

4. Chemical Composition of the Groundmass

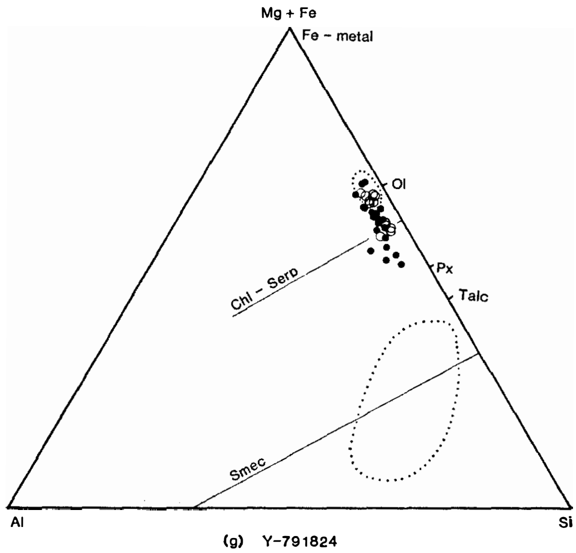
The chemical compositions of groundmasses in 7 carbonaceous chondrites studied are tabulated in Table 1, and plotted in diagrams of (Mg+Fe)-Al-Si in Fig. 2 and Si-Mg-Fe in Fig. 3. The groundmasses of Y-791717 and Y-74135 consist of clear glasses or devitrified glasses, and are plotted in the wide areas near the Si apices of the diagrams, as shown in Figs. 2a and 2b and Figs. 3a and 3b. These areas coincide with the compositional range of mesostasis glasses of chondrule groundmasses in two unaltered C3 chondrites, ALH-77003 (IKEDA, 1982) and Y-790992 (IKEDA, 1983). In contrast to the above-stated two chondrites, the groundmasses of chondrules in the other 5 chondrites are shifted toward the (Mg+Fe) apex as shown in Fig. 2, and are plotted near the chlorite-serpentine composition. In particular, the groundmasses of chondrules in Y-793321 and -791198 fall in a wide range near the chlorite-serpentine join; these may consist mainly of chlorite and probably serpentine, of relatively high Al contents.

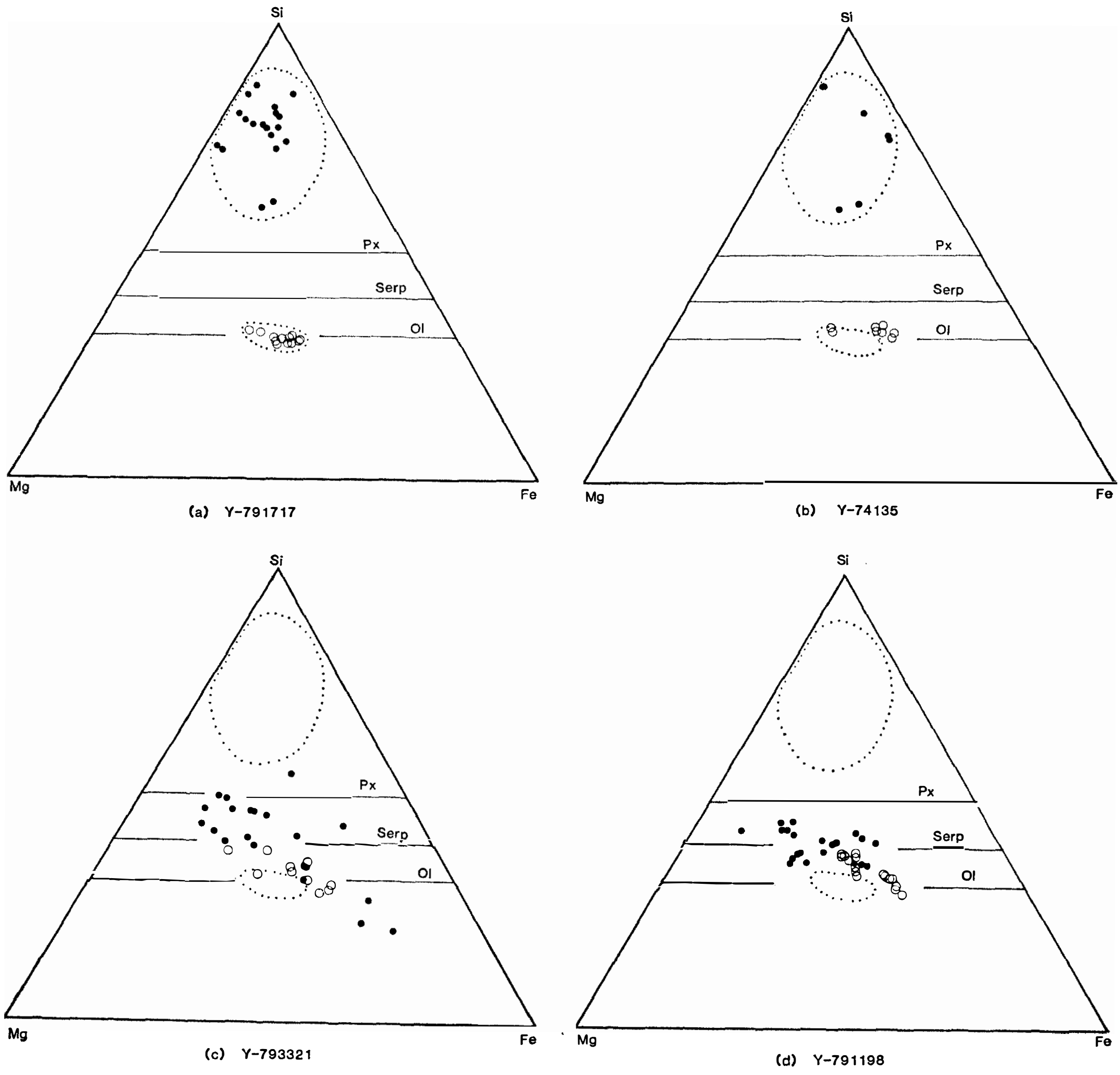
Table 1. Representative chemical compositions of groundmass phyllosilicates in chondrules.

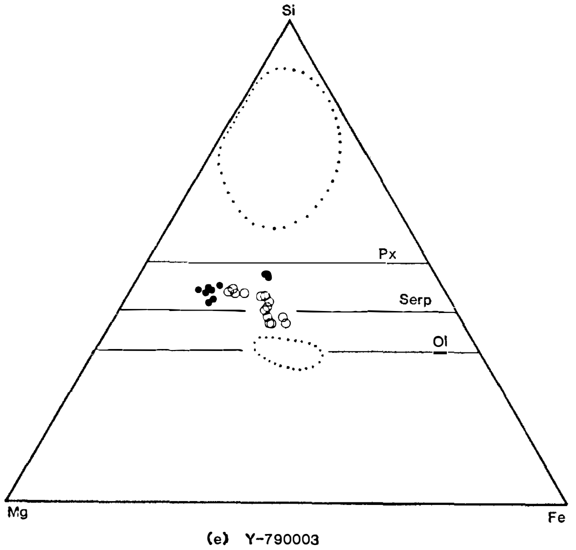
Name	Yamato-791717		Yamato-74135		Yamato-793321		Yamato-791198		Yamato-790003		Belgica-7904		Yamato-791824	
	(13)	(44)	(26)	(2-20)	25	69	3	57	19	37	7	39	12	30
SiO_2	51.20	54.65	59.81	50.08	36.72	30.88	30.82	28.07	38.09	34.13	34.42	28.68	20.94	28.49
Al_2O_3	22.92	11.81	16.52	13.19	2.32	6.90	5.78	6.97	2.38	6.30	4.99	3.18	3.01	2.53
TiO_2	0.21	0.64	0.32	0.24	0.41	0.58	0.16	0.15	0.10	0.09	0.10	0.11	0.10	0.15
Cr_2O_3	0.01	0.51	0.37	0.04	0.67	0.36	0.29	0.52	0.80	0.40	0.94	0.73	0.15	0.17
MgO	4.13	11.90	5.22	3.71	23.03	13.17	12.43	21.81	25.61	22.76	23.65	23.98	13.73	16.05
FeO	2.04	3.42	1.02	10.61	14.38	18.02	26.20	20.01	12.46	15.36	11.33	12.43	30.42	24.80
MnO	0.16	0.39	0.30	0.07	0.19	0.46	0.30	0.19	0.19	0.13	0.15	0.16	0.15	0.24
CaO	16.62	13.77	12.12	13.51	4.00	7.33	1.04	0.09	0.06	0.02	0.32	0.31	0.82	2.17
Na_2O	2.34	2.61	2.77	4.44	0.34	0.67	0.32	0.04	0.45	0.32	1.10	0.89	0.23	0.44
K_2O	0.13	0.01	0.03	0.52	0.05	0.14	0.20	0.01	0.11	0.09	0.13	0.11	0.11	0.06
Total	99.76	99.63	98.48	96.41	82.11	78.51	77.39	77.87	80.24	79.61	77.11	80.58	69.66	75.10

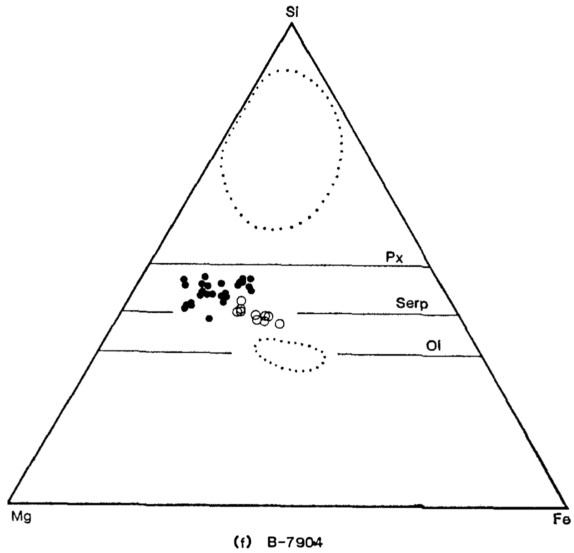

Mg + Fe
Fe – metal
Ol
Px
Talc
Chl – Serp
Smec
Al
Si
(a) Y-791717
(b) Y-74135
(c) Y-793321
(d) Y-791198
(e) Y-790003
(f) B-7904

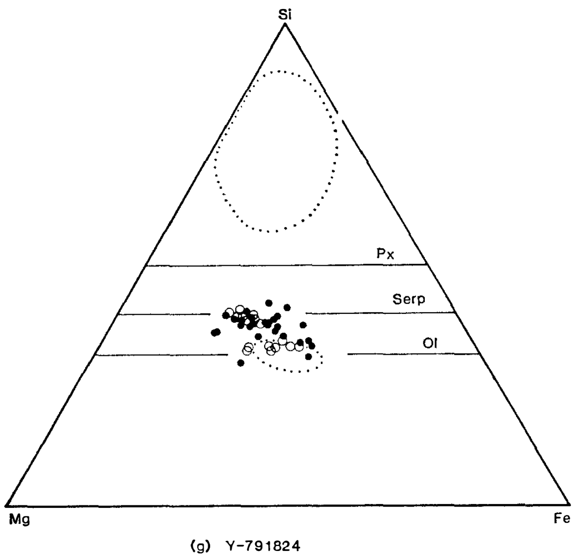
Figs. 2(a–g). Compositions (atomic %) of groundmass phyllosilicates (solid circles) and matrices (open circles) in Y-791717(a), Y-74135(b), Y-793321(c), Y-791198(d), Y-790003(e), B-7904 (f) and Y-791824(g) in a (Mg+Fe)-Al-Si diagram. Compositional ranges of unaltered groundmasses of chondrules in Y-791717 and Y-74135 and unaltered matrices in Y-791717 (dotted lines) are shown for comparison. Chl= chlorite, Serp=serpentine, Ol=olivine, Px= low-Ca pyroxene, Smec=smectite.











Figs. 3(a–g). Compositions of groundmass phyllosilicates and matrices in a Si-Mg-Fe diagram. Symbols and fields are the same as in Fig. 2.

Figure 3c shows that the groundmass phyllosilicates of Y-793321 are plotted in a field that is richer in SiO_2 than the tie line connecting Fe apex with En. Those of Y-791198 show the same trend as Y-793321 (Fig. 3d), but the former has a higher Mg/Fe ratio than the latter. The groundmasses of chondrules in Y-790003 and B-7904 are plotted in more narrowly defined areas than those of Y-793321 and -791198, as shown in Figs. 2e and 2f, and also Figs. 3e and 3f. In Figs. 3e and 3f, the groundmasses of Y-790003 and B-7904 are plotted between the pyroxene and serpentine joins. The groundmasses of Y-791824 are poorest in Al_2O_3 and SiO_2 among all the chondrites studied, and richer in FeO than the groundmasses of Y-790003 and B-7904 (Fig. 3g).

5. Chemical Compositions of Matrices

The chemical compositions of the matrices in chondrites (Table 2) studied are plotted in the same diagrams (Figs. 2 and 3) as the groundmasses. Figure 2 shows that the Al_2O_3 contents of matrices in the 7 specimens are nearly same. The matrix of Y-791717 is plotted near the composition of an olivine containing a minor amount of Al. Those of Y-790003 and B-7904 are plotted near the serpentine range, and the remaining for matrices (Y-74135, -793321, -791198, -791824) are plotted between the compositions of olivine and serpentine with a low Al_2O_3 content.

Figure 3 shows an interesting compositional trend of the matrices. The compositions of matrices in Y-791717 are plotted nearly in the same area of mean composition of matrices in Allende CV3 except for slightly low contents of Si (Fig. 3a). The compositional range of matrix in Y-74135 is plotted on the Fe-rich side of Allende matrix.

Table 2. Representative chemical compositions of matrices.

Name	Yamato-791717		Yamato-74135		Yamato-793321		Yamato-791198		Yamato-790003		Belgica-7904		Yamato-791824	
	(11)	(20)	2-9	2-18	32	110	19	40	6	39	13	41	19	35
SiO_2	26.27	27.97	27.83	29.80	22.97	25.27	27.78	25.61	28.79	28.56	32.68	30.02	24.49	30.18
Al_2O_3	1.64	1.51	2.02	1.83	2.58	2.81	2.16	3.18	2.11	2.32	2.75	2.30	1.66	2.29
TiO_2	0.14	0.07	—	0.00	0.04	0.02	0.05	0.17	0.06	0.08	0.11	0.15	0.06	0.05
Cr_2O_3	0.36	0.23	0.15	0.11	0.39	0.28	0.45	0.20	0.33	0.28	0.34	0.40	0.17	0.42
MgO	19.02	20.81	15.29	21.75	13.16	14.07	15.83	15.52	18.18	17.60	21.09	17.20	18.29	19.22
FeO	40.26	37.62	38.43	32.14	34.69	30.64	27.76	32.83	25.52	26.05	20.45	24.07	27.29	19.40
MnO	0.18	0.19	0.17	0.13	0.23	0.26	0.11	0.20	0.33	0.22	0.19	0.26	0.10	0.28
CaO	0.23	0.21	0.45	0.40	0.77	0.93	0.30	0.31	0.30	0.31	1.78	0.63	0.05	0.37
Na_2O	0.06	0.09	0.25	0.65	0.64	0.77	0.21	0.14	0.65	0.36	0.52	0.64	0.42	0.43
K_2O	—	0.02	0.09	0.17	0.09	0.08	0.08	0.06	0.12	0.09	0.06	0.12	0.09	0.09
Total	88.15	88.71	84.66	86.96	75.54	75.11	74.71	78.22	76.38	75.86	79.97	75.78	72.63	72.74

The matrices of Y-793321 and -791198 plot in nearly linear fields located to the high-Si side of the tie line connecting the Fe-apex with En in Figs. 3c and 3d. The matrices of Y-790003 and B-7904 show the same trend as those of Y-793321 and -791198, but they are plotted toward the Fe-poor side of the latter two. The compositions of matrices in Y-791824 are plotted in nearly the same area as the groundmasses of chondrules in Y-791824 (Fig. 3g), being poorer in SiO_2 than Y-790003 and B-7904 matrices.

6. Discussion

6.1. *Alteration of chondrules*

IKEDA (1983) classified chondrule alteration optically into the following four stages. (I) No or slight alteration. (II) Alteration of chondrule groundmass. (III) Alteration of low-Ca pyroxene: a, partly altered; b, wholly altered. (IV) Alteration of olivines in chondrules. According to this classification, the chondrule-alteration in Y-791717 and Y-74135 corresponds to stage I. Y-793321 is altered to stage II, with minor IIIa. Y-791198 is altered to stages IIIa and IIIb. Y-790003 and B-7904 are in stage IIIb with minor IV. Y-791824 is in stage IVb and IV. Thus the degree of chondrule-alteration changes from weak to intense in following order:

Y-791717 Y-74135 Y-793321 Y-791198 Y-790003 B-7904 Y-791824.

As mentioned before, a systematic trend among groundmass compositions of the chondrules in 7 carbonaceous chondrites can be seen in the diagram of Si-Mg-Fe (Fig. 3). Figure 4 shows the compositional fields of chondrule groundmasses for all seven carbonaceous chondrites. The shift of the compositional fields indicated by the arrows in Fig. 4, which proceeds according to the above-stated order, shows that the alteration trend is continuous with two turning points.

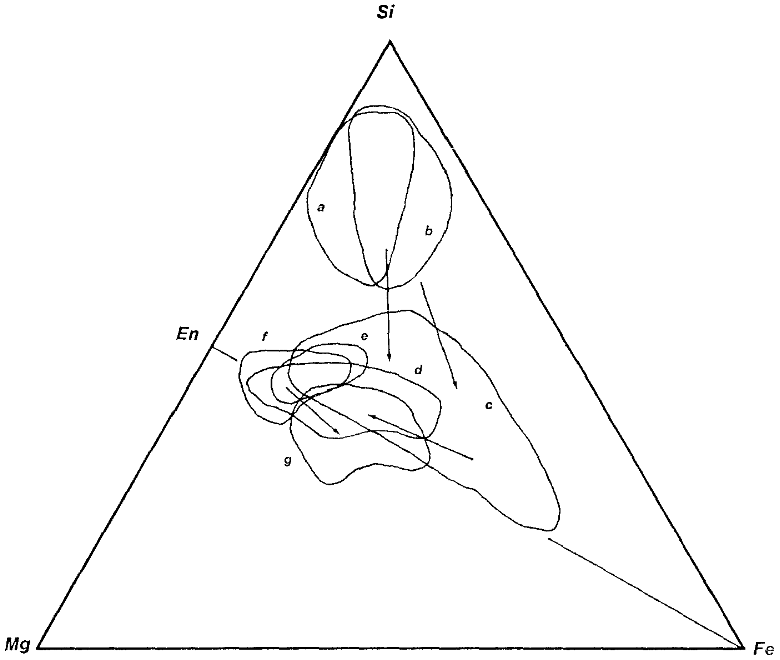


Fig. 4. Variation of positions of compositional fields of groundmass phyllosilicates in Y-791717(a), Y-74135(b), Y-793321(c), Y-791198(d), Y-790003(e), B-7904(f) and Y-791824(g), in Si-Mg-Fe. Arrows show the trend with increasing degree of alteration.

The chemical compositions of groundmasses of stage I chondrules are characterized by high SiO_2 contents and the absence of H_2O. The fresh groundmasses of stage I are altered first to stage II. This alteration involves the following reaction:

$$\text{Mesostasis glass} + \text{Fe metal} + MgO + H_2O \longrightarrow \text{groundmass phyllosilicate} + \text{alkalis} + CaO. \quad (1)$$

Fe-metal grains that commonly occur in the groundmass glass of chondrules are easily altered along with the host groundmass glasses. These Fe-metals may be the source of some FeO in the groundmass-phyllosilicate in the right hand side of eq. (1). The remaining FeO may have been derived from the matrix. However, small spherical Fe-metals inclusions in pyroxenes and olivines in chondrules are still fresh in this stage, so the groundmass phyllosilicates of stage II are richer in FeO than the groundmasses of stage I (Fig. 4). Most of the phyllosilicates in Y-790123 (IKEDA, 1983) belong to this stage II. In the case of chondrules with groudmass glasses that are free of Fe-metals, the alteration products may be MgO-rich rather than FeO-rich. Some chondrules in Y-793321 are examples of this case (Fig. 4).

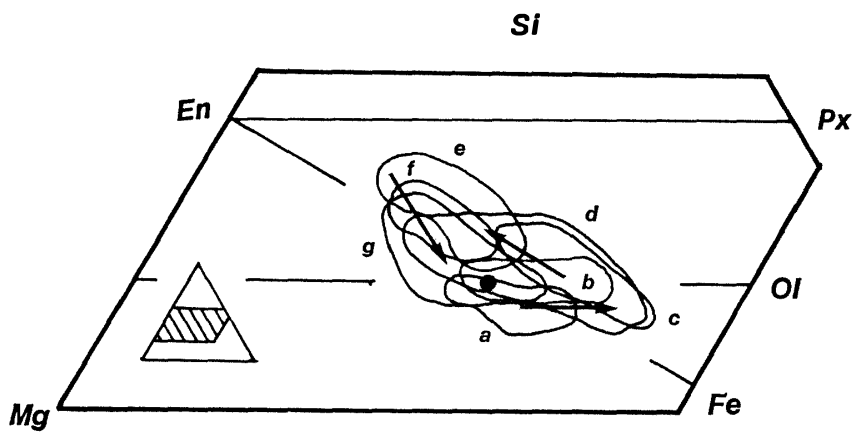


Fig. 5. Variation of positions of compositional fields of matrices. Symbols are the same as in Fig. 4. Solid circle shows the matrix composition of Allende.

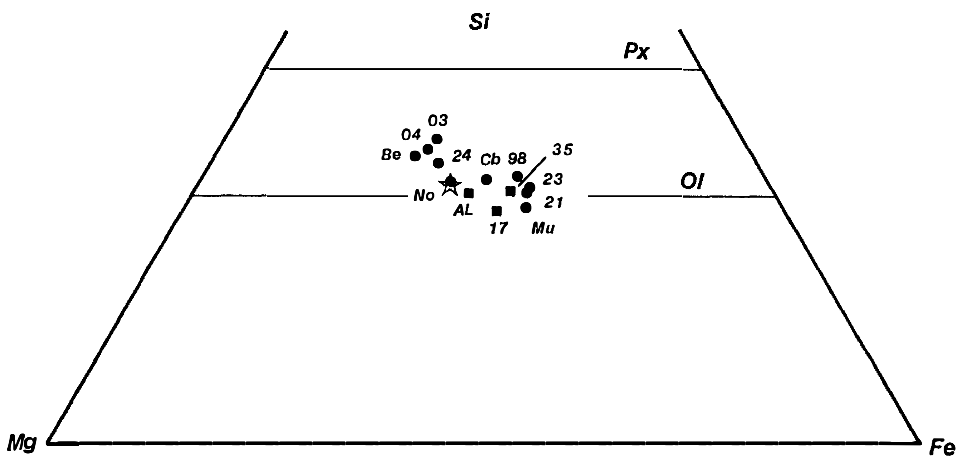


Fig. 6. Comparison of compositions of matrices in Y-791717(17), Y-74135(35), Y-793321(21), Y-791198(98), Y-790003(03), B-7904(04), Y-791824(24), Y-790123(23), Murchison(Mu), Cold Bokkeveld(Cb), Bells(Be), Nogoya(No), Allende(Al), and the mean value of CM chondrites(open star).

If the alteration from stage I to stage II took place in the parent meteorite body, MgO and H_2O in the left-side hand of eq.(1) may have been derived from matrices as discussed in the next subsection. The alteration of chondrule-groundmasses proceeds from stage II to stage III, by a reaction that may be represented as follows:

Groundmass-phyllosilicate (stage II)+low-Ca pyroxene in chondrules
$+H_2O \longrightarrow$ Groundmass-phyllosilicate (stage III; Mg, Si-rich). (2)

This reaction produces stage III groundmass-phyllosilicate. In this stage, low-Ca pyroxenes showing polysynthetic twinning decompose and become altered material. Increasing degrees of alteration of low-Ca pyroxenes correspond to increasing SiO_2 and MgO-contents of the groundmass-phyllosilicates in the right-hand side of eq.(2). Thus the alteration products are richer in MgO and SiO_2 than are the stage II pyllosilicates. Most of the groundmass phyllosilicates in Y-790003 and B-7904 belong to stage IIIb. Their compositions are plotted in narrow areas at the MgO-rich end of the tie line connecting En with the pyroxene Fe-apex. On the other hand, those of Y-791198 belong to stage IIIa and IIIb, and their compositions are plotted in a broad field along the tie line connecting En with the Fe-apex (Fig. 4). This shows the alteration products change, from stage II to stage III, toward a composition richer in the enstatite component. The reaction of groundmass-alteration from stage III to stage IV is as follows:

Groundmass-phyllosilicate (stage III) + olivine + Fe-bearing phase $\longrightarrow$
groundmass-phyllosilicate (stage IV, Si-poor, Al-poor). (3)

In addition to low-Ca pyroxenes, olivines and Fe-bearing phases (Fe-sulfides or PCP) are altered into groundmass-phyllosilicates. Nearly half of the chondrules in Y-791824 contain partly-altered olivines. Olivines with high-Fa contents appear to be altered more readily than those with low-Fa contents. Therefore, the compositions of groundmass-phyllosilicates in stage IV are poorer in SiO_2 and richer in FeO than those in stage III.

6.2. Alteration of matrix

The compositional variation of matrices shows the same trend as that of the groundmasses in chondrules. The compositional trend with increasing degrees of alteration is indicated by the arrows in Fig. 5.

The matrix of Y-791717 has suffered no alteration, and its chemical composition is similar to that of Allende except for a slightly lower content of SiO_2 in the former (Fig. 6). In BUNCH and CHANG (1978), AKAI (1982) and IKEDA (1983), the Allende matrix was assumed to be a precursor material for the more altered matrices. This assumption is also applied here. Compared with the Allende matrix, the matrices of Y-74135, -793321 and -791198 are richer in Fe and poorer in Mg. MgO lost from the matrices during alteration may have gone to groundmass-phyllosilicates in the chondrules, as discussed in Subsection 6.1. Additional Fe is derived from FeO-rich materials of the matrices, which may have been formed by the oxidation of Fe metals occurring in the matrices.

Y-790003 and B-7904 have suffered more intense alteration than the above-mentioned four meteorites. The chemical compositions of their matrices are richer in MgO and SiO_2 and poorer in FeO than the matrices of Y-791717, etc. These chemical changes are correlated with petrographic evidence of the alteration of low-Ca pyroxenes. The additional MgO and SiO_2 may have been derived from the decomposition of low-Ca pyroxenes in the chondrules, and of fragments set directly in the matrices, during the alteration process. MCSWEEN (1979) explained this chemical change as a depletion in FeO. Minor depletion in FeO of the matrices may have occurred, but a more important factor was the addition of MgO and SiO_2 derived from the decomposition of low-Ca pyroxenes.

The alteration of Y-791824 is the most intense among all the chondrites studied. According to BUNCH and CHANG (1980), 95% of the Nogoya meteorite consists of alteration products; its matrix was nearly completely altered to mixtures of Mg-serpentine and Fe-serpentine. The chemical composition of the matrix in Nogoya (MCSWEEN, 1977) is the same as its bulk composition (MASON, 1963) and the mean bulk composition of CM chondrites (MCSWEEN and RICHARDSON, 1977) (Fig. 6).

The trend of the intense alteration corresponding to that for Y-791824 leads to homogeneity of the whole meteorite. The matrix of Y-791824 is poorer in SiO_2 and richer in FeO than those of Y-790003 and B-7904. This change is due to the alteration of olivines occurring in the chondrules and as fragments, as well as the receipt of FeO components from Fe-rich PCP and Fe-sulfide set in the matrix. According to BUNCH and CHANG (1980), PCP occurring in intensely altered CM chondrites is poorer in Fe than that in weakly-altered ones. In weakly-altered CM chondrites, pyrrhotite is more abundant than pentlandite; but intensely altered Y-791824 contains only pentlandite. Fe-sulfides such as pyrrhotite may have been altered completely in the intensely-altered chondrites. Fe-rich PCP and other Fe-sulfides may have been partially consumed for the formation of Fe-rich matrix materials during this stage of alteration.

6.3. Alteration of CM and CO chondrites

As described in the previous sections, CM and CO chondrites have suffered aqueous alteration of various degrees. The two principal constituents of carbonaceous chondrites, chondrules and matrix, show the particular process and degree of alteration. MCSWEEN (1979) classified CM chondrites into three types (partially altered, altered and highly altered), based on modal variations in the matrices. However, the process and the degree of alteration were not categorized systematically.

Based on the petrographic properties and chemical characteristics of the two major constituents, chondrules and matrix, the process and degree of alteration of CM and CO chondrites are examined below in the following order of increasing alteration :

(1) Unaltered stage,
(2) Weakly-altered stage,
(3) Moderately altered stage,
(4) Intensely altered stage.

(1) Unaltered stage

Most CO chondrites belong in this stage. The groundmasses of chondrules consist of clean transparent glass or devitrified glass, and belong to stage I (IKEDA, 1983). Fe-Ni metals are set in the groundmasses and matrices.

(2) Weakly-altered stage

In this stage, chondrules in stages II and IIIa of alteration predominate, with minor examples of IIIb and rare cases of stage I. The main phyllosilicate of chondrule groundmasses in this stage may be chlorite. Some particles of Fe-metal are still present in matrices, surrounded by oxidized rims mainly of magnetite.

The composition of matrix phyllosilicates is characterized by the presence of additional FeO derived from the alteration of Fe-metals, and the depletion of MgO, relative to those of no-alteration stage 1. The matrix phyllosilicates may be largely Fe-rich serpentine.

The two CM chondrites in this paper, Y-793321 and -791198, and three other CM chondrites, Y-74662, -75293 and -790123 (IKEDA, 1983), belong to this stage. Mighei, Murchison and Murray (MCSWEEN, 1979) also probably belong to this stage.

(3) Moderately altered stage

Chondrules of stage IIIb are abundant, with smaller numbers in stage IV. Minor taenite remains in the matrix; low-Ni Fe metal spheroids occur only as inclusions in relic olivine grains. The phyllosilicates in both groundmass and matrix are richer in

MgO and SiO_2 than those of the weakly-altered stage, and may be serpentine. However, phyllosilicates of chondrules are slightly richer in MgO and SiO_2 than those of the matrix. The additional MgO and SiO_2 were derived from the alteration of low-Ca pyroxenes that occur in the chondrules and as fragments. Y-790003 belongs to this stage. Bells (MCSWEEN, 1979) also probably belong to this stage (Fig. 6)

(4) Intensely altered stage

Here all pyroxenes are altered to hydrous materials, and only portions of forsterite grains remain as relics. The chondrules and matrix have been merged together. The phyllosilicates of both groundmasses and matrix approach compositional homogeneity. The phyllosilicates of this stage are slightly poorer in SiO_2 and richer in FeO than those of the moderate-alteration stage. This change is caused by the alteration of olivines in the chondrules and fragment, in addition to the receipt of FeO from PCP and Fe-sulphide. The composition of alteration products has become the same as the average bulk composition of CM chondrites. Therefore, the final stage of alteration is apparently represented by the homogenization of whole meteorites. The Nogoya meteorite (BUNCH and CHANG, 1980; MCSWEEN, 1979) belongs to this stage. The alteration degree of Y-791824 falls between the stages of moderate-alteration and intense-alteration. *In situ* alteration is characteristic of this stage of alteration.

6.4. Dehydration of CM chondrites

B-7904 is an unusual carbonaceous chondrite. It has suffered intense alteration, as discussed in the previous section; but there is evidence that this stone has undergone dehydration after its alteration.

(1) As a rule, in intensely altered specimens low-Ni sulfides disappear completely during alteration, and only pentlandite remains. However, numerous micron-size sulphides (Ni 0.5%) are set in the matrix in the B-7904 chondrite.

(2) According to GIBSON *et al.* (1984), the total carbon content of B-7904 is 0.972%. This value is lower than that of typical CM chondrites, but similar to that of C3 chondrites.

(3) Bulk analysis shows the volatile component (including H_2O and C) of Y-7904 is 2.6 wt% (HARAMURA *et al.*, 1983), which is similar to typical C3 chondrite values.

(4) Recrystallized olivines (several microns) occur in the matrix of B-7904. These observations show that B-7904 suffered intense heating after the alteration of its chondrules and matrix, resulting in precipitation of numerous sulphide grains, escape of carbon-oxides, dehydration of hydrous minerals, and recrystallization of olivine from hydrous minerals. The intense heating may have been due to shock-heating, or metamorphism on or in the parent body.

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