

# ALTERATION OF CHONDRULES AND MATRICES IN THE FOUR ANTARCTIC CARBONACEOUS CHONDRITES ALH-77307(C3), Y-790123(C2), Y-75293(C2), AND Y-74662(C2)

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**Abstract:** Alteration products of the groundmasses in chondrules of the C chondrites ALH-77307, Y-790123, Y-75293, and Y-74662 consist mainly of chlorite (and/or berthierine) containing high  $Al_2O_3$  contents, and those of the matrices are mainly serpentine with minor amounts of  $Al_2O_3$  contents. This difference reflects that of their precursor materials prior to the alteration.

The degrees of chondrule alteration are various within a chondrite and among the four chondrites studied, and are classified into four stages (I, II, III, and IV ranging from weak to intense alteration) according to petrographic criteria. Most chondrules in ALH-77307 are stage II, and those in Y-74662 are stage III. Y-790123 and Y-75293 include the chondrules of stages II and III. The alteration of chondrules and matrices took place prior to the final agglomeration of these chondrites.

## 1. Introduction

C2 and some C3 carbonaceous chondrites contain many kinds of hydrous silicates (BUNCH and CHANG, 1980; BARBER, 1981; MACKINNON, 1982). Chondrules in all C2 and some C3 chondrites include hydrous phyllosilicates which are called "spinach" (FUCHS *et al.*, 1973). Spinach is considered to be formed from groundmass (or mesostasis) glasses as alteration products (BUNCH and CHANG, 1978; RICHARDSON and MCSWEEN, 1978). The matrices in all C2 and some C3 chondrites also consist mainly of hydrous phyllosilicates which are considered to be formed by alteration (MCSWEEN and RICHARDSON, 1977; BUNCH and CHANG, 1979; MCSWEEN, 1979).

In this paper, attention is focussed on the alteration of groundmass glasses in chondrules of C2 and C3 chondrites. Reference is also made to the alteration of their matrices, in order to clarify the alteration process in carbonaceous chondrites.

## 2. Sample Descriptions

The samples studied are four Antarctic carbonaceous chondrites, ALH-77307(C3), Y-790123(C2), Y-75293(C2), and Y-74662(C2), and their brief petrographic descriptions are as follows.

### 2.1. ALH-77307

This chondrite consists of chondrules, amoeboid olivine inclusions, olivine-spinel aggregates, devitrified glass fragments, silicate and opaque mineral fragments, opaque

clots, and matrix (here, matrix is defined to be aggregates of minerals and amorphous materials finer than micron size). Most of the chondrules are olivine-pyroxene porphyritic types; olivine porphyritic or barred-olivine chondrules also occur. Their sizes are less than 1.2 mm, many being less than 0.6 mm in diameter.

The groundmasses of most chondrules are pale brown to reddish brown altered materials. However, most olivine and pyroxene in chondrules are fresh and unaltered. But in rare highly-altered chondrules, polysynthetic-twinned pyroxenes have suffered weak alteration. Small spherical or irregular opaque materials commonly included in Ol-Px porphyritic chondrules are Fe-Ni metal, troilite and/or magnetite. If Fe-Ni metal grains are present, they are often surrounded by troilite and/or magnetite.

Devitrified glass fragments in this chondrite also take the form of pale to dark brown altered materials. Silicate mineral fragments, mainly olivine and minor pyroxene, are dispersed in the matrix. These fragments are generally fresh, and have not suffered any alteration. Opaque minerals, mainly troilite and minor Fe-Ni metal, also occur set in the matrix. Sometimes Fe-Ni metal grains occur directly in contact with the matrix. Opaque clots are a few tens to several hundred microns in diameter; their shapes are sometimes spherical and sometimes irregular. These are aggregates of poorly-characterized phase (PCP) with troilite and magnetite. As Fe-Ni metals are observed as relic minerals in the central part of some opaque clots, the latter seems to have been formed by the alteration of materials consisting mainly of Fe-Ni metals. The Ni contents of sulfides are less than 0.5%, and this chondrite is classified as a C3 type according to the criteria of VAN SCHMUS and WOOD (1967). A petrologic study of this chondrite was reported by NAGAHARA and KUSHIRO (1982).

## 2.2. Y-790123

This chondrite consists of chondrules, amoeboid olivine inclusions, Sp-Ol aggregates, devitrified glass fragments, silicate and opaque mineral fragments, calcite fragments, opaque clots, and matrix. The matrix and opaque clots are predominant in amounts, and chondrules are not abundant.

The major type of chondrule is Ol-Px porphyritic varieties, with minor Ol porphyritic and barred-Ol chondrules. Their sizes are less than about 1 mm in diameter.

The groundmasses of most chondrules are red to dark brown altered materials. Low-Ca pyroxenes showing polysynthetic twinning in some chondrules also have altered to dark brown materials, although the olivines in all chondrules remain fresh. However, one Ol porphyritic chondrule (chondrule No. 40) has a groundmass of unaltered clean glass including Fe-Ni metal spherules and quench-olivine needles in the glass.

Amoeboid olivine inclusions consist mainly of olivine grains with variable amounts of magnetite and dark brown materials. The magnetite seems to be the alteration products of Fe-Ni metal or troilite. Devitrified glass fragments also have altered to yellowish brown to red brown materials. Silicate mineral fragments are mainly olivine and pyroxene. Some fragments of low-Ca pyroxenes showing polysynthetic twinning occur set in the matrix, and seem not to have altered. Calcite fragments smaller than 200 microns occur set in the matrix. They are angular and often show polysynthetic twinning, being fragments of larger calcite crystals. Abundant opaque clots occur set in the matrix; their diameters are mainly smaller than 100 microns.

### 2.3. Y-75293

This chondrite resembles Y-790123, consisting of chondrules, amoeboid olivine inclusions, Sp-Ol aggregates, devitrified glass fragments, silicate and opaque mineral fragments, calcite fragments, opaque clots, and matrix.

The chondrules are smaller than 1.5 mm in diameter, Ol-Px porphyritic chondrules being the main type. Barred-Ol, Ol porphyritic, and radial-Px chondrules also occur. One Ol porphyritic chondrule (chondrule No. 2) remains fresh, its groundmass consisting of clean transparent glass. This chondrule includes many spheres of Fe-Ni metal less than 40 microns in diameter. Although this chondrule did not suffer any alteration, most other chondrules suffered alteration and their groundmasses have changed to brown to greenish brown materials. The groundmasses of some chondrules suffered intense alteration, and show parallel-growth textures of hydrous silicates. All olivines and most pyroxenes in chondrules are fresh, but sometimes low-Ca pyroxenes showing polysynthetic twinning are seen to have suffered slight alteration.

Silicate mineral fragments, mainly olivine and pyroxene, remain fresh in general. Calcite fragments are less than 100 microns in size and often show polysynthetic twinning. Opaque clots occur set in the matrix, their sizes being smaller than about 100 microns across.

### 2.4. Y-74662

This chondrite consists of chondrules, Sp-Ol aggregates, amoeboid olivine inclusions, devitrified glass fragments, silicate and opaque mineral fragments, calcite fragments, opaque clots, and matrix.

The chondrules are smaller than 1.5 mm across, the main type being Ol-Px porphyritic chondrules. Most chondrules have suffered intense alteration. The groundmasses of all chondrules are altered to greenish yellow, dark or greenish brown materials. Low-Ca pyroxenes showing polysynthetic twinning in chondrules also have suffered alteration in various degrees, although the olivines in chondrules remain fresh. Fe-Ni metal grains in chondrules have altered completely to Fe-hydrates and/or oxides. A hibonite-bearing inclusion, about 200 microns in size, occurs set in the matrix. This consists of a nodule, about 80 microns in diameter, and dark greenish brown materials, the former being an aggregate of Mg-Al spinel and hibonite ( $\text{MgO}=3.62$  wt%,  $\text{Al}_2\text{O}_3=79.72$ ,  $\text{CaO}=7.99$ ,  $\text{TiO}_2=8.47$ ,  $\text{FeO}=0.14$ ).

Devitrified glass fragments have altered to pale brown to dark brown materials. Calcite fragments are less than 200 microns across, and are more abundant than in Y-790123 and Y-75293. Many show polysynthetic twinning. Some are fragments of larger single crystals, but others are polycrystals, being the fragments of larger crystal aggregates. Opaque clots are set in the matrix, many being less than 100 microns in diameter. These are massive aggregates of very fine-grained materials, in some cases including calcite or olivine grains.

Phyllosilicates in this chondrite were studied by AKAI (1982) who reported the occurrence of several kinds of phyllosilicates and amorphous materials in the matrix.

## 3. Chemical Compositions of the Groundmasses, Matrix, and Opaque Clots

Chemical analyses of aggregates of hydrous phyllosilicates in the groundmass

Table 1. Chemical compositions of groundmass phyllosilicates in chondrules in ALH-77307, Y-790123, Y-75293, and Y-74662. "FeO" means the sum of FeO and Fe<sub>2</sub>O<sub>3</sub>. Nos. 40-6\* and 40-7\* are clean glass of an unaltered chondrule No. 40 in Y-790123. No. 57-2\* is a small glass inclusion in a large magnesian olivine fragment (Fo<sub>99.1</sub>Fa<sub>0.1</sub>La<sub>0.7</sub>), set in the matrix of Y-790123. Nos. 2-6\*, 2-8\*, 2-10\*, 2-12\*, and 2-14\* are groundmass clean glass of an unaltered chondrule No. 2 in Y-75293.

ALH-77307														
	121-1	121-2	121-3	13-2	13-3	13-4	13-5	18-3	18-4	22-1	22-2	2-4	2-5	2-7
Na <sub>2</sub> O	0.87	1.22	1.87	0.58	0.65	0.62	0.49	1.07	1.35	0.82	1.19	1.10	1.13	0.98
MgO	6.02	5.64	4.63	6.89	6.85	7.82	7.17	6.05	4.62	10.12	11.25	8.69	9.72	9.16
Al <sub>2</sub> O <sub>3</sub>	9.67	10.32	11.08	7.74	7.31	10.10	8.32	11.06	10.26	9.16	9.01	11.19	12.23	9.35
SiO <sub>2</sub>	28.39	32.49	33.46	34.25	34.78	34.34	35.79	32.70	30.08	33.60	32.46	30.50	29.64	32.18
K <sub>2</sub> O	0.34	0.41	0.38	0.50	0.67	0.53	0.50	0.52	0.32	0.29	0.23	0.35	0.37	0.36
CaO	1.69	2.34	2.34	0.39	0.54	0.31	0.93	0.38	9.80	5.61	4.66	4.60	5.17	4.17
TiO <sub>2</sub>	0.16	0.35	0.20	0.30	0.38	0.20	0.37	0.29	0.40	1.27	0.60	0.58	0.30	0.55
Cr <sub>2</sub> O <sub>3</sub>	0.21	0.17	0.33	0.07	0.15	0.09	0.11	0.09	0.00	0.84	0.86	0.20	0.46	0.46
MnO	—	—	—	—	—	—	—	—	—	—	—	—	—	—
FeO	33.86	33.31	36.44	30.24	29.14	28.76	29.17	31.83	28.06	26.23	28.45	24.30	22.77	22.42
Total	81.22	86.24	90.73	80.96	80.47	82.76	82.86	83.99	84.88	87.95	88.71	81.52	81.79	79.63

ALH-77307												
	20'-1	200"-1	105-1	304-5	304-6	19-6	300-3	300-5	55-3	5-4	302-4	303-2
Na <sub>2</sub> O	0.80	1.47	0.43	1.66	0.83	1.69	1.04	1.18	1.49	1.09	0.93	1.43
MgO	6.37	5.99	6.72	6.47	5.00	4.70	7.57	4.58	4.18	4.95	4.92	8.15
Al <sub>2</sub> O <sub>3</sub>	10.51	9.59	3.89	13.72	8.06	10.33	8.43	12.61	12.18	10.26	8.37	12.45
SiO <sub>2</sub>	26.96	33.38	36.53	28.50	21.27	29.18	29.12	29.28	25.82	23.89	27.59	27.74
K <sub>2</sub> O	0.59	0.55	0.50	0.48	0.18	0.21	0.33	0.35	0.53	0.37	0.26	0.26
CaO	0.50	0.96	0.26	2.39	2.19	6.80	3.36	0.97	0.56	1.36	1.75	2.10
TiO <sub>2</sub>	—	—	—	—	—	—	—	—	—	—	—	—
Cr <sub>2</sub> O <sub>3</sub>	—	—	—	—	—	—	—	—	—	—	—	—
MnO	0.12	0.17	0.17	0.36	0.21	0.25	0.41	0.46	0.06	0.29	0.67	0.33
FeO	34.58	33.88	31.96	33.60	39.49	31.01	28.77	35.66	36.19	42.45	43.64	35.82
Total	80.42	85.99	80.48	87.18	77.22	84.16	79.04	85.10	81.01	84.65	88.14	88.28

Table 1. Continued.

Y-790123												
	40-6*	40-7*	57-2*	30-4	41-2	41-3	41-4	66-2	66-4	15-1	13-3	13-1
Na <sub>2</sub> O	7.69	7.54	0.03	0.60	0.32	0.39	0.70	0.68	0.58	0.74	0.43	0.50
MgO	0.69	0.58	3.75	6.76	10.23	11.97	5.29	8.23	8.32	6.38	5.79	4.15
Al <sub>2</sub> O <sub>3</sub>	13.56	14.13	29.02	7.61	9.36	11.94	6.29	3.74	3.57	9.59	9.79	8.26
SiO <sub>2</sub>	58.65	60.15	46.00	21.87	23.66	29.26	21.86	25.07	26.75	21.79	21.76	20.50
K <sub>2</sub> O	0.37	1.11	0.00	0.07	0.00	0.07	0.00	0.08	0.08	0.05	0.05	0.01
CaO	8.64	8.01	21.03	0.14	0.08	0.28	0.03	0.88	0.95	0.12	0.17	0.10
TiO <sub>2</sub>	0.63	0.77	0.27	—	—	—	—	—	—	—	—	—
Cr <sub>2</sub> O <sub>3</sub>	—	—	0.00	—	—	—	—	—	—	—	—	—
MnO	0.00	0.00	0.00	0.23	0.24	0.34	0.31	0.31	0.48	0.19	0.15	0.09
FeO	8.84	8.22	0.26	45.82	35.08	33.16	51.74	44.35	45.03	45.17	46.18	47.87
Total	99.07	100.52	100.36	83.08	78.97	87.40	86.22	83.33	85.76	84.03	84.34	81.48

Y-790123								Y-75293				
	65-1	49-1	49-3	47'-1	47-2	47-3	38-1	2-6*	2-8*	2-10*	2-12*	2-14*
Na <sub>2</sub> O	0.56	0.34	0.34	0.49	0.34	0.54	0.37	1.63	0.89	1.20	1.32	1.19
MgO	7.52	14.54	15.84	8.85	14.52	13.13	10.78	3.51	3.99	4.23	4.02	3.96
Al <sub>2</sub> O <sub>3</sub>	3.77	5.46	4.83	4.88	4.94	7.88	4.39	18.23	18.62	18.36	18.83	18.58
SiO <sub>2</sub>	22.27	33.99	31.82	25.73	34.86	28.01	26.14	57.59	57.96	57.17	56.48	57.50
K <sub>2</sub> O	0.09	0.07	0.07	0.03	0.02	0.08	0.01	0.03	0.07	0.03	0.06	0.03
CaO	0.07	3.42	3.47	0.68	3.33	2.61	1.91	16.09	16.56	16.68	16.26	16.72
TiO <sub>2</sub>	—	—	—	—	—	—	—	0.78	1.03	0.99	1.04	1.18
Cr <sub>2</sub> O <sub>3</sub>	—	—	—	—	—	—	—	—	—	—	—	—
MnO	0.16	0.27	0.45	0.34	0.46	0.33	0.33	0.12	0.34	0.04	0.06	0.11
FeO	47.81	32.62	28.92	42.85	29.43	29.40	43.36	0.08	0.01	0.08	0.00	0.02
Total	82.26	90.70	85.74	83.85	87.90	82.01	87.27	98.06	99.46	98.78	98.07	99.29

Table 1. Continued.

	Y-75293										Y-74662				
	28-2	28-4	33-4	39-3	39-6	19-2	19-3	23	33-2	40	28-2	1-8	1-9	1-10	37-2
Na <sub>2</sub> O	0.23	0.27	0.35	0.22	0.25	0.48	0.46	0.25	0.37	0.38	0.47	0.29	0.26	0.33	0.15
MgO	9.21	8.76	7.12	14.41	13.54	9.60	8.52	11.36	10.82	8.39	11.32	10.14	10.63	11.12	5.70
Al <sub>2</sub> O <sub>3</sub>	13.74	13.28	8.95	6.46	6.63	8.67	8.93	3.51	6.96	4.34	8.05	10.68	9.17	11.63	9.31
SiO <sub>2</sub>	23.22	24.75	22.91	32.51	29.20	27.19	25.87	28.27	28.68	29.00	28.81	24.33	23.78	25.53	21.72
K <sub>2</sub> O	0.03	0.09	0.09	0.47	0.39	0.14	0.10	0.05	0.07	0.05	0.03	0.01	0.00	0.03	0.00
CaO	1.24	1.75	0.10	0.17	0.41	3.94	2.59	1.58	4.71	4.04	3.51	0.47	0.79	0.60	0.07
TiO <sub>2</sub>	0.15	0.61	0.18	0.34	0.30	—	—	—	—	—	—	0.08	0.06	0.26	0.12
Cr <sub>2</sub> O <sub>3</sub>	—	—	—	—	—	0.46	0.33	0.49	0.37	0.21	0.66	—	—	—	—
MnO	0.26	0.15	0.12	0.37	0.11	0.06	0.22	0.28	0.33	0.10	0.11	0.05	0.09	0.14	0.00
FeO	26.04	28.18	46.05	25.16	25.04	31.80	33.30	37.26	33.50	38.91	33.52	34.96	35.78	33.26	44.66
Total	74.11	77.84	85.86	80.12	75.86	82.34	80.32	83.04	85.80	85.43	86.49	81.01	80.56	82.90	81.72

	Y-74662														
	73-1	73-4	73-5	73-6	48-3	48-4	48-5	48-6	48-7	5-1	12-1	60-1	60-4	67-2	67-3
Na <sub>2</sub> O	0.22	0.23	0.29	0.24	0.22	0.30	0.53	0.26	0.20	0.27	0.26	0.17	0.26	0.15	0.21
MgO	15.58	12.48	15.79	13.51	12.59	21.70	18.15	13.54	15.52	19.82	14.79	12.53	16.27	15.37	15.59
Al <sub>2</sub> O <sub>3</sub>	8.36	7.79	6.34	9.81	6.54	3.53	4.00	7.70	7.49	4.77	7.20	11.99	7.80	9.44	9.45
SiO <sub>2</sub>	30.89	28.26	29.58	27.86	31.07	31.05	31.18	27.92	27.97	29.20	28.82	32.03	26.45	32.00	29.13
K <sub>2</sub> O	0.09	0.12	0.17	0.16	0.16	0.00	0.00	0.13	0.05	0.04	0.02	0.00	0.05	0.05	0.05
CaO	0.34	0.88	0.43	0.27	0.42	0.11	0.06	4.67	1.54	0.16	0.20	5.29	0.74	0.23	0.37
TiO <sub>2</sub>	0.20	0.22	0.07	0.14	0.27	0.18	0.22	0.15	0.34	0.07	0.26	0.62	0.45	0.27	0.41
Cr <sub>2</sub> O <sub>3</sub>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
MnO	0.15	0.28	0.23	0.26	0.31	0.13	0.20	0.21	0.20	0.12	0.19	0.34	0.19	0.47	0.39
FeO	25.84	29.47	27.55	27.64	26.69	24.11	31.58	24.20	25.14	27.20	27.21	23.88	27.62	23.29	22.34
Total	81.67	79.73	80.45	79.90	78.27	81.11	85.91	78.78	78.47	81.66	78.96	86.86	79.83	81.28	77.94

of chondrules and matrix, and opaque clots were performed using the defocused beam, about 5 to 50 microns across, of an electron-probe microanalyzer. The correction method is according to BENCE and ALBEE (1968).

### 3.1. Groundmass phyllosilicates

The chemical compositions of groundmass phyllosilicates in chondrules are shown in Table 1. The total wt % values of groundmass phyllosilicates are concentrated in the range of 80 to 90 wt % for most analyses. Water probably accounts for the remaining 10–20 %. In Table 1, columns 40–6, 40–7, 57–2, 2–6, 2–8, 2–10, 2–12, and

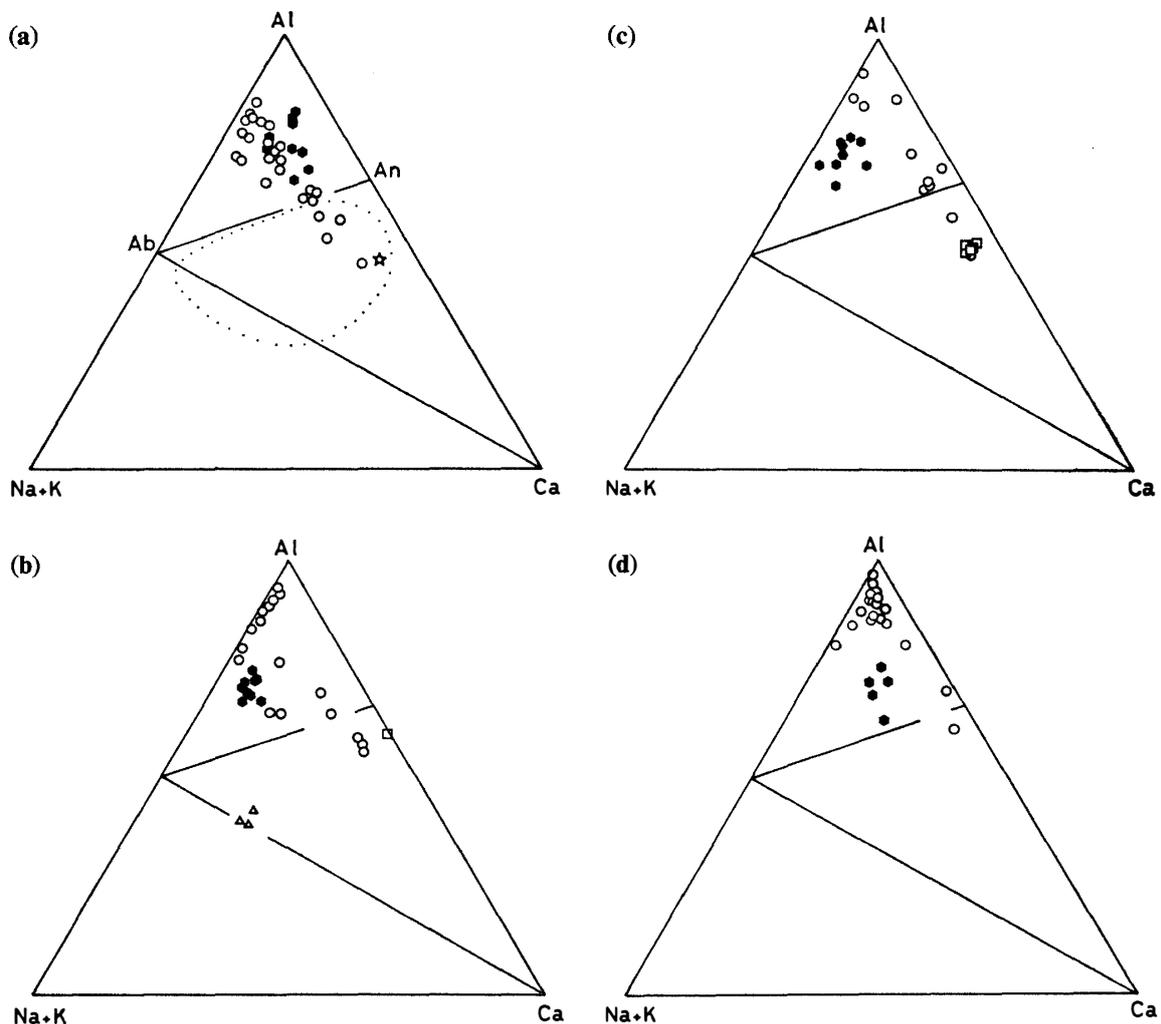


Fig. 1. Compositions (atom %) of groundmass phyllosilicates (open circles) and matrices (solid hexagons) in ALH-77307 (a), Y-790123 (b), Y-75293 (c), and Y-74662 (d). Open triangles and an open square in (b) are clean glass of an unaltered chondrule (Nos. 40–6 and 40–7 in Table 1) and glass inclusion in olivine fragment (No. 57–2 in Table 1), respectively. Open squares in (c) are clean glass of an unaltered chondrule (Nos. 2–6 to 2–14 in Table 1). In (a), the matrix composition of Allende (open star) and the main compositional range of the groundmasses of chondrules in ALH-77003 and Y-790992 (dotted line) are shown for comparison. An and Ab are anorthite and albite, respectively.

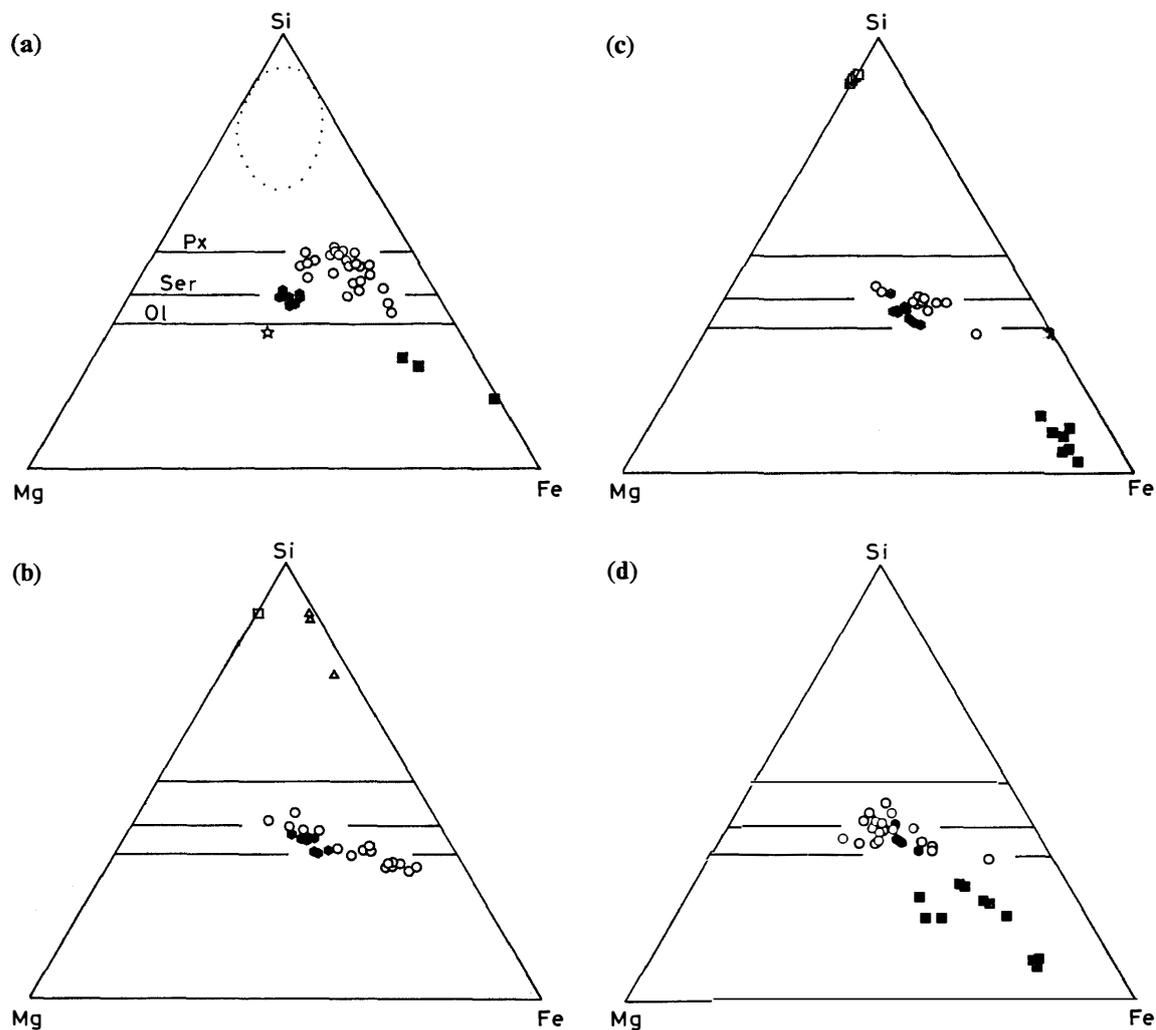


Fig. 2. Compositions (atom %) of groundmass phyllosilicates, matrices, and opaque clots (solid squares). The symbols and fields are the same as in Fig. 1. Px, Ser, and Ol are low-Ca pyroxene, Al-free serpentine, and olivine, respectively.

2-14 are the analyses of clean glasses that did not suffer any alteration; their sums are close to 100 wt %.

The chemical compositions of groundmass phyllosilicates are plotted in Figs. 1 to 3, together with the average chemical composition of the matrix of Allende meteorite (McSWEEN and RICHARDSON, 1977) and the compositional range of clean glasses of chondrule groundmasses in two unaltered C3 chondrites, ALH-77003 (IKEDA, 1982) and Y-790992 (IKEDA, in preparation). Figure 1 shows that the groundmass phyllosilicates of ALH-77307 have fairly uniform  $(\text{Na} + \text{K})/\text{Al}$  ratios, and these are higher than those of the other chondrites, Y-790123, Y-75293, and Y-74662. The groundmass phyllosilicates of Y-74662 are the poorest in alkalis and CaO. In Fig. 2, the groundmass phyllosilicates of ALH-77307 have  $\text{FeO}/(\text{MgO} + \text{FeO})$  ratios higher than those of Y-74662 as a whole. The  $\text{FeO}/(\text{MgO} + \text{FeO})$  ratios of Y-790123 and Y-75293 are intermediate. As Fig. 3 shows, the groundmass phyllosilicates in ALH-77307 are richer in  $\text{SiO}_2$  than those in the other three chondrites, and most of them plot in the range

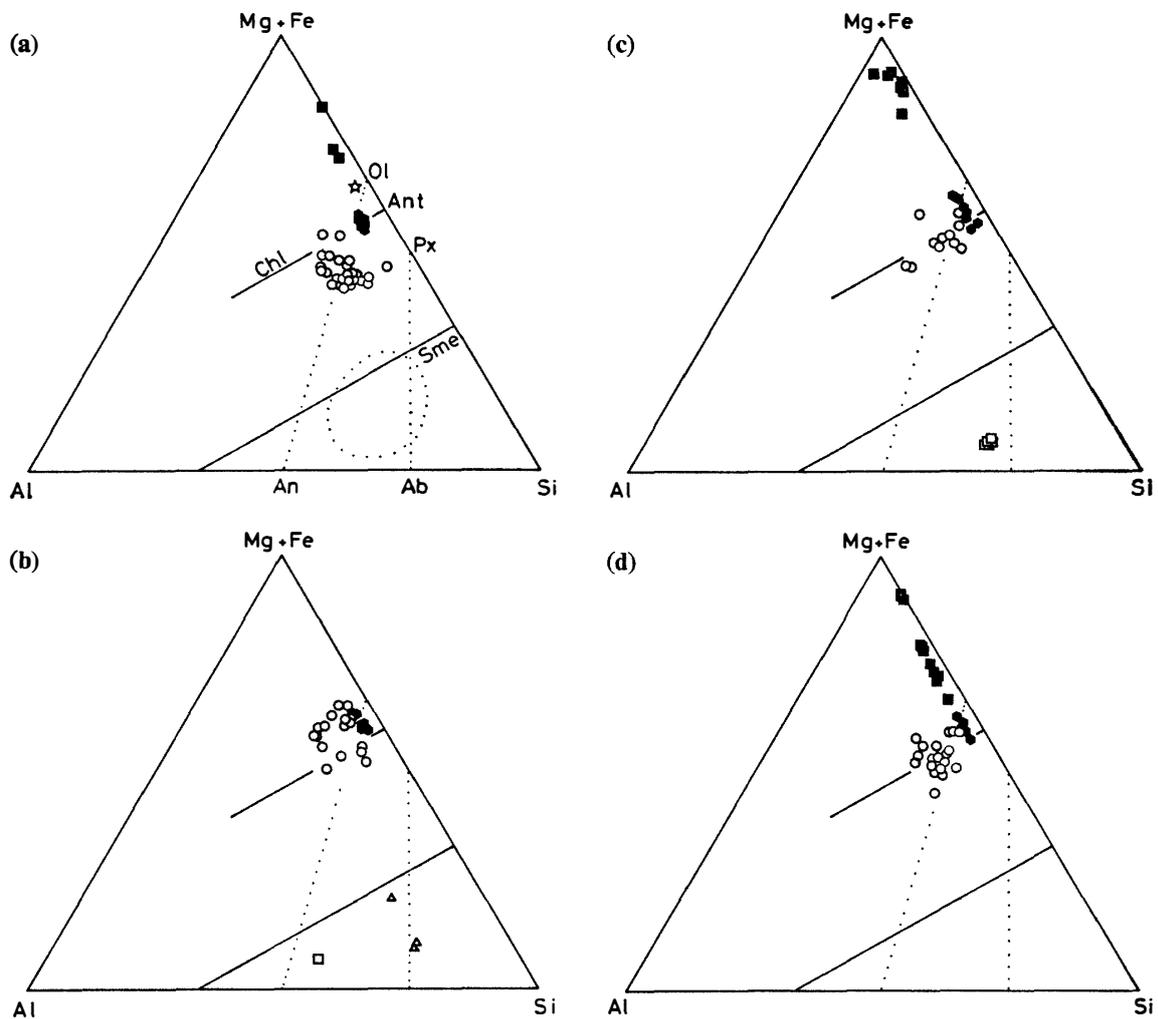


Fig. 3. Compositions (atom %) of groundmass phyllosilicates, matrices and opaque clots. The symbols and fields are the same as in Figs. 1 and 2. Chl, Ant, and Sme are chlorite solid solution, antigorite, and smectite solid solution, respectively.

between chlorite and smectite; whereas the groundmass phyllosilicates in the other three chondrites plot near the chlorite composition, with or without minor amounts of smectite or (Mg+Fe)-rich phases such as brucite, PCP, etc.

Although there are conspicuous differences in chemical compositions of the groundmass phyllosilicates among these four chondrites, the main phyllosilicate of chondrule groundmasses in these chondrites may be chlorite (and/or berthierine) whose compositions range from  $(\text{Mg, Fe})_{11.5}\text{AlSi}_{7.5}\text{O}_{20}(\text{OH})_{16}$  to  $(\text{Mg, Fe})_{10}\text{Al}_4\text{Si}_6\text{O}_{20}(\text{OH})_{16}$ .

### 3.2. Matrix phyllosilicates

The chemical compositions of the matrices in the chondrites studied are shown in Table 2. The total values of the analyses are 74–83 wt % for the matrix of ALH-77307; Sums for the other three C2 chondrites are lower, ranging from 65 to 78 wt %. The S contents of these matrices are less than 5 wt %, and their low sums are probably due to their  $\text{H}_2\text{O}$  and hydrocarbon contents.

Table 2. Chemical compositions of matrices in ALH-77307, Y-790123, Y-75293 and Y-74662. "FeO" is the sum of FeO and Fe<sub>2</sub>O<sub>3</sub>.

	ALH-77307							Y-790123				
	2-M	124-M	59-M	67-M1	12-M	118-M	67-M3	17-M	1-M	51-M3	42-M3	17-M
Na <sub>2</sub> O	0.27	0.26	0.20	0.19	0.40	0.39	0.33	0.40	0.36	0.44	0.31	
MgO	13.40	13.96	14.75	15.17	13.38	14.99	14.58	12.03	12.23	10.91	11.66	
Al <sub>2</sub> O <sub>3</sub>	3.72	3.76	4.00	4.10	4.09	4.28	3.80	2.33	2.10	2.88	2.23	
SiO <sub>2</sub>	29.10	28.01	30.31	28.93	29.59	29.20	26.44	24.55	24.28	22.22	21.16	
K <sub>2</sub> O	0.15	0.09	0.09	0.06	0.24	0.23	0.22	0.05	0.09	0.08	0.06	
CaO	0.79	0.95	0.62	0.61	1.28	0.63	0.48	0.20	0.36	0.30	0.18	
TiO <sub>2</sub>	0.00	0.00	0.09	0.05	—	—	—	0.02	—	—	—	
Cr <sub>2</sub> O <sub>3</sub>	0.03	0.18	0.11	0.12	0.23	0.35	0.44	0.22	0.41	0.34	0.34	
MnO	—	—	—	—	0.04	0.15	0.24	—	0.08	0.18	0.21	
FeO	29.46	27.56	26.00	25.93	29.62	26.81	27.68	28.37	28.03	32.54	29.30	
NiO	—	—	—	—	3.57	4.74	2.59	—	2.13	1.95	2.25	
Total	76.91	74.76	76.17	75.15	82.45	81.78	76.80	68.17	70.09	71.84	67.70	

	Y-75293				Y-74662				
	19-M2	1-M	39-M1	28-M	1-M1	1-M2	44-M	60-M	0-M
Na <sub>2</sub> O	0.30	0.31	0.54	0.34	0.03	0.25	0.28	0.28	0.23
MgO	11.01	12.16	10.72	11.75	13.42	13.71	12.77	14.19	14.25
Al <sub>2</sub> O <sub>3</sub>	2.53	2.60	2.54	2.27	3.04	2.89	2.36	2.43	2.97
SiO <sub>2</sub>	22.88	24.49	21.62	23.34	27.51	26.74	25.89	28.05	28.03
K <sub>2</sub> O	0.05	0.12	0.09	0.07	0.04	0.08	0.10	0.06	0.07
CaO	0.22	0.18	0.37	0.22	0.77	0.70	0.53	0.47	0.59
TiO <sub>2</sub>	—	—	—	0.00	0.00	0.26	0.20	0.18	—
Cr <sub>2</sub> O <sub>3</sub>	0.37	0.45	0.59	0.37	—	—	—	—	0.43
MnO	0.08	0.24	0.09	—	0.10	0.21	0.23	0.19	0.23
FeO	26.71	26.86	31.48	26.94	32.26	30.62	35.29	31.07	29.84
NiO	2.07	2.67	1.76	—	—	—	—	—	—
Total	66.23	70.07	69.81	65.26	77.47	75.47	77.64	76.91	76.63

The matrices of the four chondrites are roughly similar in chemical composition each other, as shown in Figs. 1 to 3, although they are decidedly depleted in MgO and CaO in comparison to the Allende matrix. The Al<sub>2</sub>O<sub>3</sub> contents of the matrices are nearly constant ranging from 2.1 to 4.3 wt %, which contrasts with the high Al<sub>2</sub>O<sub>3</sub> contents of the groundmass phyllosilicates ranging from 3.6 to 13.7 wt %. But, the matrix of ALH-77307 is slightly richer in Al<sub>2</sub>O<sub>3</sub> contents than those of the other three C2 chondrites. The compositions of the matrix of ALH-77307 plot just on the serpentine whose composition is (Mg, Fe)<sub>11.5</sub>AlSi<sub>7.5</sub>O<sub>20</sub>(OH)<sub>16</sub>, but the matrices of the other three chondrites are slightly richer in FeO than the matrix of ALH-77307, resulting in SiO<sub>2</sub>-poor composition corresponding to serpentine with minor amounts of PCP components (Figs. 2 and 3).

### 3.3. Opaque clots

The chemical compositions of opaque clots which are composed mainly of PCP are shown in Table 3. The sums of analyses in Table 3 are variable, and their low sums are probably due to their S, H<sub>2</sub>O, oxygens for ferric irons, etc. (the S contents of opaque

Table 3. Chemical compositions of opaque clots in ALH-77307, Y-75293, and Y-74662. "FeO" means total Fe as FeO, including FeO, Fe<sub>2</sub>O<sub>3</sub>, FeS, etc.

	ALH-77307			Y-75293					
	PCP-1	PCP-2	PCP-3	PCP-1	PCP-3	PCP-4	PCP-5	PCP-6	PCP-7
Na <sub>2</sub> O	0.61	0.51	0.47	0.28	0.40	0.22	0.10	0.27	0.12
MgO	5.92	7.19	0.25	4.84	4.64	4.13	4.64	3.18	4.37
Al <sub>2</sub> O <sub>3</sub>	2.14	2.02	0.00	2.97	1.17	0.90	1.59	1.13	1.62
SiO <sub>2</sub>	17.48	19.14	10.00	8.04	5.98	5.68	2.87	6.81	3.70
K <sub>2</sub> O	0.22	0.26	0.02	0.03	0.03	0.01	0.01	0.02	0.00
CaO	1.89	0.63	0.11	0.06	0.08	0.07	0.07	0.08	0.06
TiO <sub>2</sub>	—	—	—	—	—	—	—	—	—
Cr <sub>2</sub> O <sub>3</sub>	0.28	0.27	1.96	0.18	0.14	0.11	0.16	0.11	0.11
MnO	0.03	0.21	0.09	0.00	0.01	0.01	0.10	0.03	0.04
FeO	57.60	54.50	62.92	56.81	59.96	66.11	60.71	64.23	66.80
NiO	2.41	2.15	20.54	2.12	1.53	0.89	1.94	1.02	1.77
Total	88.57	86.88	96.36	75.34	73.94	78.13	72.18	76.87	78.59

	Y-74662										
	PCP-1	PCP-2	PCP-3	PCP-4	PCP-5c	PCP-5m	PCP-6	PCP-7	PCP-8r'	PCP-8c	PCP-8r''
Na <sub>2</sub> O	0.20	0.34	0.29	0.15	0.44	0.30	0.44	0.33	0.09	0.16	0.16
MgO	13.56	8.92	7.24	15.15	10.65	15.07	10.13	8.39	5.14	5.02	5.36
Al <sub>2</sub> O <sub>3</sub>	1.55	1.64	1.43	1.50	1.92	1.69	1.99	1.50	0.34	0.30	0.34
SiO <sub>2</sub>	13.02	15.79	13.17	13.07	19.41	17.41	18.56	15.51	4.66	3.61	4.71
K <sub>2</sub> O	0.03	0.01	0.02	0.00	0.03	0.00	0.00	0.00	0.02	0.05	0.04
CaO	0.14	0.15	0.16	0.12	0.10	0.09	0.18	0.19	0.39	0.22	0.25
TiO <sub>2</sub>	—	—	—	—	—	—	—	—	—	—	—
Cr <sub>2</sub> O <sub>3</sub>	0.24	0.18	0.16	0.14	0.17	0.24	0.25	0.07	2.61	2.39	2.52
MnO	0.20	0.12	0.06	0.01	0.08	0.06	0.15	0.21	0.11	0.00	0.16
FeO	44.19	50.06	53.55	41.66	46.10	40.72	45.77	51.80	47.74	44.02	46.44
NiO	2.79	1.67	2.05	3.44	2.08	3.05	1.12	1.65	8.45	8.58	8.51
Total	75.90	78.88	78.12	75.24	80.95	78.62	78.58	79.66	69.55	64.35	68.49

clots are variable ranging from 4 to 19 wt % for Y-75293 and Y-74662, whereas those in ALH-77307 show lower S contents less than 6 wt %).

The chemical compositions of opaque clots are shown in Figs. 2 and 3. They plot along a line connecting the matrix phyllosilicates with the Fe apex in Figs. 2 and 3.

#### 4. Discussion

##### 4.1. Degree of chondrule alteration

The carbonaceous chondrites studied include chondrules that have suffered various degrees of alteration. Some chondrules are free from any alteration, whereas some have experienced intense alteration. The degrees of chondrule alteration are classified into the following stages, in order of increasing alteration;

- I. No alteration, or only very weak alteration in peripheral parts of chondrules.
- II. Alteration of chondrule groundmass.
- III. Alteration of low-Ca pyroxenes showing polysynthetic twinning.
  - III-a. Partly altered. III-b. Wholly altered.

#### IV. Alteration of olivines in chondrules.

Stage I means that chondrules suffer no alteration or very weak alteration of glasses only in the rims of chondrules. Chondrule No. 40 in Y-790123 and chondrule No. 2 in Y-75293 belong to stage I. Stage II represents alteration of the whole groundmass into an aggregate of very fine-grained hydrous minerals, but phenocrystic, barred, or radial crystals of olivine and pyroxene in chondrules remain unaltered. The resulted products are creamy or pale yellow to dark brown materials, but are free from any greenish tinge. They are rich in  $\text{Al}_2\text{O}_3$  because most original groundmasses generally contain large amounts of the component. Stage III includes the alteration of low-Ca pyroxenes showing polysynthetic twinning in addition to the alteration of groundmass; but phenocrystic or barred olivine crystals remain fresh. The alteration products are pale to dark brown- or green-colored phyllosilicates. III-a means alteration where less than half of the low-Ca pyroxenes in a chondrule are altered. III-b is total alteration, such that relic crystals of low-Ca pyroxenes are scarce. Stage IV includes the alteration of phenocrystic olivines in addition to the alteration of groundmass and pyroxenes. The resulted phyllosilicates may be richer in MgO and poorer in  $\text{Al}_2\text{O}_3$  than those of stage II.

In ALH-77307 chondrules of stage II are abundant, along with rare chondrules of stage III-a. In Y-790123 and Y-75293 chondrules of stage II and stage III-a are predominant, with one example of stage I in each chondrite. In Y-74662 chondrules of stage III-a are most numerous with minor chondrules of stage II and stage III-b. Chondrules of stage IV were not observed in these four chondrites. Thus the ALH-77307 chondrite consists mainly of weakly-altered chondrules, the Y-74662 chondrite consists mainly of intensely-altered chondrules, and the two chondrites Y-790123 and Y-75293 are intermediate.

The chemical compositions of groundmass phyllosilicates seem to correlate closely with the degree of alteration. They shift from ferrous and richer in alkalis and CaO components in ALH-77307 to magnesian and poorer in the components in Y-74662, via Y-790123 and Y-75293, as shown in Figs. 1 and 2. In addition to these trends, the abundance of calcite fragments set in the matrices also roughly correlates with the degree of alteration. That is, calcite fragments are abundant in Y-74662 and occur in smaller amounts in Y-790123 and Y-75293, whereas ALH-77307 is free from calcite fragments.

DESNOYERS (1980) concluded from the study of the Niger chondrite (C2) that interstitial glass was altered first, then pyroxene. This agrees with my observation that stage II precedes stage III in the alteration process. On the other hand, RICHARDSON (1981) described the alteration of chondrule mesostasis in C2 chondrites and concluded that a two stage alteration process acted on mesostasis glass; the first stage was pervasive alteration that produced magnesian phyllosilicates, and a second, less intense stage produced the Fe-enriched spinach compositions. However, the chondrules in ALH-77307 which include Fe-enriched phyllosilicates of stage II seem not to have suffered intense alteration nor to have contained magnesian phyllosilicates prior to the formation of the Fe-enriched ones. Therefore, I prefer a progressive alteration in which spinach changes from ferrous chlorite (and/or berthierine) containing high  $\text{Al}_2\text{O}_3$  contents with minor smectite components in stage II towards magnesian serpentine con-

taining less  $\text{Al}_2\text{O}_3$  contents in stage IV, via intermediate chlorite (and/or berthierine) in stage III.

#### 4.2. Alteration of groundmass glass

In general, the compositions of the original groundmass materials that were altered to phyllosilicates can not be known. However, the chondrules in the altered C chondrites studied resemble in textures and mineral compositions to those in unaltered C chondrites. Thus, I assume that the original compositions of the altered groundmasses were the same as the groundmass glasses of chondrules in two unaltered C3 chondrites ALH-77003 (IKEDA, 1982) and Y-790992 (IKEDA, in preparation).

Table 4. Average chemical compositions of groundmasses in chondrules (atomic proportions, normalized to Al=1).

	(1)	(2)	(3)	(4)	(5)
Na	0.5	0.18	0.12	0.07	0.05
Mg	0.3	0.86	1.73	1.59	2.24
Al	1	1	1	1	1
Si	2.5	2.62	3.32	2.84	2.99
Ca	0.7	0.23	0.16	0.24	0.11
Fe	0.2	2.29	4.34	2.84	2.51

(1): clean glass groundmasses in ALH-77003(C3) and Y-790992(C3), (2): altered groundmasses in ALH-77307, (3): altered groundmasses in Y-790123 (except for clean glass groundmass in chondrule No. 40), (4): altered groundmasses in Y-75293 (except for clean glass groundmass in chondrule No. 2), and (5): altered groundmasses in Y-74662.

The average chemical compositions of the altered groundmasses in the four chondrites studied are shown in Table 4 together with the average chemical composition of the clean glass groundmasses of ALH-77003 and Y-790992. Comparing the chemical compositions of the altered groundmasses with the presumed original composition under the assumption that Al atoms were fixed in the groundmass during alteration reactions, the contents of Mg and Fe are largely different between them (Table 4). This difference can be explained more easily by the addition of MgO and FeO to the original material during their alteration than by the substitution of  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  in a constant ratio (Fig. 3). The addition of FeO may be supplied by oxidation of Fe-Ni metals or troilites. The source of MgO will be discussed in the next section. Extreme loss of alkali and CaO from the original material may occur during alteration (Fig. 1 and Table 4). The degree of depletion of these components in the altered groundmasses may depend partly upon the amounts of smectite, which includes these cations in its structure, that are created. Some Na released may go to form opaque clots set in the altered matrices. The loss of Ca from the original material may result finally in the formation of calcite crystals the fragments of which are observed set in the matrices of Y-790123, Y-75293, and Y-74662.

#### 4.3. Alteration of matrix and opaque clots

The main phyllosilicate in the matrices of the C chondrites studied is serpentine containing low  $\text{Al}_2\text{O}_3$  contents, whereas that in chondrule groundmasses is chlorite (or berthierine) containing high  $\text{Al}_2\text{O}_3$  contents. This difference is due to that of the chemical compositions of their precursor materials. According to BUNCH and CHANG (1978), the precursor material of altered matrix in CM chondrites is equivalent to the dark halo material surrounding chondrules and aggregates in Allende. AKAI (1982) also concluded that the phyllosilicates in the matrix of Y-74662 were derived by alteration from such precursor materials as CV chondrites (*e.g.* Allende). Thus I assume Allende matrix (MCSWEEN and RICHARDSON, 1977) as a possible original material that gave rise to the altered matrices in the four chondrites studied. The chemical composition of the matrix of Allende is shown in Table 5 together with the average composition of matrices of ALH-77307, Y-790123, Y-75293, and Y-74662.

Table 5. Average chemical compositions of matrices (atomic proportions, normalized to Al=1).

	(1)	(2)	(3)	(4)	(5)
Na	0.156	0.12	0.26	0.20	0.13
Mg	11.1	4.6	6.2	5.8	6.3
Al	1	1	1	1	1
Si	10.4	6.2	7.9	7.9	8.4
Ca	0.933	0.17	0.099	0.091	0.20
Fe	9.87	4.9	8.8	8.0	8.2

(1): Allende (MCSWEEN and RICHARDSON, 1977),  
 (2): ALH-77307, (3): Y-790123, (4): Y-75293, and (5): Y-74662.

In order to obtain the average altered matrix compositions (Table 5) by hydration reactions from the assumed original material, under the assumption that Al atoms were fixed through the alteration reactions, large amounts of Mg and Ca and minor amounts of Si must be lost from the matrix. The released Mg may be partly used in chondrules for the formation of altered groundmasses and the released Ca may form calcite crystals set in matrices of C2 chondrites. The minor  $\text{SiO}_2$  may be used to form the opaque clots.

The opaque clots set in matrices of many C chondrites are composed mainly of PCP, which is thought to have been produced by the alteration of Fe-Ni metals or sulfides (BUNCH and CHANG, 1978; DESNOYERS, 1980). The clots contain variable amounts of NiO and S, and probably also C and  $\text{H}_2\text{O}$ , in addition to  $\text{SiO}_2$  and MgO (Table 3). The high NiO and S contents (up to 20 wt % of each) support the idea that opaque clots were formed from Fe-Ni metals or Fe-Ni sulfides by alteration. In this case, the opaque clots must have an external source; a possible candidate is the  $\text{SiO}_2$  released during matrix alteration. The MgO of the opaque clots also may derived from the MgO released during matrix alteration.

#### 4.4. The place of alteration

The alteration of carbonaceous chondrites is considered to have taken place in

nebula, in parent bodies, or on terrestrial surface. The terrestrial alteration is weathering or aqueous alteration on the earth surface after the meteorites fall. The nebula-stage alteration refers to the low-temperature reaction of the condensed dusts or chondrules with surrounding nebular gas to produce hydrous silicates before their accretion onto the parent bodies (FUCHS *et al.*, 1973; McSWEEN and RICHARDSON, 1977; OLSEN and GROSSMAN, 1978). Parent body-stage alteration is the reaction of the accreted materials with aqueous fluids in or on their parent bodies after accretion. The parent body-stage alteration pictured includes "*in-situ* alteration" (BUNCH and CHANG, 1980) and "two-stage alteration" with regolith gardening (RICHARDSON, 1981).

*In-situ* alteration on the parent body is considered to have been an important process in the intensely-altered C1 and C2 chondrites (such as Orguil, Ivuna, Nogoya, Murray, and Cold Bokkeveld) which show cross-cutting veins and/or colloform texture (RICHARDSON, 1978; BUNCH and CHANG, 1980). However, the alteration of ALH-77307, Y-790123, Y-75293, and Y-74662 is not due to *in-situ* alteration, for the following reasons: (1) Chondrules in one chondrite show varying degrees of chondrule alteration, ranging from stage I to stage III. (2) In Y-790123, chondrule No. 40 is a broken chondrule containing unaltered clean glass; the clean glass which is directly in contact with the matrix remain fresh. (3) Some small Fe-Ni metal grains occur set in the matrix of ALH-77307 in spite of the facts that the Fe-Ni metal grains in some altered chondrules have changed completely to PCP.

These observations indicate that the chondrules suffered their alteration prior to the final agglomeration of the chondrites. Therefore, the alteration of chondrules and matrices in the chondrites studied is due either to nebula-stage alteration or two or more stage alteration with regolith gardening on their parent bodies.

## 5. Conclusion

The alteration of chondrules and matrix, and the formation of opaque clots, took place in intimate relationship in ALH-77307, Y-790123, Y-75293, and Y-74662. The products of chondrule alteration are mainly chlorite (or berthierine) containing high  $\text{Al}_2\text{O}_3$  contents, whereas those of matrix alteration are mainly serpentine containing low  $\text{Al}_2\text{O}_3$  contents. This mineralogical and chemical difference is due to the chemical compositions of the two reactants prior to the alteration. The main product of chondrule alteration changes from ferrous chlorite (or berthierine) with minor smectite components via intermediate chlorite (or berthierine) to magnesian serpentine, according to increasing degree of the alteration.

The effects of *in-situ* alteration are not present in the carbonaceous chondrites studied. The observed alteration must have taken place prior to their final agglomeration of these chondrites.

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