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PETROLOGY OF THE YAMATO-8449 CR CHONDRITE

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Abstract: The Yamato (Y)-8449 chondrite is a new CR (Renazzo-type) chondrite, and the constituent minerals coincide in chemical composition with those of the other CR chondrites except phyllosilicate and metal. FeO and Al_2O_3 contents of phyllosilicates in Y-8449 are richer than those in other CR chondrites. Fe-Ni metal in Y-8449 is classified into two types; one type has an exsolution texture indicating a slow cooling rate of the metal, and the other type has a massive texture free from exsolution texture. Massive Fe-Ni metal in Y-8449 is more homogeneous than that in the other CR chondrites. Groundmass glass and phenocrystic enstatite in Y-8449 chondrules have been replaced by phyllosilicate in the chondrule rims, and the aqueous alteration reaction that produced the phyllosilicate had possibly taken place in a nebula at low temperatures prior to accretion onto the parent body.

1. Introduction

The Yamato-8449 (Y-8449) chondrite is a small Antarctic carbonaceous chondrite; its weight is 14.5 g (YANAI and KOJIMA, 1987). It was previously classified as an E4, but we found that it is a CR (Renazzo-type) chondrite. CR chondrites were once very rare, but recently many CR chondrites have been recovered from Antarctica and the Sahara (WEISBERG *et al.*, 1993; BISCHOFF *et al.*, 1993a, b), increasing the number of meteorites in this group. CR chondrites have been previously studied by several researchers (MCSWEEN, 1979; LEE *et al.*, 1992; WEISBERG *et al.*, 1993; BISCHOFF *et al.*, 1993a, b; ZOLENSKY *et al.*, 1993; KALLEMEYN *et al.*, 1994; ENDRESS *et al.*, 1994). In this paper we present a detailed petrographic and mineralogic study of Y-8449 in order to compare it to the other CR chondrites and discuss its petrogenesis.

2. Analytical Methods

Chemical compositions of the constituent minerals in Y-8449 were determined by a JOEL JCXA-733 electron-probe micro-analyzer (EPMA). Accelerating voltage of 15 kV and sample currents of 3 to 20 nA were used. The counting times were 20–100 s for peak and 20–100 s for background measurements. The BENCE and ALBEE (1968) method was used for the correction of silicates and oxides. Metal was corrected according to the ZAF method. The EPMA was also used to determine chemical compositions of glass in chondrules using a defocused beam with a diameter of 10–50

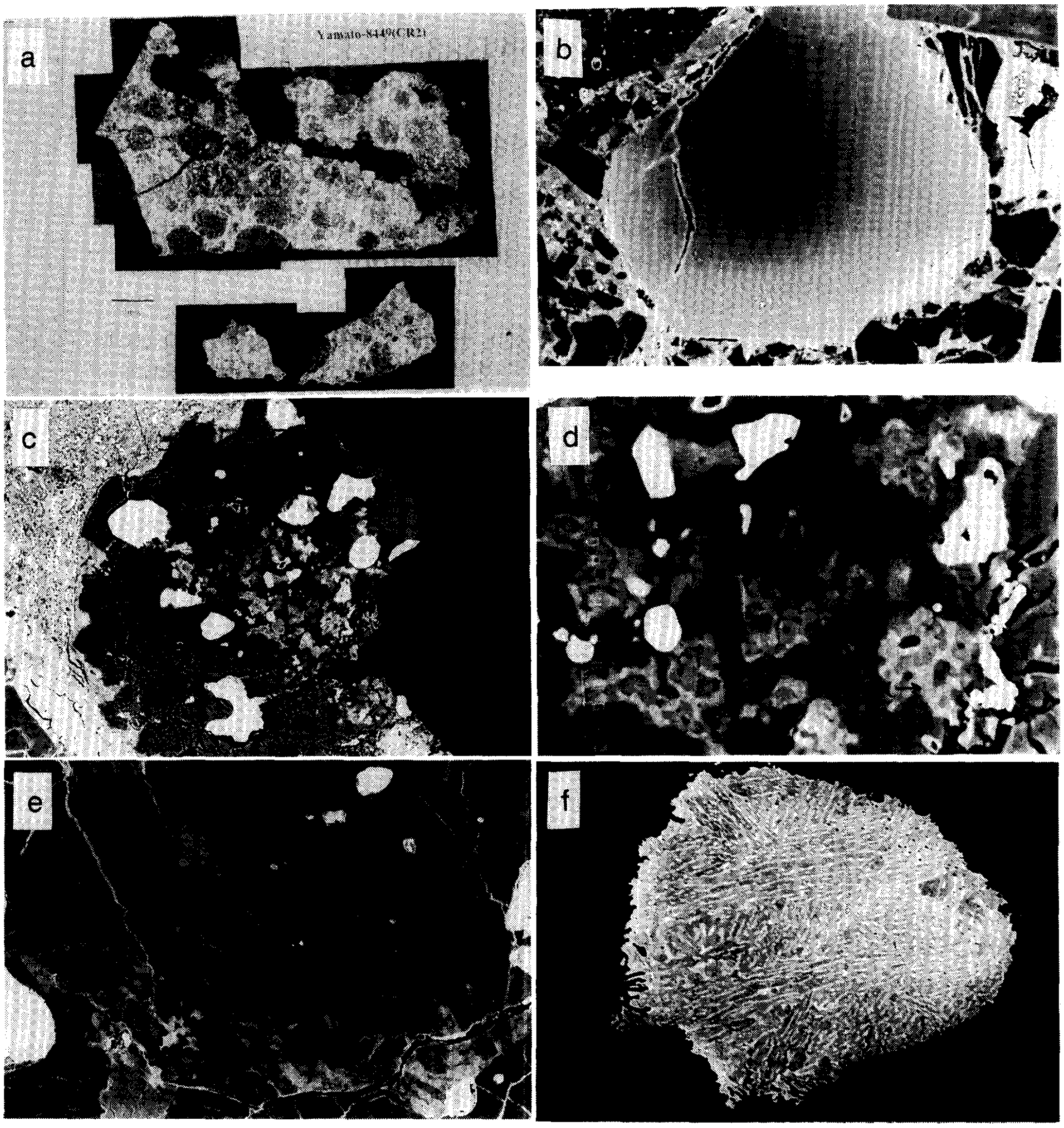


Fig. 1. Back-scattered electron (BSE) images.

(a) Yamato-8449 meteorite. Width of 1.4 cm.

(b) A ferroan olivine fragment. This type shows distinct chemical zoning from magnesian core to ferroan rim. Width 120 microns.

(c) A magnesian olivine fragment. This type does not show compositional zoning, and includes many irregular inclusions. Width 350 microns.

(d) Enlarged image of Fig. 1c. The host olivine is a single crystal and includes plagioclase surrounded by high-Ca pyroxene. Ol, An, Cpx, and Met are olivine, anorthite, high-Ca pyroxene, and metal, respectively. Width 60 microns.

(e) Chondrule No. 11 in Yamato-8449. Si-phase, LCa-Px, Cpx, Pl, and Phy are silica phase, low-Ca pyroxene, high-Ca pyroxene, plagioclase, and phyllosilicate, respectively. Width 330 microns.

(f) A metal grain with exsolution texture. This type consists of a kamacite host (dark) and taenite lamellae (bright). Width 120 microns.

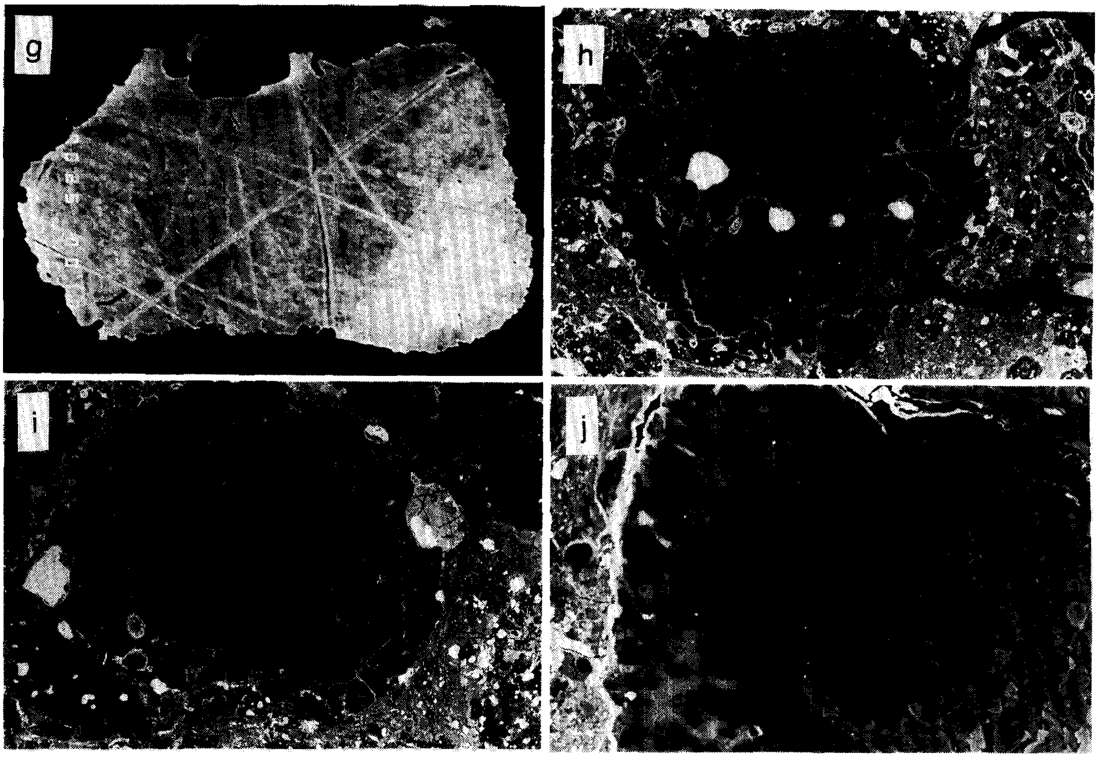


Fig. 1. (Continued)

(g) A metal grain with massive texture. Width 120 microns.
(h) Chondrule No. 7. Metal occurs at chondrule interior. Width 1.4 mm.
(i) Chondrule No. 4. Metal occurs at chondrule rim. Width 1.1 mm.
(j) Chondrule No. 12. Cpx, LCa-Px, Gl, and Phy are high-Ca pyroxene, low-Ca pyroxene, groundmass glass, and phyllosilicate, respectively. Width 120 microns.

micrometers, and data corrections were made with the BENCE and ALBEE (1968) method.

3. Petrography

Y-8449 consists of chondrules, isolated minerals, and matrix (Fig. 1a). Most of the chondrules are 0.5 to 1.1 mm in diameter; porphyritic olivine, porphyritic olivine pyroxene, and porphyritic pyroxene chondrules are the most abundant textural types. Olivines and pyroxenes in the rims are generally of smaller grain size than those in the cores. Only one barred olivine chondrule and one cryptocrystalline microchondrule were observed in the polished thin section studied (Y-8449,92-1). Most chondrules are composed of olivine, pyroxene, Fe-Ni metal, and a glassy groundmass. In some chondrules the groundmass glass has been replaced by phyllosilicate in the peripheral portions of chondrules.

Olivine, low-Ca pyroxene, and Fe-Ni metal occur as isolated minerals in Y-8449. Two types of isolated olivine were observed; one type is zoned ferroan olivine grains (Fo_{30-80}) free of inclusions (Fig. 1b), and the other type is homogeneous magnesian olivine (Fo_{98-100}) having small size inclusions of high-Ca pyroxene, plagioclase, phyllosilicate, Fe-Ni metal, and/or spinel (Figs. 1c, d). For convenience, the former is called ferroan olivine fragments, and the latter is referred to as magnesian olivine fragments in this paper. Fe-Ni metal in the matrix ranges in size from a few micrometers to several hundreds of micrometers, but many grains of Fe-Ni metal have been altered to limonite by terrestrial weathering. Sulfides are very rare in Y-8449 and have been altered. The matrix of this meteorite is composed of fine-grained phyllosilicates smaller than several micrometers.

On the other hand, BISCHOFF *et al.* (1993a) and WEISBERG *et al.* (1993) described the CR chondrites as consisting of chondrules, chondrule fragments, Fe-Ni metal and sulfides, dark inclusions, mineral fragments, and refractory inclusions. However, dark inclusions and refractory inclusions are not observed in Y-8449.

4. Mineralogy

Chemical compositions and the compositional ranges of the constituent minerals in Y-8449 are shown in Tables 1, 2, 3, and 4.

4.1. *Olivine*

Olivine in all chondrules is forsteritic (Fo_{92-99}), and does not show chemical zoning. Most of the chondrule olivine is between 97 and 98 mol% Fo, and contain 0.05–1.2 wt% Cr_2O_3 and 0.0–1.1 wt% MnO (Fig. 2). Ferroan olivine fragments show distinct zoning from their magnesian cores to ferroan rims (*e.g.* Fo_{30-80}), and these olivine grains contain 0.1–0.6 wt% Cr_2O_3 and 0.1–0.6 wt% MnO (Fig. 2). The Cr_2O_3 contents of ferroan olivine fragments in Y-8449 seem to decrease with increasing FeO content (Fig. 2). Magnesian olivine fragments (Fo_{98-100}) contain 0.1–0.2 wt% Cr_2O_3 and 0.0–0.1 MnO (Fig. 2). Chondrule olivine in Y-8449 is similar in FeO, MnO, and Cr_2O_3 contents to chondrule olivine in the other CR chondrites, as shown in Fig. 2. The MnO/FeO and Cr_2O_3/FeO weight ratios of ferroan olivine fragments in Y-8449 are close to those of the solar abundances, but there is considerable scatter in the data (Fig. 2).

4.2. *Pyroxene*

One of the most abundant minerals in Y-8449 is pyroxene. Three types of pyroxene occur, including low-Ca pyroxene, high-Ca pyroxene, and fassaitic pyroxene with Al_2O_3 content of more than 5 wt%. Fassaitic pyroxene and high-Ca pyroxene occur in chondrules and as irregular inclusions in magnesian olivine fragments. Low-Ca pyroxene occurs in chondrules and as isolated minerals. Low-Ca pyroxene in Y-8449 is compositionally similar than in the other CR chondrites except for Cr_2O_3 content which is slightly higher in Y-8449 pyroxene (Fig. 3). High-Ca pyroxene in Y-8449 contains high chromium content up to 3.5 wt% Cr_2O_3 (Fig. 3).

4.3. *Plagioclase*

Plagioclase occurs in the groundmasses of some chondrules; its composition ranges from An_{28} to An_{99} with negligible Or. Plagioclase compositions are different among chondrules (*e.g.* An_{88-90} in chondrule No. 4, An_{38-80} in chondrule No. 6), and

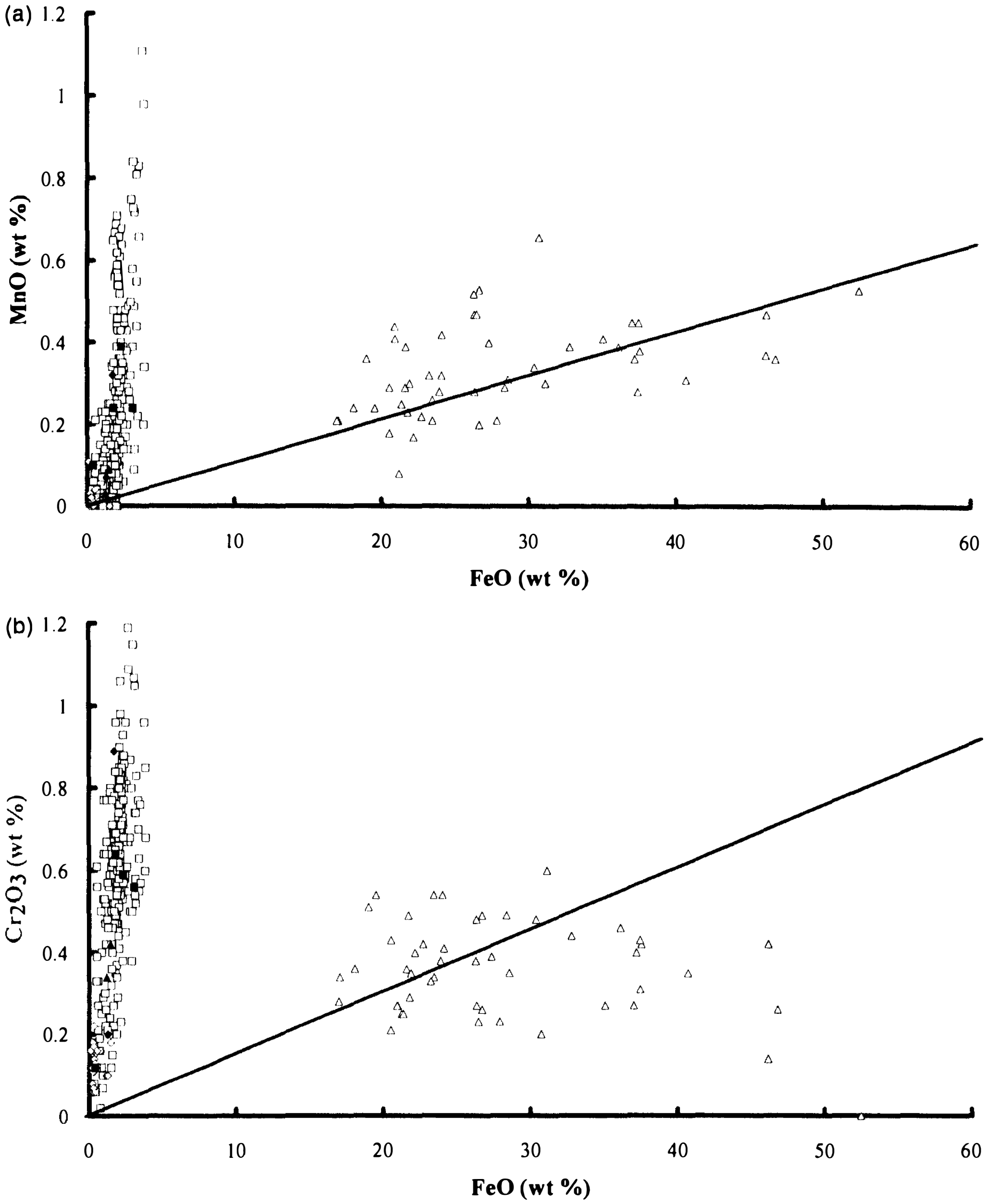


Fig. 2. Chemical compositions of chondrule olivines (open squares), magnesian olivine fragments (open diamonds), and ferroan olivine fragments (open triangles) in Y-8449, chondrule olivines in Renazzo (solid diamonds), Al Rais (solid squares), and Y-790112 (solid triangles) included for reference. The solid line is the weight ratio of MnO/FeO (a) and Cr_2O_3/FeO (b) of the solar system elementary abundances (ANDERS and GREVESSE, 1989). The data of Renazzo, Al Rais, and Y-790112 are quoted from WEISBERG et al. (1993).

does not show distinct chemical zoning.

The sizes of irregular plagioclase inclusions in the magnesian olivine fragments are very small, as shown in Fig. 1d; thus it is difficult to obtain chemical data of this plagioclase by EPMA.

Table 1. Average chemical compositions of isolated olivines (ferroan and magnesian olivine fragments) and chondrule olivines in Y-8449.

	Ferroan olivine	Magnesian olivine	Chondrule olivine
SiO_2	36.77	43.11	42.18
TiO_2	bd	bd	bd
Al_2O_3	0.02	0.33	0.04
Cr_2O_3	0.36	0.13	0.59
FeO	28.08	0.45	2.42
MnO	0.34	0.02	0.25
MgO	32.60	56.30	54.62
CaO	0.16	0.62	0.21
Na_2O	bd	bd	bd
K_2O	bd	bd	bd
Total	98.97	100.53	100.40

bd-below detection (<0.1%).

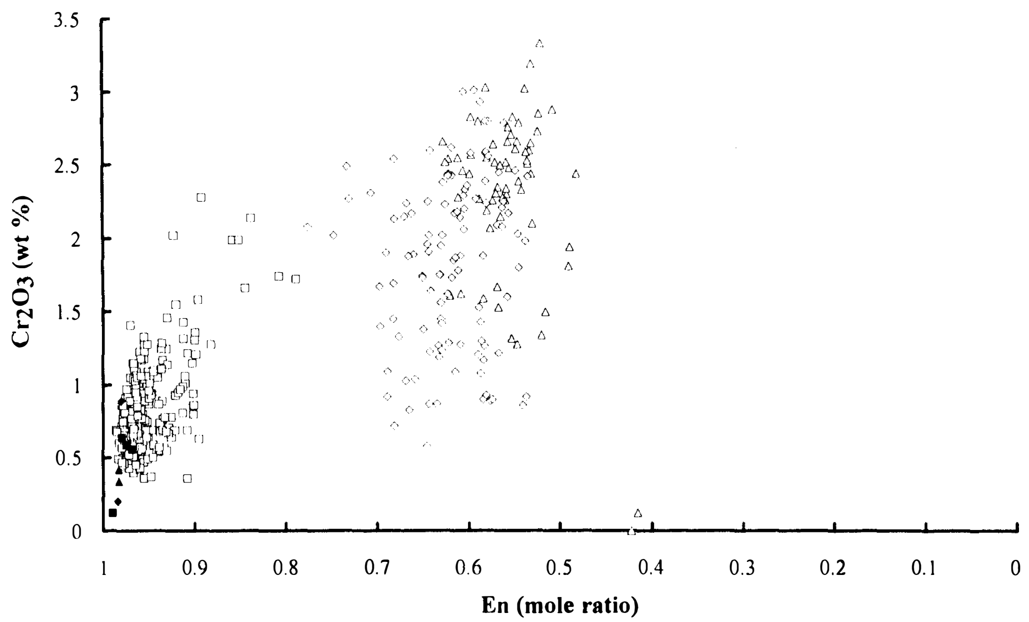


Fig. 3. Chemical compositions of low-Ca pyroxenes (open squares), high-Ca pyroxenes (open diamonds), and fassaitic pyroxenes (open triangles) in Y-8449, with pyroxenes in Renazzo (solid diamonds), Al Rais (solid squares), and Y-790112 (solid triangles) included for reference. The data of Renazzo, Al Rais, and Y-790112 are quoted from Weisberg *et al. (1993).*

4.4. Glass

Glass in chondrules has a wide compositional range, and the normative compositions are enriched in the plagioclase component, ranging from $An_{95}Or_0$ to An_4Or_5. In chondrules where the plagioclase coexists with glass, the normative plagioclase composition of the glass is more sodic than that of the coexisting

Table 2. Representative chemical compositions of pyroxenes in Y-8449.

	Low-Ca pyroxene				High-Ca pyroxene				Fassaitic pyroxene			
SiO_2	57.47	57.22	58.38	58.16	51.92	52.22	51.28	53.30	49.27	49.44	48.73	46.68
TiO_2	bd	bd	0.05	0.05	0.95	0.50	0.52	0.43	1.08	0.96	1.12	0.68
Al_2O_3	0.24	0.46	0.32	0.55	3.80	4.84	4.62	2.56	8.36	7.81	8.47	12.63
Cr_2O_3	0.91	1.09	0.83	0.57	2.80	2.59	2.93	1.79	1.53	1.61	1.59	1.50
FeO	2.26	2.89	1.86	1.68	3.29	2.26	2.71	3.91	0.49	0.58	0.56	1.13
MnO	0.34	0.48	0.27	0.21	1.29	1.18	1.10	1.25	0.09	0.23	0.11	0.21
MgO	38.31	37.20	37.93	38.43	18.80	18.89	19.52	19.91	18.48	21.01	19.59	16.15
CaO	0.40	0.45	0.32	0.33	16.48	17.19	17.02	16.51	19.25	17.47	19.01	20.25
Na_2O	0.01	0.02	0.03	0.03	0.08	0.15	0.17	0.34	0.02	0.02	0.06	0.05
K_2O	bd	bd	bd	bd	bd	bd	bd	bd	bd	bd	bd	bd
Total	100.06	99.82	100.02	100.00	99.43	99.87	99.90	100.09	98.60	99.19	99.33	99.36

bd-below detection (<0.1%).

plagioclase. Groundmass glass in a chondrule (No. 12) is replaced by phyllosilicates in the peripheral portions of the chondrule (Fig. 1j).

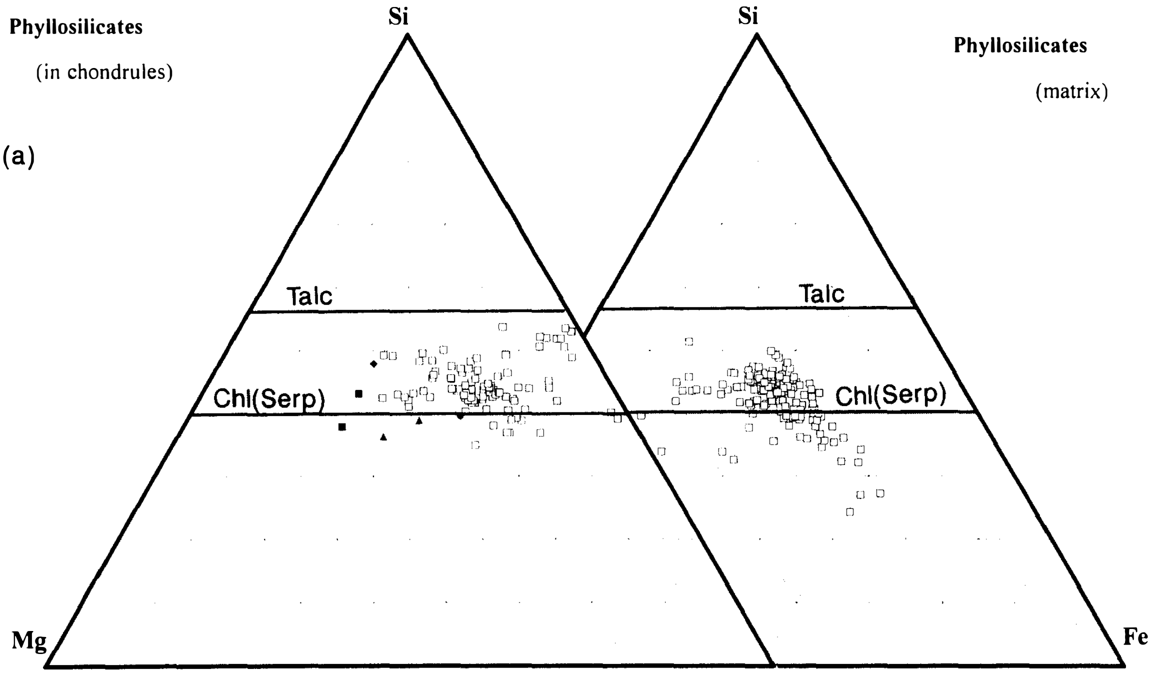
4.5. *Phyllosilicate*

Phyllosilicate occurs in chondrules, as inclusions in magnesian olivine fragments, and in the matrix. The chemical compositions of phyllosilicates in Y-8449 and other CR chondrites are plotted in Fig. 4 between the compositional range of chlorite (or serpentine) and talc (or smectite). FeO and Al_2O_3 contents of chondrule phyllosilicates in Y-8449 are richer than those in Renazzo, Al Rais, and Y-790112 (Fig. 4). Phyllosilicates in Y-8449 chondrules are different in chemical composition from Y-8449 matrix phyllosilicates; MgO contents of matrix phyllosilicates are higher than those of chondrule phyllosilicates, and Al_2O_3 contents of matrix phyllosilicates are lower than those of chondrule phyllosilicates (Fig. 4). Phyllosilicate inclusions in magnesian olivine fragments, plotted near the chlorite line in Fig. 4. SiO_2 content of chondrule phyllosilicate is higher than the phyllosilicate content of inclusions in magnesian olivine fragments. The Na_2O+K_2O contents (wt%) of chondrule and matrix phyllosilicates in Y-8449 are plotted against their Al_2O_3 (wt%) in Fig. 5. Phyllosilicates in Y-8449 contain alkali components ranging up to 2 wt%.

According to Zolensky *et al.* (1993), matrices of two CR chondrites, Renazzo and EET87770, consist mainly of serpentine and saponite. Average chemical compositions (Table 3) of matrix phyllosilicates in Y-8449, Renazzo, and EET87770 are similar in chemical composition, suggesting that the matrix phyllosilicates in Y-8449 are serpentine and saponite. In contrast, the Al_2O_3 contents of chondrule phyllosilicates in Y-8449 are higher (Fig. 4, Table 3), suggesting that they are chlorite.

4.6. *Chromite and silica phase*

Chromite occurs in one ferroan olivine fragment and is about 7 micrometers across. Its chemical composition is 0.67–1.01 wt% TiO_2, 5.40–6.35 wt% Al_2O_3, 57.13–57.54 wt% Cr_2O_3, 0.23–0.41 wt% MnO, 24.83–25.37 wt% FeO, and 6.62–6.79 wt% MgO.



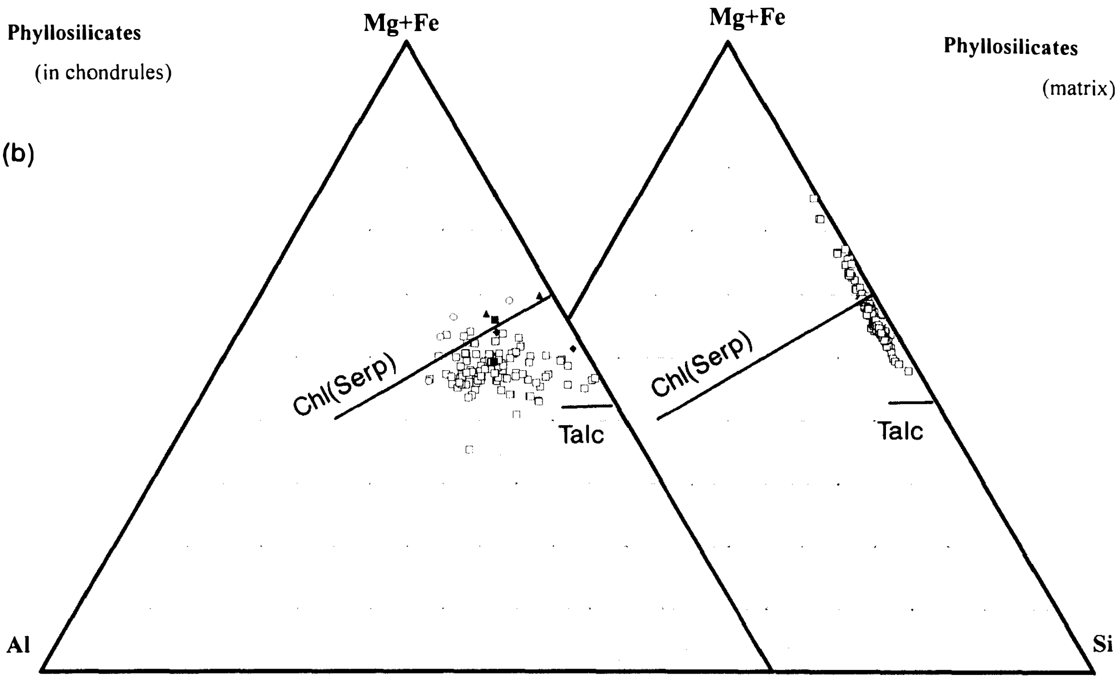


Fig. 4. Atomic plot of Si-Mg-Fe ratios (a) and (Mg+Fe)-Al-Si ratios (b) of Y-8449 phyllosilicates in chondrules and the matrix (open squares) and in magnesian olivine fragments (open circles) with those in Renazzo (solid diamonds), Al Rais (solid squares), and Y-790112 (solid triangles) included for reference. Chl (Serp) is chlorite or serpentine. The data of Renazzo, Al Rais, and Y-790112 are quoted from WEISBERG *et al. (1993).*

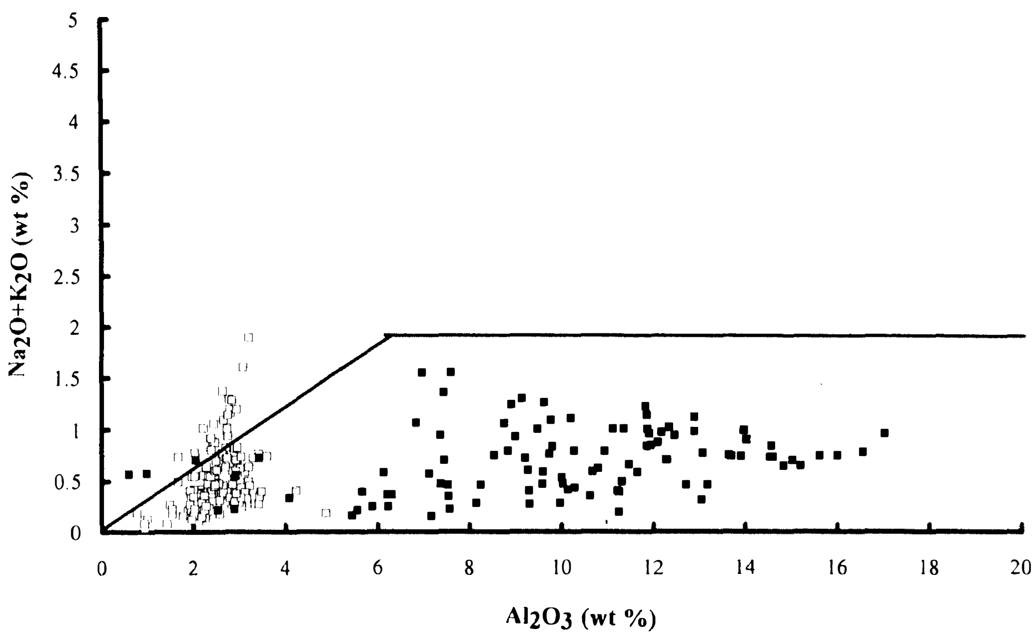


Fig. 5. Chemical composition of Y-8449 phyllosilicates in chondrules (solid squares) and matrices (open squares). Solid lines show chemical compositions of phyllosilicates in Belgica-7904 chondrules (IKEDA and PRINZ, 1993).

Table 3. Average chemical compositions of phyllosilicates in Y-8449, Renazzo, and EET87770.

	Y-8449** (chondrule)	Y-8449** (M.O.F)	Y-8449** (matrix)	Renazzo*	EET87770*
SiO_2	32.00	29.60	32.48	34.62	30.73
TiO_2	0.18	0.23	0.02	0.06	0.08
Al_2O_3	9.90	13.45	2.54	3.07	2.02
Cr_2O_3	0.16	0.18	0.32	0.31	0.44
FeO	32.55	24.4	31.25	27.47	33.10
NiO	0.11	0.12	1.61	2.14	1.78
MnO	0.23	0.12	0.18	0.23	0.26
MgO	8.37	21.73	13.87	16.63	17.36
CaO	0.58	1.13	0.47	0.06	0.08
Na_2O	0.44	0.24	0.41	0.78	0.54
K_2O	0.25	0.08	0.10	0.10	0.10
P_2O_5	0.12	0.23	0.10	0.07	0.43
SO_3	0.06	0.29	3.38	2.43	3.29
Total	85.35	91.81	86.81	88.50	91.09

*ZOLENSKY *et al.* (1993). **this work, M.O.F. is magnesian olivine fragments.

A silica-rich phase occurs only in the groundmass at the center of only one chondrule (No. 11) (Fig. 1e). This chondrule shows a porphyritic pyroxene texture with a mineral assemblage of pyroxene, plagioclase, phyllosilicate, and a silica-rich phase. The chemical composition of the silica-rich phase is 97.0–98.9 wt% SiO_2, 0.77–0.89 wt% Al_2O_3, and 0.26–0.55 wt% CaO.

4.7. *Carbonate*

Carbonate occurs only in the center of one chondrule (No. 16) which has a porphyritic olivine-pyroxene texture. The chemical composition of the carbonate is 51.5 wt% CaO, and 1.24 wt% FeO. The MnO content is lower than the detection limit of about 0.1 wt%. This carbonate may be calcite ($CaCO_3$). WEISBERG *et al.* (1993) reported that Ca-carbonate occurs as submicrometer-size particles throughout the matrix and dark inclusions and rims in some CR chondrites, although such Ca-carbonate was not observed in the Y-8449 matrix.

4.8. *Fe-Ni metal*

Fe-Ni metal occurs as individual grains within chondrules, in magnesian olivine fragments with irregular inclusions, and in the Y-8449 matrix. Rarely, the magnesian olivine in chondrules contains small metal inclusions, and the ferroan olivine fragments do not contain Fe-Ni metal. Fe-Ni metal is classified into two types; one type has an exsolution texture (Fig. 1f), and the other type has a massive texture (Fig. 1g). The massive Fe-Ni metal in Y-8449 occurs in chondrule interiors (Fig. 1h), chondrule rims (Fig. 1i), and in the Y-8449 matrix. But the metal with exsolution texture occurs only in chondrule interiors, and the exsolved taenite lamellae are about 4 micrometers in width. The Co contents (wt%) of the metal are plotted against their

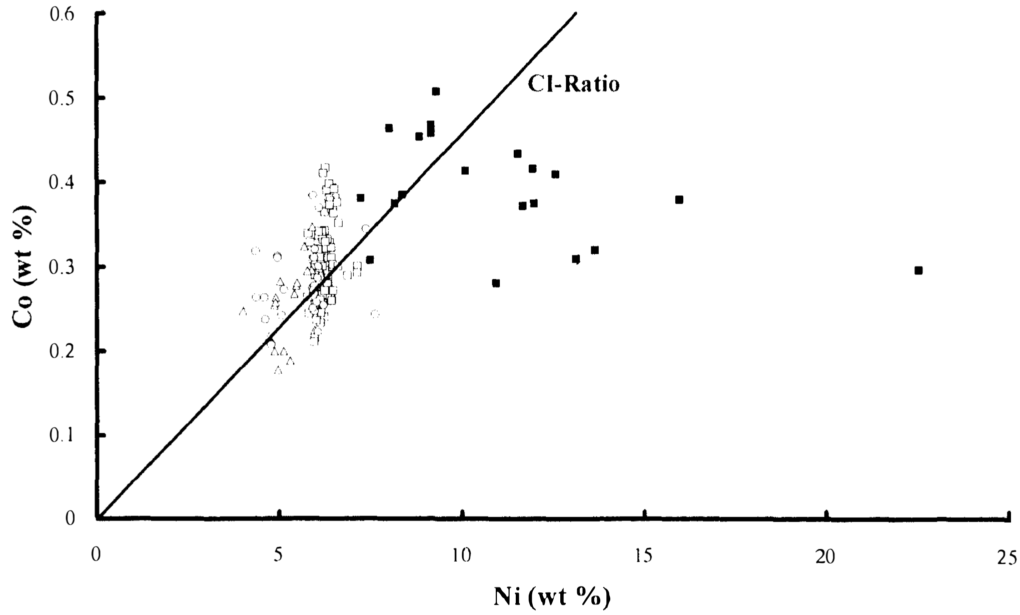


Fig. 6. Co-Ni plot for metal occurring in chondrule interiors (open squares), chondrule rims (open triangles), the matrix (open circles), and metal with exsolution lamella (solid squares). The solid line is the CI ratio (ANDERS and GREVESS, 1989).

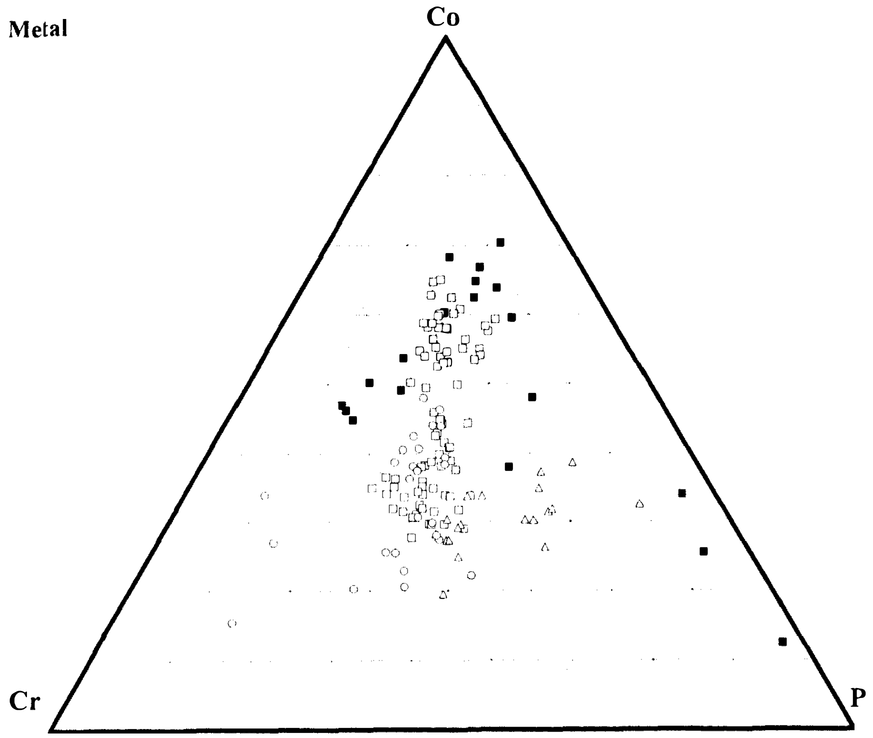


Fig. 7. Atomic plot of Co-Cr-P for metal occurring in chondrule interiors (open squares), chondrule rims (open triangles), the matrix (open circles), and metal with exsolution lamella (solid squares).

Table 4. Average compositions and compositional ranges (wt. %) of Fe-Ni metal in Y-8449.

	Metal with exsolution lamella	Metal in chondrule interior	Metal in chondrule rim	Metal in matrix
Fe	87.7(77.875–91.573)	91.6(88.787–93.268)	92.2(91.351–93.229)	91.5(88.982–93.898)
Ni	11.08(7.227–22.544)	6.25(5.757–7.126)	5.26(3.955–5.943)	5.62(4.33–7.62)
Co	0.39(0.281–0.508)	0.31(0.211–0.417)	0.26(0.178–0.347)	0.28(0.208–0.384)
Cr	0.15(0.054–0.336)	0.22(0.069–0.426)	0.25(0.074–0.396)	0.37(0.205–1.327)
P	0.32(0.091–1.938)	0.19(0.082–0.287)	0.35(0.293–0.437)	0.24(0.103–0.389)

Ni (wt%) in Fig. 6, and the Co and Ni contents of the host and their lamellae may be contaminated from each other. The Co/Ni ratio of the massive metals in Y-8449 is nearly the same as that of the CI chondrites as shown in Fig. 6. The massive metal in Y-8449 is more homogeneous than that of the other CR chondrites; the Ni content of metal in Y-8449 ranges from 4 to 8 wt%, whereas the Ni content of metal in Renazzo, Al Rais, Y-790112, El Djouf001, EET87770, and MAC87320 ranges 4 to 14 wt% (WEISBERG *et al.*, 1993). Atomic ratios of Co-Cr-P for Y-8449 metal are shown in Fig. 7, where the metal in different textural settings is plotted in different compositional ranges. Metal in chondrule interiors has the highest Co content, metal in chondrule rims has the highest P content, and metal in the matrix has the highest Cr content (Table 4).

5. Discussion

5.1. Cooling rate of metal with exsolution lamella

In Y-8449, metal in chondrule interiors has an exsolution texture (Fig. 1f), and consists of kamacite and taenite. The other CR chondrites do not have metal with exsolution lamellae, although the Ni content of the other CR chondrite metal is higher than that of Y-8449. Therefore, the cooling rate of Y-8449 metal may have been slower than that of metal in the other CR chondrites.

Fe-Ni metal in chondrule rims is compositionally different from that in the chondrule cores for some CR chondrites (Weisberg *et al.*, 1993). Lee *et al.* (1992) reported that metal in chondrule interiors has a positive Ni-Co trend and suggested that the Ni-Co trend may be the result of reduction in the nebula. Zanda *et al.* (1993) also implied that the trend is due to reduction. On the other hand, Weisberg *et al.* (1988) suggested that the Ni-Co trend of metal in ALH85085 and in the CR chondrites can be explained by condensation from a nebular gas. As shown in Fig. 8, metal in the Y-8449 overlaps with the condensation trend calculated from data obtained by Grossman and Olsen (1974), supporting the idea of Weisberg *et al.* (1988) that metal was produced by condensation from a nebular gas.

5.2. Hydrous alteration reaction

Phyllosilicates in Y-8449 occur in chondrules, as irregular inclusions in magnesian olivine fragments, and in the Y-8449 matrix. Groundmass glass and

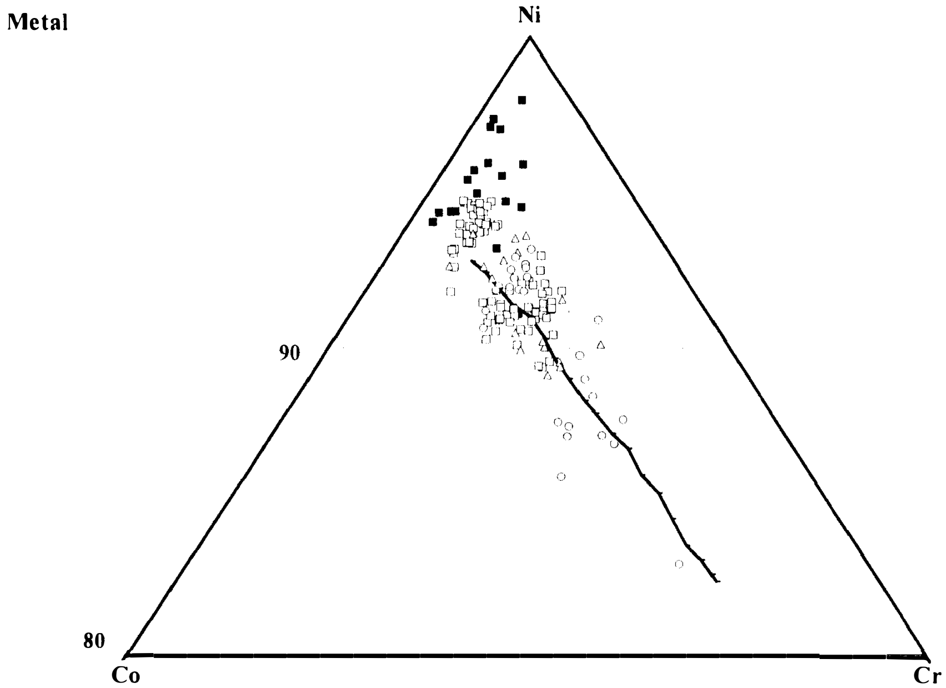


Fig. 8. Atomic plot of Ni-Co-Cr for Y-8449 metal that occurs in chondrule interiors, chondrule rims, and the matrix. Symbols are the same as those in Fig. 7. The solid line is a condensation trend of a canonical nebular gas at temperatures ranging from 1470 K to 1380 K with a total pressure of 10^{-4} atoms (Grossman and Olsen, 1974).

enstatite phenocrysts in some chondrules (*e.g.* No. 12) are replaced by phyllosilicates in the chondrule rim, but high-Ca pyroxene remains unaltered (Fig. 1j). The precursor of these phyllosilicates must have been both the groundmass glass and the enstatite phenocrysts. Si-Mg-Fe and (Mg+Fe)-Al-Si atomic ratios of the groundmass glass and the phyllosilicates in chondrule No.12 are shown in Fig. 9, and the average chemical composition of the groundmass glass in chondrule No. 12 is tabulated in Table 5. We calculated the normative composition of the groundmass glass, and the hydrous alteration reaction that produced the phyllosilicates in chondrule No.12 may have been as follows:

$$\underbrace{[12NaAlSi_3O_8+4CaAl_2Si_2O_8+19SiO_2+2MgSiO_3+CaSiO_3]}_{\text{Glass}}+\underbrace{41MgSiO_3}_{\text{Enstatite}}$$
$$+64.6FeO+59.2H_2O+5CO_2$$
$$\rightarrow \underbrace{5(Mg_4Fe_6)Al_2Si_6Al_2O_{20}(OH)_{16}}_{\text{Chlorite (Serpentine)}}+\underbrace{9.6(Mg_{2.4}Fe_{3.6})Si_8O_{20}(OH)_4}_{\text{Talc (Smectites)}}$$
$$+\underbrace{5CaCO_3}_{\text{Calcite}}+6Na_2O, \qquad (1)$$

where the components in parentheses on the left-hand side of eq. (1) are normative components of the glass and enstatite refers to the enstatite phenocrysts in chondrule No. 12. FeO, H_2O, and CO_2 in the reactants were introduced into the chondrule to produce the phyllosilicates, and alkali components in the products were lost from the chondrule. Modal compositions of the enstatite phenocrysts and the glassy groundmass in the unaltered portion of chondrule No. 12 are 70% and 30%, respectively. Those of relic enstatite and phyllosilicate in the altered portion of the chondrule are 43.4% and 56.6%, respectively. Therefore, the glass in the chondrule (30%) reacted with enstatite (70% minus 43.4%) to produce the phyllosilicate in the altered portion of chondrule No. 12, indicating that the volume ratio of glass/enstatite was 30/26.6 for the hydration. On the other hand, the volume ratio of glass and enstatite on the left hand side of eq. (1) is estimated roughly by the numbers of oxygens; the total number of oxygens in glass is 175, that in enstatite is 123, and the ratio of oxygens is 175/123. This is similar to the volume ratio of glass/enstatite obtained above.

The problem is whether the hydrous alteration took place in a nebula or in the parent body. Evidence for alteration on the parent body, such as colloform texture or veins of carbonate and phyllosilicate, was not observed in Y-8449. The boundary between chondrule phyllosilicates and matrix phyllosilicates is sharp, as shown in Fig. 1j, and chondrule phyllosilicates are different in chemical composition from Y-8449 matrix phyllosilicates, as shown in Fig. 4, suggesting that chondrule phyllosilicates were produced in a nebula prior to accretion onto the parent body. In Y-8449, the hydrous alteration reaction produced chlorite (or serpentine) and calcite, chondrule olivine remains unaltered, part of the chondrule pyroxene was altered, and magnetite was not observed in Y-8449. These observations are consistent with the conclusion of IKEDA and PRINZ (1993) that chondrule phyllosilicate in CM chondrites was produced by hydrous alteration reactions with a nebular gas at low temperatures ranging from 500 K to 300 K.

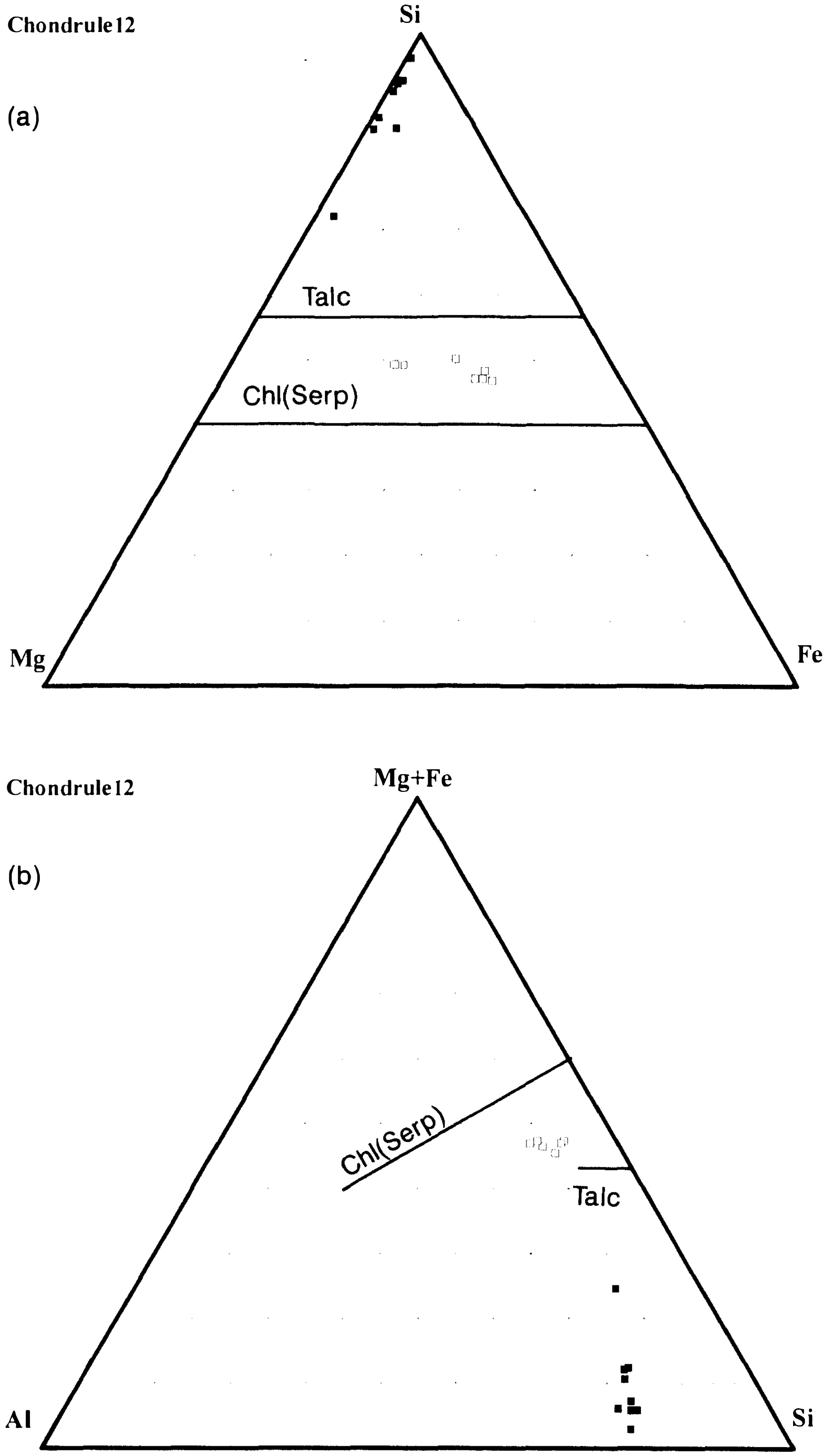


Fig. 9. Atomic plot of Si-Mg-Fe ratios (a) and (Mg+Fe)-Al-Si ratios (b) of phyllosilicates (open squares) and groundmass glass (solid squares) in chondrule No. 12. Chl (Serp) is chlorite or serpentine.

Table 5. Average chemical compositions and compositional ranges of groundmass glass, phyllosilicate, and phenocrystic enstatite in chondrule No. 12

	Groundmass glass	Phyllosilicate	Phenocrystic enstatite
SiO_2	68.57(63.16–72.33)	37.54(34.18–42.13)	57.98(56.6–58.71)
TiO_2	0.28(0.21–0.35)	0.25(0.15–0.44)	0.01(0.00–0.05)
Al_2O_3	17.69(15.54–21.31)	6.86(5.45–8.16)	0.40(0.22–0.67)
Cr_2O_3	0.00(0.00–0.01)	0.20(0.06–0.48)	0.91(0.80–1.09)
FeO	0.45(0.02–0.82)	27.98(22.38–31.40)	2.57(1.86–3.59)
MnO	0.13(0.00–0.21)	0.38(0.28–0.56)	0.46(0.27–0.68)
MgO	1.01(0.03–1.72)	11.24(8.39–16.56)	37.19(36.84–38.31)
CaO	4.84(1.81–7.68)	0.58(0.20–1.92)	0.42(0.32–0.49)
Na_2O	6.41(4.88–7.25)	0.12(0.09–0.14)	0.02(0.00–0.04)
K_2O	0.10(0.08–0.18)	0.12(0.10–0.26)	0.01(0.00–0.04)
Total	99.51	85.79	100.27

6. Conclusions

(1) Massive Fe-Ni metal in Y-8449 is more homogeneous than that in the other CR chondrites, and it may have been produced by condensation from a nebular gas. Chondrule interior metal shows exsolution lamellae, indicating a slow cooling rate for this metal.

(2) The boundary between chondrule phyllosilicates and matrix phyllosilicates is very sharp in Y-8449, and they are different in chemical composition from each other, suggesting that the hydrous alteration which produced chondrule phyllosilicates probably took place in the nebula.

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