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COMPARATIVE STUDY OF ANHYDROUS ALTERATION OF CHONDRULES IN REDUCED AND OXIDIZED CV CHONDRITES

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Abstract: Chondrules in three CV chondrites of the reduced subgroup (Leoville, Efremovka and Vigarano) were studied to explore the effect of anhydrous alteration, in comparison to those in Allende of the oxidized subgroup. The alteration consists of secondary olivine zonation, replacement of low-Ca pyroxene by ferroan olivine, and replacement of primary groundmass by nepheline and sodalite. The highest degree of alteration occurs in chondrules of Allende. Leoville chondrules show only olivine zonation and seem not to have experienced replacement of pyroxene and groundmass. Some chondrules in Efremovka have replacement textures of groundmass and show olivine zonation. On the other hand, many chondrules in Vigarano were subjected to all types of alteration. Thus, chondrules even in reduced CV chondrites do not completely preserve their primary features, although the degree of alteration for the reduced CVs varies, and is lower on the whole than that of Allende. The differences between CV chondrites of the oxidized and reduced subgroups appear to be determined by the degree of secondary alteration and oxidation of Fe. The alterations took place prior to the final consolidation with the matrix on the CV parent body.

1. Introduction

Most chondrules in the Allende CV chondrite were subjected to anhydrous alteration (IKEDA and KIMURA, 1995; KIMURA and IKEDA, 1995). Three different processes have been described: secondary olivine zonation, replacement of low-Ca pyroxene phenocrysts by ferroan olivine, and replacement of primary groundmass (glassy material and plagioclase) by nepheline and sodalite (called alkali-Ca exchange reaction). Some Ca-rich phases including hedenbergite, grossular, andradite, kirschsteinite and wollastonite, formed during the alkali-Ca reaction. IKEDA and KIMURA (1996) suggested that the alteration temperatures and duration were about 600–400°C and 10–10^4 years, respectively.

CV chondrites are divided into two subgroups, oxidized and reduced (MCSWEEN, 1977). In addition to Allende, anhydrous alteration commonly took place in chondrules of the other oxidized CVs, such as Y-86751 (MURAKAMI and IKEDA, 1994) and a CV-like chondrite, Ningqiang (KIMURA *et al.*, 1997; WEISBERG *et al.*, 1996). On the other hand, chondrules in reduced CVs have been considered to preserve almost their primordial features (*e.g.*, KROT *et al.*, 1995).

In this paper, we studied CV chondrites of reduced subgroup, and compared them

with Allende. The purposes of this study are (1) to explore whether alteration took place in chondrules in reduced CVs, and (2) to compare the alteration degrees between both subgroups.

2. Samples and Analytical Methods

We studied a polished thin section of each of three reduced CV chondrites: Leoville, Efremovka and Vigarano. Phase compositions were determined with a JEOL 733 electron-probe microanalyzer (EPMA); the accelerating voltage and beam current were 15 kV and 3 to 10 nA, respectively. Bulk compositions of plagioclase with nepheline lamellae were determined using a defocused beam of EPMA with 10 μm diameter. Bence-Albee correction methods was used for the analyses of silicates and oxides.

3. Petrography of Chondrules

3.1. Leoville

Chondrules in Leoville are mostly broken to show irregular outlines, consistent with the high shock degree (S3) of Leoville (SCOTT *et al.*, 1992). Nevertheless, most chondrules seem to preserve their primordial texture and mineralogy. Seven chondrules, 0.7–1.9 mm in size, were selected for detailed study. These include 6 olivine-pyroxene porphyritic chondrules and one barred-olivine chondrule.

Phenocrystic phases are usually olivine and low-Ca pyroxene (defined as $Wo_{15>}$), often with high-Ca pyroxene and plagioclase. Some chondrules contain cryptocrystalline or plagioclase groundmasses, which are, hereafter, designated primary groundmasses, like those in Allende (KIMURA and IKEDA, 1995). We noticed neither replacement texture of low-Ca pyroxene by ferroan olivine, nor replacement of primary groundmass in Leoville chondrules.

Plagioclases in phenocrysts and groundmasses in a few chondrules contain lamellae of nepheline, less than 3 μm in width (Fig. 1a). Some chondrules also include blebs of a silica phase, less than 2–3 μm in size, mixed with plagioclase in groundmass. Nepheline and silica occur in almost every part of the groundmass in these chondrules.

The opaque minerals, kamacite, taenite and troilite, commonly occur in these chondrules. Magnetite has not been observed. This is a characteristic feature of reduced CVs (MCSWEEN, 1977).

3.2. Efremovka

Although Efremovka has also been subjected to shock metamorphism (shock stage S4 after SCOTT *et al.*, 1992), chondrules preserve their primordial textures. Thirteen chondrules, 0.3–3 mm in size, were selected from a thin section. Except for one barred-olivine, they are olivine-pyroxene porphyritic chondrules. Most of these chondrules consist of olivine and low-Ca pyroxene phenocrysts often with high-Ca pyroxene set in cryptocrystalline to holocrystalline groundmasses. Fine-grained Ca-phosphate occurs in one chondrules. One ferroan chondrule contains chromite.

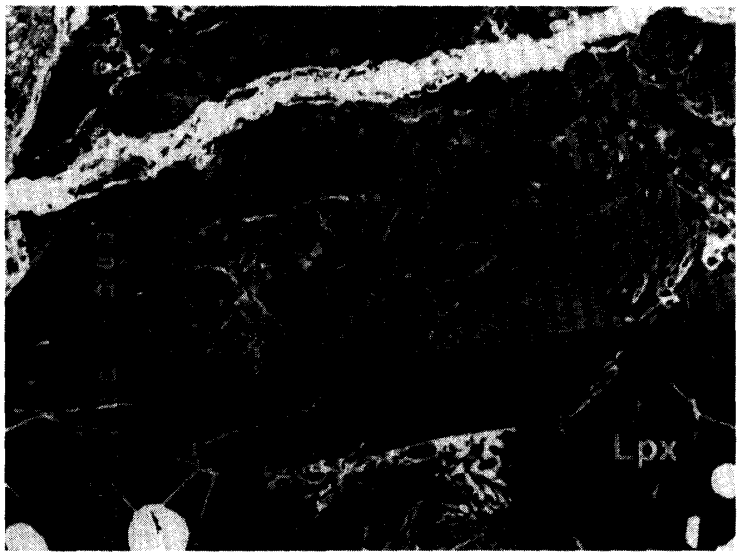

Fig. 1a. Back-scattered electron (BSE) image of a chondrule in Leoville, mainly consisting of low-Ca pyroxene (Lpx), plagioclase (Pla) and high-Ca pyroxene (Hpx). Note that nepheline (Nep) lamellae and blebs of silica phase (Sil) occur in association with plagioclase. Width of 120 microns.

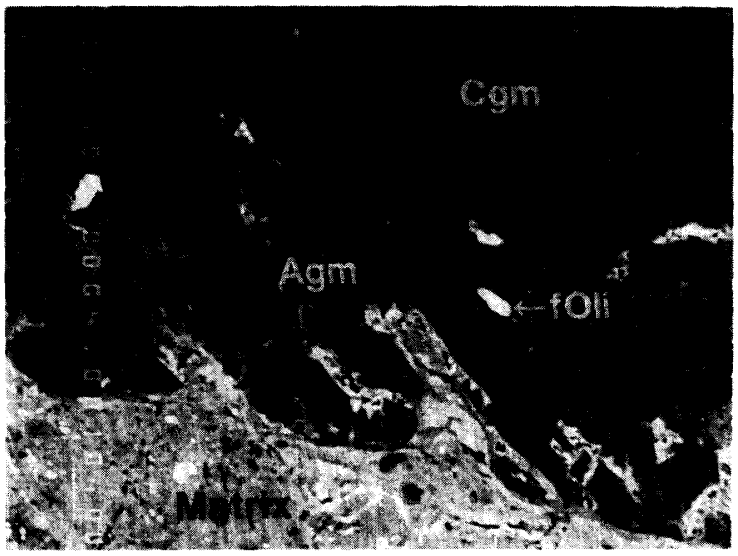

Fig. 1b. BSE image of a chondrule in Efremovka. Primary cryptocrystalline groundmass (Cgm) is partly replaced by altered groundmass (Agm) in the peripheral part of the chondrule. Fine-grained ferroan olivine (fOli) occurs in the groundmass. Width of 120 microns.

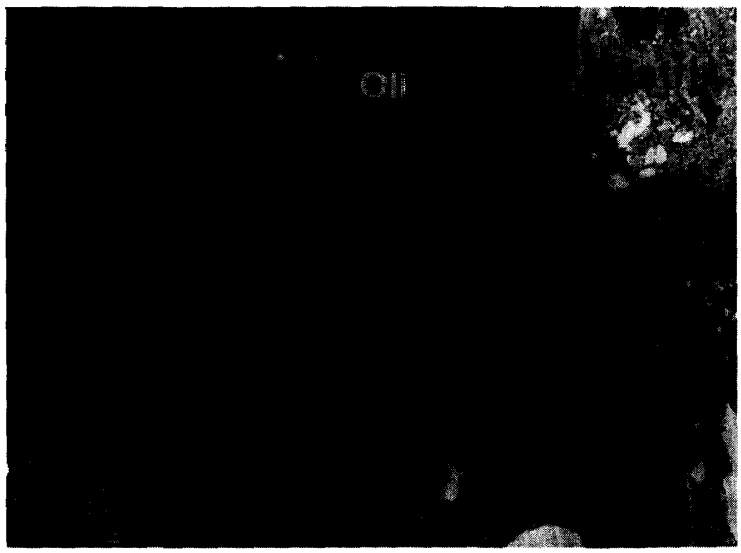

Fig. 1c. BSE image of a chondrule in Vigarano. Phenocrysts of olivine (Oli) and low-Ca pyroxene (Lpx), and groundmass plagioclase (Pla) escaped from alteration reactions, even along the boundary between chondrule and the matrix. Width of 190 microns.

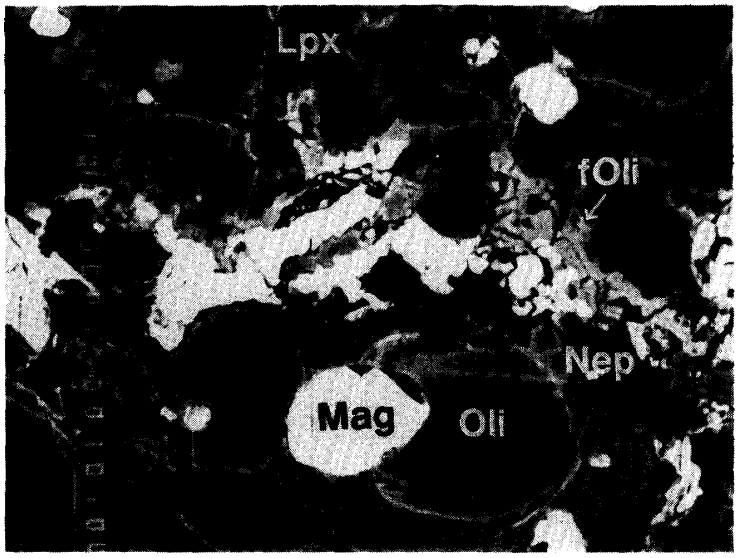

Fig. 1d. BSE image of an altered chondrule in Vigarano. Olivine phenocrysts (Oli) show distinct zoning. A Low-Ca pyroxene phenocryst (Lpx) is replaced by ferroan olivine (fOli) in the marginal parts. Plagioclase groundmass is also replaced by nepheline (Nep). Magnetite spherules (Mag) occur in this chondrule. Width of 120 microns.

Nine of the chondrules do not show any alteration textures. However, groundmasses in four chondrules are partly dark brown to black in color under an optical microscope, especially in the peripheral parts, where primary groundmass is replaced by fine-grained aggregates enriched in a nepheline component rarely with sodalite (Fig. 1b). KIMURA and IKEDA (1995) described this as "altered groundmass" in Allende chondrules. One of these chondrules includes fine-grained hedenbergite, 3–4 μm in size, associated with nepheline and plagioclase in the groundmass. The altered groundmass often contains fine-grained ferroan olivines, 2–10 μm in size, like those in Allende chondrules. No replacement textures of low-Ca pyroxene are observed in Efremovka chondrules. Nepheline lamellae within plagioclase, like those in Leoville, are observed in three Efremovka chondrules. Two of them are altered chondrules, although nepheline lamellae do not occur in close association with altered groundmass.

Opaque minerals in Efremovka chondrules include kamacite, taenite and troilite.

3.3. Vigarano

Vigarano is well known as a breccia (shock stage S1-2), but our thin section does not show any brecciated structure. We studied 9 chondrules in detail, 0.7–2 mm in size. Except for one barred-olivine, they are olivine-pyroxene porphyritic chondrules. They consist of olivine and low-Ca pyroxene phenocrysts, often with high-Ca pyroxene, set in cryptocrystalline to holocrystalline groundmasses. Fine-grained Ca-phosphate and spinel occur in one chondrule.

Two chondrules do not show any reaction textures. One of them is broken, and the primary plagioclase groundmass is in direct contact with the chondrite matrix (Fig. 1c). The other chondrules show various degrees of replacement of low-Ca pyroxene and primary groundmass (Fig. 1d), and resemble those in Allende. In these chondrules, olivine phenocrysts show distinct zoning under back-scattered electron images. The altered groundmass is more extensive in Vigarano than in Efremovka, but less than in Allende, as discussed later. The altered groundmasses are aggregates of fine-grained crystals of submicron to 10 μm in size. Groundmass in one chondrule is an aggregate

of fine-grained nepheline, sodalite and ferroan olivines without any primary groundmass, similar to the assemblage that is often encountered in Allende chondrules. One chondrule contains hedenbergite, 3 μm in size, associated with nepheline, sodalite and plagioclase. Fine-grained ferroan olivines also occur in the altered groundmass. Nepheline lamellae, less than 6 μm in width, occur within plagioclase groundmasses in two altered chondrules.

In addition to kamacite, taenite and troilite, chondrules in Vigarano usually contain magnetite.

4. Mineralogy of Chondrules

4.1. Olivine

Table 1 gives representative compositions of silicate and oxide phases. Three types of olivine occurrence were noticed in chondrules: phenocrysts, small grains set in altered groundmass, and fine-grained crystals replacing low-Ca pyroxene. In Leoville, only the first type is encountered. In Efremovka, the third type is not observed. All of these types occur in Vigarano. Olivine phenocrysts in these three reduced CVs usually show normal zoning. However, compositional ranges of the zoning are different between the three meteorites (Fig. 2); the ranges of Leoville (Fo_{82-100}) and Efremovka (Fo_{80-100}) are narrower than those of Vigarano (Fo_{62-100}) and Allende (Fo_{65-100}). Chondrules in Vigarano which contain abundant altered groundmass, have distinctly zoned phenocrysts (*e.g.*, Fo_{62-100}), whereas olivines in Vigarano chondrules free from altered groundmass do not show distinct zoning (*e.g.*, Fo_{93-100}). In the CVs studied here, some phenocrystic olivines in chondrules and some isolated olivines set in chondrite matrices hardly show zoning toward the matrices, ranging from Fo_{99-100} to Fo_{98-99}. One chondrule in Efremovka includes ferroan olivine phenocrysts (Fo_{46-71}).

Fine-grained olivines in altered groundmass in an Efremovka chondrule are extremely enriched in FeO (Fo_{15-33}). Fine-grained olivines in altered groundmass in Vigarano chondrules have a similar compositional range (Fo_{53-69}) to those in Allende (Fo_{49-70}). Olivines replacing low-Ca pyroxenes in Vigarano are enriched in FeO (Fo_{45-65}) overlapping the range of compositions in Allende (Fo_{54-75}) (IKEDA and KIMURA, 1995).

4.2. Pyroxene

Low- and high-Ca pyroxenes in all three reduced CVs are very similar in composition (Fig. 3), respectively; low-Ca pyroxenes ($En_{81-99}Fs_{0.5-6}Wo_{0.5-14}$) occur as phenocrysts, whereas high-Ca pyroxenes ($En_{50-82}Fs_{0-9}Wo_{16-48}$) occur as phenocrysts and as elongated laths in primary and altered groundmasses. The compositions of these pyroxenes resemble those in Allende ($En_{85-99}Fs_{0-7}Wo_{0.5-14}$ and $En_{44-84}Fs_{0-7}Wo_{15-55}$), respectively. Hedenbergite ($En_{9-12}Fs_{42}Wo_{46-49}$) which occurs as small grains only in altered groundmasses in Efremovka and Vigarano, is similar in composition to hedenbergites in Allende (KIMURA and IKEDA, 1995).

Table 1. Representative compositions of phases in chondrules (wt%).

Phase	Chondrite	Occurrence	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	NiO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	Cl	Total	Fo	Wo/An	En/Ab	Fs/Or
Olivine	Leoville	Phenocryst core	43.38	0.00	0.05	0.15	0.58	0.00	0.00	55.71	0.40	0.00	0.00	0.00	0.00	0.00	100.27	99.4			
Olivine	Leoville	Phenocryst rim	40.72	0.00	0.00	0.18	6.17	0.04	0.28	52.05	0.20	0.00	0.00	0.00	0.00	0.01	99.65	93.8			
Olivine	Efremovka	Phenocryst core	42.54	0.14	0.00	0.24	0.46	0.00	0.00	55.48	0.51	0.00	0.00	0.00	0.00	0.00	99.37	99.5			
Olivine	Efremovka	Phenocryst rim	40.86	b.d.	b.d.	0.29	10.98	0.09	0.16	47.37	0.24	0.09	b.d.	b.d.	b.d.	b.d.	100.13	88.5			
Olivine	Efremovka	Phenocryst core	34.34	b.d.	0.13	0.13	41.75	b.d.	0.45	22.22	0.08	0.40	b.d.	0.10	b.d.	b.d.	99.67	48.7			
Olivine	Efremovka	Fine-grain in groundmass	31.33	0.23	0.66	b.d.	55.19	b.d.	0.42	9.74	0.46	0.27	b.d.	b.d.	b.d.	b.d.	98.49	23.9			
Olivine	Vigarano	Phenocryst core	42.16	b.d.	b.d.	0.63	0.85	b.d.	b.d.	55.88	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	99.63	99.1			
Olivine	Vigarano	Phenocryst rim	36.00	b.d.	b.d.	0.17	32.90	0.11	0.21	30.34	0.10	0.05	b.d.	b.d.	b.d.	b.d.	99.89	62.2			
Olivine	Vigarano	Replacing low-Ca pyroxene	35.78	b.d.	0.33	0.34	32.80	b.d.	b.d.	29.84	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	99.24	61.9			
Olivine	Vigarano	Fine-grain in groundmass	35.26	b.d.	0.07	0.13	36.12	b.d.	0.10	26.72	0.28	b.d.	b.d.	b.d.	b.d.	b.d.	98.74	56.9			
Lpx	Leoville	Phenocryst	58.86	0.11	1.27	0.46	0.92	b.d.	b.d.	37.56	0.38	b.d.	b.d.	b.d.	b.d.	b.d.	99.62		0.7	97.9	1.4
Lpx	Efremovka	Phenocryst	59.19	0.07	0.69	0.75	0.50	b.d.	0.19	38.08	0.43	b.d.	b.d.	b.d.	b.d.	b.d.	99.97		0.8	98.5	0.7
Lpx	Vigarano	Phenocryst	58.06	0.12	0.76	0.59	0.66	b.d.	b.d.	36.39	2.90	b.d.	b.d.	b.d.	b.d.	b.d.	99.55		5.4	93.7	1.0
Hpx	Leoville	Lath in groundmass	52.20	0.97	2.48	2.78	2.08	b.d.	2.76	21.67	14.10	b.d.	b.d.	b.d.	b.d.	b.d.	99.21		30.8	65.7	3.5
Hpx	Efremovka	Phenocryst	50.16	1.03	6.92	1.62	0.68	b.d.	0.40	18.51	19.91	0.31	b.d.	0.05	b.d.	b.d.	99.68		43.1	55.8	1.1
Hpx	Vigarano	Phenocryst	54.83	0.58	1.82	0.30	0.33	0.11	b.d.	24.40	16.64	0.06	b.d.	b.d.	b.d.	b.d.	99.11		32.7	66.8	0.5
Hpx	Vigarano	Fine-grain in groundmass	45.99	0.57	1.68	0.30	22.79	b.d.	b.d.	2.85	20.56	b.d.	b.d.	b.d.	b.d.	b.d.	94.82		48.6	9.4	42.0
Pla	Leoville	Anhedral grain in groundmass	45.02	b.d.	34.32	b.d.	0.66	0.11	b.d.	0.08	17.68	0.81	b.d.	b.d.	b.d.	b.d.	98.68		92.4	7.6	0.0
Pla	Efremovka	Anhedral grain in groundmass	45.34	b.d.	33.88	b.d.	0.53	0.11	b.d.	0.24	17.84	1.35	b.d.	b.d.	b.d.	b.d.	99.43		87.9	12.0	0.1
Pla	Vigarano	Anhedral grain in groundmass	42.91	b.d.	35.32	b.d.	0.15	b.d.	b.d.	0.39	19.66	0.54	b.d.	0.09	b.d.	b.d.	99.09		95.3	4.7	0.0
Nep	Efremovka	Fine-grain in groundmass	45.12	b.d.	34.61	0.11	0.63	b.d.	b.d.	0.63	1.60	16.98	0.19	0.15	b.d.	b.d.	100.12				
Nep	Vigarano	Fine-grain in groundmass	43.67	0.05	33.34	b.d.	0.67	b.d.	b.d.	0.08	0.67	18.99	1.64	b.d.	b.d.	b.d.	99.14				
Nep	Vigarano	Lamella in plagioclase	42.04	b.d.	34.78	0.11	0.45	0.15	0.09	0.20	b.d.	21.66	b.d.	0.23	b.d.	b.d.	99.72				
Sodalite	Vigarano	Fine-grain in groundmass	38.80	b.d.	30.24	0.17	0.73	b.d.	b.d.	0.30	1.24	21.20	0.05	b.d.	b.d.	6.20	97.84				
Cry gm	Leoville	Groundmass	50.06	0.10	22.95	b.d.	2.60	0.10	b.d.	3.63	16.23	3.32	0.16	b.d.	b.d.	b.d.	99.15				
Cry gm	Efremovka	Groundmass	52.17	0.65	18.35	0.48	0.88	b.d.	0.16	10.32	14.23	2.46	b.d.	b.d.	b.d.	0.06	99.89				
Cry gm	Vigarano	Groundmass	51.02	0.36	20.43	0.63	1.46	b.d.	0.09	11.54	11.03	3.65	0.21	b.d.	b.d.	b.d.	100.43				
Alt gm	Efremovka	Groundmass	41.49	b.d.	16.99	b.d.	20.67	b.d.	0.15	6.44	4.80	6.31	0.30	b.d.	b.d.	0.67	97.74				
Alt gm	Vigarano	Groundmass	44.59	0.13	23.85	b.d.	6.40	b.d.	0.08	8.17	8.02	8.22	b.d.	b.d.	0.14	1.50	100.82				
Silica	Leoville	Fine-grain in plagioclase	94.60	b.d.	1.08	b.d.	1.46	b.d.	b.d.	0.15	0.25	0.21	b.d.	b.d.	b.d.	b.d.	97.83				
Pla-Nep*	Leoville	Groundmass	44.19	b.d.	33.63	b.d.	1.98	n.a.	b.d.	0.88	13.97	4.60	b.d.	n.a.	n.a.	n.a.	99.28				
Pla-Nep*	Vigarano	Groundmass	43.92	0.05	34.20	b.d.	0.39	n.a.	b.d.	1.36	18.15	1.95	b.d.	n.a.	n.a.	n.a.	100.07				
Magnetite	Vigarano	Spherule in groundmass	b.d.	b.d.	1.27	1.25	89.13	b.d.	b.d.	0.12	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	91.85				

Lpx: low-Ca pyroxene, Hpx: high-Ca pyroxene, Pla: plagioclase, Nep: nepheline, Cry gm: cryptocrystalline groundmass, Alt gm: altered groundmass.
b.d.: below detection, 0.03 for SiO_2, Al_2O_3, CaO, 0.04 for TiO_2, Na_2O, K_2O, P_2O_5 and Cl, 0.08 for NiO and MnO, and 0.10 for Cr_2O_3 and SO_3.
*: analyzed by defocused beam (n.a.: not analyzed)

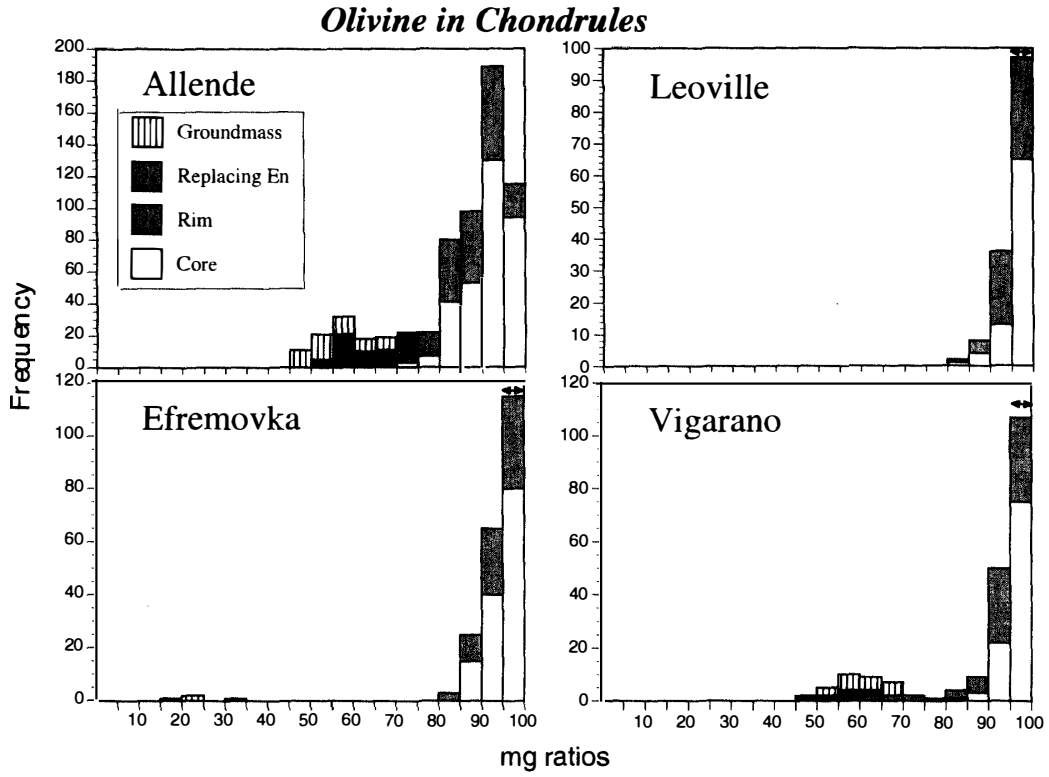

Fig. 2. Histograms of Mg/(Mg+Fe) atomic ratios (mg ratios) of olivines in magnesian chondrules in reduced CV chondrites, compared with those in Allende (IKEDA and KIMURA, 1995). Olivine compositions are plotted in four occurrence types, i.e., fine grains in groundmass, fine grains replacing low-Ca pyroxene, and core and rim of phenocryst. The arrows show the compositional ranges of coexisting pyroxenes. The diagrams contain the data from 7 chondrules in Leoville, 12 in Efremovka, 9 in Vigarano and 11 in Allende.

4.3. Groundmass phases

Plagioclase is similar to one another in composition in reduced and oxidized CVs: An_{60-90} in Efremovka, An_{69-92} in Leoville, An_{68-95} in Vigarano, and An_{59-100} in Allende (KIMURA and IKEDA, 1995). K-feldspar components are below 0.8 mol% in all plagioclase compositions determined.

Cryptocrystalline and altered groundmasses are similar in composition in the reduced CVs, although Leoville does not contain altered groundmass. Primary cryptocrystalline groundmass contains higher SiO_2 (45.1–55.0 wt%) and CaO (8.1–17.0%) and lower FeO (0.5–4.3%), Na_2O (1.4–4.9%) and Cl (below detection, <0.07%) than altered groundmass (34.1–47.7% SiO_2, 0.3–11.9% CaO, 0.6–20.7 % FeO, 6.1–21.2% Na_2O and 0.0–6.2% Cl). Primary cryptocrystalline groundmass is enriched in normative anorthite and diopside, whereas altered groundmass contains abundant normative nepheline and/or sodalite (Fig. 4). The chemical compositions of primary and altered groundmasses are the same as those in Allende (KIMURA and IKEDA, 1995).

Nephelines replacing primary groundmass usually contain <2.6 wt% CaO and <1.6% K_2O. On the other hand, nepheline lamellae in plagioclase are nearly stoichiometric with <0.5% CaO and <0.1% K_2O.

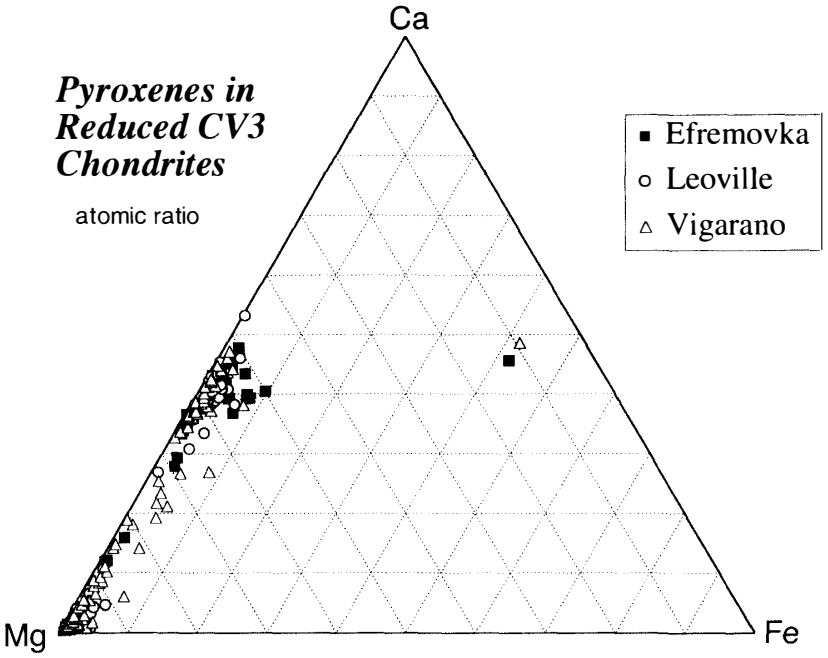

Fig. 3. Plot of atomic Ca-Mg-Fe ratio for pyroxene in chondrules in reduced CV chondrites. Hedenbergites occur as fine grains in altered groundmasses in Efremovka and Vigarano chondrules.

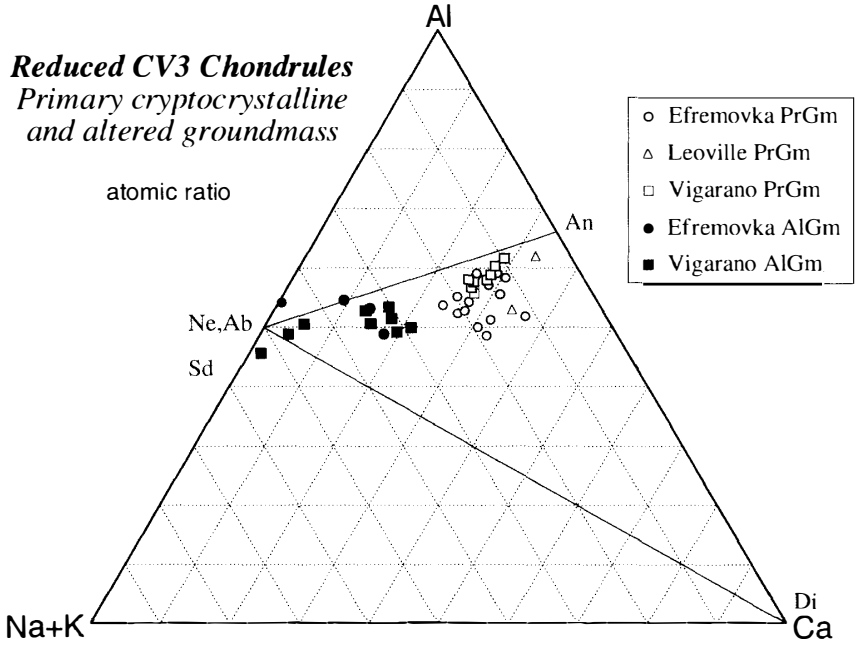

Fig. 4. Plot of atomic Al-(Na + K)-Ca ratio for primary cryptocrystalline (open symbols) and altered groundmass (filled symbols). Note that primary groundmass is enriched in anorthite component. On the other hand, altered groundmass is depleted in SiO_2 (Table 1) and enriched in nepheline component. An, Ne, Ab, Sd and Di are anorthite, nepheline, albite, sodalite and diopside, respectively.

5. Discussion

5.1. Anhydrous alteration in reduced CV chondrites

IKEDA and KIMURA (1995), and KIMURA and IKEDA (1995) pointed out three processes as secondary anhydrous alterations of chondrules: replacement of primary groundmass by nepheline and/or sodalite (alkali-Ca exchange reaction), replacement of low-Ca pyroxene by ferroan olivine, and secondary olivine zonation.

The replacement texture of primary groundmass is noticed in many chondrules in Vigarano and a few in Efremovka. Hedenbergite, which is common in altered groundmasses in Allende, occurs in altered groundmasses in both chondrites. The replacement of low-Ca pyroxene is observed only in Vigarano chondrules.

Olivine phenocrysts in reduced CVs usually show normal zoning, although the degree of zoning varies. On the other hand, all coexisting pyroxenes remain magnesian and have nearly constant mg ratios (Fig. 2). This suggests that the ferroan olivine was secondary, as pointed out by IKEDA and KIMURA (1995).

In summary, secondary phases in reduced CVs are similar in occurrence, mineral assemblage and composition to those in oxidized CVs. This suggests that similar alteration mechanisms took place in both subgroups.

Nepheline lamellae often occur in plagioclase in the reduced CVs studied here. Bulk compositions of grains consisting of plagioclase and nepheline lamellae (Table 1) imply that they contain about 10–30 mol% nepheline. MACPHERSON and DAVIS (1993) also reported the presence of nepheline lamellae in anorthite in a type B Ca-Al-rich inclusion in Vigarano, and suggested that they formed either by exsolution from plagioclase or secondary alteration. Although the solubility of nepheline in anorthite has not been determined, we suspect that a nepheline component can abundantly solve into anorthite at higher temperatures. If the nepheline formed by secondary alteration, it appears that the alkali-Ca exchange reaction started to take place in Leoville as well as Efremovka and Vigarano.

5.2. Comparison of reaction degrees between CV chondrites

IKEDA and KIMURA (1995) defined the overall degree of anhydrous alteration in individual chondrules, based on the area percentages of altered groundmass and replacement of low-Ca pyroxene, and the abundance ratio of ferroan rim to magnesian core of zoned olivine compared with coexisting pyroxene. The degrees are grouped into the following three categories: Slight (0–5%), Moderate (5–50%), and Intense (50–100%). All these types of alteration are observed in every Allende chondrule, although the degree of alteration based on olivine zonation is higher than the others in each chondrule.

These categories are also used for reduced CVs (Table 2). The degrees of groundmass and pyroxene replacement are lower in Leoville and Efremovka than in Vigarano and Allende. The degree of olivine zonation increases in the order of Leoville < Efremovka <Vigarano <Allende. The overall degree of chondrule alteration increases in the order of Leoville <Efremovka <Vigarano < Allende. Thus, alteration took place in reduced CVs to varying degrees, with the degree of alteration are lower in reduced CVs than in Allende.

Table 2. Degrees of anhydrous alterations in chondrules.

Chondrite	Chondrule No.	Groundmass alteration	Low-Ca pyroxene replacement	Secondary olivine zoning	Overall degree
Leoville	1, 2, 3, 6, 8	Slight	Slight	Moderate	Slightly
	4, 9	Slight	Slight	Slight	Slightly
Efremovka	1	Slight	(No low-Ca px)	Moderate	Slightly
	2, 3, 4, 6, 7	Slight	Slight	Moderate	Slightly
	5, 12	Slight	Slight	Slight	Slightly
	8	Slight	Slight	Intense	Slightly
	9	Slight	(No low-Ca px)	Intense	Slightly
	10	Slight	(No low-Ca px)	No	Slightly
	13	Slight	(No low-Ca px)	Moderate	Slightly
	14	Slight	(No low-Ca px)	Slight	Slightly
Vigarano	1	Moderate	Moderate	Intense	Slightly
	2	Slight	Slight	Moderate	Slightly
	3	Slight	Slight	Moderate	Slightly
	5, 8	Intense	Moderate	Intense	Moderately
	6	Slight	Slight	Moderate	Slightly
	9	Slight	Moderate	Moderate	Slightly
	10	Intense	Intense	Intense	Highly
	11	Slight	Slight	Slight	Slightly

Degrees: Slight 0–5%, Moderate 5–50%, Intense 50%<.

Table 3. Comparison of alteration features in chondrules in CV chondrites.

	Reduced subgroup			Oxidized subgroup
	Leoville	Efremovka	Vigarano	Allende[3]
Magnetite / (magnetite + kamacite)[1]	~0	~0	0.1–0.3(1)[2]	~1
Groundmass alteration	S	S	S–I	S–I
Low-Ca pyroxene replacement	S	S	S–I	S–I
Secondary olivine zonation	S–M	S–I	S–I	M–I

1) Volume ratio.
2) One highly altered chondrule contains only troilite and magnetite.
3) After IKEDA and KIMURA (1995).
S: Slight, M: Moderate, I: Intense (after IKEDA and KIMURA, 1995).

Table 3 summarizes the alteration features of chondrules in reduced CVs and Allende. It also shows the distribution of Fe as abundance ratios of magnetite and kamacite in these chondrules, although the ratio does not exactly reflect the redox conditions. Chondrules in Leoville and Efremovka studied here appear not to contain magnetite. Most Vigarano chondrules contain kamacite with minor amounts of magnetite, and one highly altered chondrule contains only magnetite. On the other hand, Allende chondrules hardly contain kamacite, except as rare occurrences in olivine phenocrysts.

From Table 3, we notice that the degrees of anhydrous alteration of chondrules are well correlated with the abundance of magnetite. Thus, chondrules in Allende are extensively subjected to both alteration and oxidation processes, whereas those in Leoville and Efremovka were hardly subjected to either. Chondrules in Vigarano are intermediate between those in Allende and Leoville. It seems that characteristic features of chondrule alteration gradually change between reduced and oxidized subgroups of CV chondrites.

Mineralogy, chemistry and occurrence of primary phases in chondrules, such as magnesian olivine, pyroxene, plagioclase and cryptocrystalline groundmass, are the same in the oxidized and reduced subgroups. Thus, the differences between the two subgroups may have been caused only by the degree of secondary alteration and oxidation of Fe. Palme and Wark (1988) also suggested that the major difference between both subgroups is the extent of gas-solid reactions on the basis of volatile element abundances.

5.3. Location of alteration reactions

The problem of when the alterations observed here took place, before or after accretion to the parent body of CV chondrites is very controversial. KOJIMA *et al.* (1993) and KOJIMA and TOMEOKA (1996) showed that some dark inclusions in Vigarano and Allende experienced hydration and/or dehydration on the parent body. Because of the similarity in mineralogy between dark inclusions and CV hosts, KROT *et al.* (1995) speculated that all alteration in CVs took place on the parent body through dehydration after hydration. However, altered chondrules studied here show textures unrelated to either hydration or dehydration, in contrast to dark inclusions. For example, fibrous morphology of olivine and vein structure, that are observed in some dark inclusions (KOJIMA and TOMEOKA, 1996), are not encountered in the reduced CV chondrules studied here. Primary groundmasses, which are the most susceptible to alteration among the constituents in chondrules (TOMEOKA and KOJIMA, 1995), are directly in contact with the matrices in Allende (KIMURA and IKEDA, 1996) and reduced CV chondrites. In the CVs studied here, some phenocrystic olivines in chondrules and some isolated olivines hardly show zoning toward the matrix. All these observations indicate that the alterations observed here took place prior to the final consolidation with the matrix and the metamorphism in the CV parent body.

6. Summary

(1) Anhydrous alteration resulting in secondary olivine zonation, replacement of low-Ca pyroxene and replacement of primary groundmass, took place in reduced CV as well as oxidized CV chondrites. Even reduced CVs do not completely preserve their primary features.
(2) The degrees of alteration for reduced CV chondrites are lower than that of Allende, and vary in reduced CVs. The degree increases in the order of Leoville < Efremovka <Vigarano <Allende.
(3) The differences between CV chondrites of oxidized and reduced subgroups are determined by the degrees of secondary alteration and oxidation of Fe.

(4) It is probable that the alteration took place prior to the final consolidation with the matrix in the CV parent body.

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