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"DEHYDRATED" CHONDRULES FROM THE MURCHISON (CM) CHONDRITE

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Abstract: Two "dehydrated" chondrules (MC-5 and MC-27) were obtained from close to the fusion crust of the Murchison (CM) meteorite. They have a porphyritic texture with angular or rounded (relict) olivines containing abundant voids, recrystallized olivines, and numerous interstitial Fe oxide grains embedded in groundmass glass. This peculiar texture is similar to that of the fusion crust from the Orgueil (CI) chondrite, indicating that the texture formed during the reheating at the atmospheric entry of the meteorite.

Isotope dilution analyses indicate that these chondrules have light-REE depleted pattern with a large negative Eu anomaly (CI normalized Sm/La ratio=1.3–2.4, Eu/Eu*=0.40–0.57). They also show relatively low Ba and Sr (0.4–1.0 × CI) concentrations and depletion of alkalies (0.2–0.4×CI). The lithophile element abundances of the two chondrules are in a similar range of those for other altered CM chondrules in the Murchison and the Yamato-793321 chondrites. It is suggested that the chemical compositions of chondrules, specifically REE and alkali abundances, remained unchanged but significant changes of petrographic texture occurred during atmospheric heating.

1. Introduction

Most of the CM chondrites have experienced aqueous alteration and brecciation (METZLER *et al.*, 1992), and chondrules are generally rare. Many chondrules in the CM chondrites, such as Murchison, are partially altered; chondrule groundmass is composed of hydrated materials, such as phyllosilicates (*e.g.*, serpentine and chlorite), along with olivine and pyroxene phenocrysts (IKEDA, 1983).

We have undertaken precise analyses of rare earth element (REE) and other lithophile element abundances in individual chondrules from two CM chondrites, Murchison and Yamato-793321 (INOUE *et al.*, 1994; INOUE and NAKAMURA, 1995). In these studies, we found two chondrules (MC-5 and MC-27) without any hydrous phases. They originated from near the fusion crust of the Murchison meteorite and have a texture similar to the fusion crust from Orgueil (CI) chondrite (BROWNLEE *et al.*, 1975). Judging from their petrographical texture, they appear to have formed through dehydra-

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tion and partial melting of aqueously altered chondrules during atmospheric reheating of the meteorite. Therefore, the analyses of these chondrules will give us an insight of chemical changes due to an atmospheric reheating of aqueously altered CM chondrules.

2. Experimental Procedures

The experimental procedures are similar to those previously described (INOUE *et al.*, 1994). Several fragments of the Murchison (CM) chondrite (specimen No. Me 2752) partly covered with the fusion crust were provided from Field Museum of Natural History. One large fragment (~18 g in weight) was subjected to freeze-thaw processing and more than 30 chondrules (0.017–1.028 mg in size) were separated for trace element analyses. Total weight (<~30 mg) of chondrules collected corresponds to less than 0.2% of the bulk meteorite. A "whole rock" sample was taken from the rest of the sample.

Individual chondrules were split into two parts; half was used for trace element analyses and the other part was for petrographical examinations. Among the 30 chondrules, two chondrules, MC-5 and MC-27 with sizes of 0.466 mg, 0.260 mg, respectively, showed unusual petrographic textures.

First, relatively thick section (A) of the chondrules was prepared, and textures and mineral compositions were examined by a scanning electron microscope (JSM-840A) equipped with energy dispersive spectroscopy (SEM-EDS) using 15 kV acceleration voltage and 1.2 nA beam current. After examination of section A, a new surface of the section B was obtained by further polishing. This section was then examined by SEM-EDS (JSM-5800) at 15 kV and 0.4 nA. Bulk chemical compositions of section A for MC-5 and MC-27 were determined by broad beam technique using an electron probe microanalyzer (EPMA, JEOL 733) operated at 15 kV and 10.9 nA. The data were obtained using an electron beam of 50 μm in diameter, and were corrected according to the method of IKEDA (1980). For comparison, the defocussed-beam analyses were also carried out for typical Murchison chondrules (MC-7, MC-26 and MC-28). Section B was also examined by a optical microscope in order to check the effect of shock reheating.

Abundances of REE, Ba, Sr, Rb, K, Mg, Ca and Fe were determined using the direct loading isotope dilution method (DL-IDMS) with a mass spectrometer model JEOL-05RB (NAKAMURA *et al.*, 1989).

3. Results and Discussion

3.1. *Petrography*

The petrographic textures of the two chondrules, MC-5 and MC-27 are presented in Table 1 and Figs. 1 and 2. Two specimens examined here appeared to be true chondrules under a binocular microscope. These two chondrules, however, do not contain any hydrous phases, such as phyllosilicates, poorly characterized phase (PCP), nor euhedral olivine and/or pyroxene phenocrysts, all of which are common in aqueously altered CM chondrules (RICHARDSON, 1981; TOMEOKA and BUSECK, 1985). Instead, both chondrules show vesicular textures and contain recrystallized olivine phenocrysts (<10 μm), abundant interstitial Fe-oxide grains (~1 μm) embedded in glassy groundmass (Figs. 1 and 2). Rarely, angular olivine and pyroxene grains (10–100 μm) were found. The angular

Table 1. Petrographic descriptions of "dehydrated" chondrules, MC-5 and MC-27 separated from the Murchison (CM) meteorite.

	Description
MC-5	Section A: Relict olivine [Fo*=95.0], Ca-poor pyroxene [En*=96.0, Wo*=1.4] and recrystallized olivine [Fo=82.3–91.0] are surrounded by glass with abundant Fe (rarely Cr) oxide grains in the vesicular phase.
	Section B: The vesicular texture consisting mostly of recrystallized olivine and interstitial phase of iron oxides. Relict olivine and pyroxene are rare and show sharp optical extinction.
MC-27	Section A: This specimen has retained the memory of chondrule texture [Fo=98.2/En=96.6, Wo=1.6]. Ca-poor pyroxene phenocrysts are enclosed in olivine. Mesostasis shows vesicular texture with iron oxide (Fe_3O_4) grains.
	Section B: The specimen shows the similar texture to that of MC-5 (*i.e.*, recrystallized olivine [Fo=67.9–88.4] surrounded by glass containing numerous iron oxide grains). Relict olivines do not show undulatory extinction.

*Mol% of forsterite [Fo] in olivine, and enstatite [En], wollastonite [Wo] in pyroxene, respectively.

or rounded olivine and pyroxene have homogeneous compositions with forsterite [Fo]=95–98 mol% or enstatite [En]=96–97 mol% and wollastonite [Wo]=1–2 mol%, which are typical of chondrule phenocrysts of Murchison (Fuchs *et al.*, 1973) and other CM chondrites (Wood, 1967). Therefore, it is possible that the coarse olivine and pyroxene are relict grains that were subjected to partial melting. As a result of optical microscopic observation, these relict olivines do not show undulatory extinction, but sharp optical extinction, suggesting that these chondrules have not experienced the shock reheating (unshocked S1 stage; Stöffler *et al.*, 1991).

Chemical compositions of constituent phases are shown in Table 2. The recrystallized olivine grains of MC-5 and MC-27 have variable Fo contents [Fo=68–91]. The interstitial glass shows much higher FeO (~27 wt%) and lower SiO_2 (~42 wt%) contents than those in mesostasis glass of typical Murchison chondrules (FeO=0.6 wt%; SiO_2=69.1 wt%; Olsen and Grossman, 1978).

The overall textual features and constituent minerals of MC-5 and MC-27 are similar to those reported for the fusion crust of Orgueil chondrite (Brownlee *et al.*, 1975). In addition, the texture of section A of CM-27 (Fig. 2a) resembles those of porphyritic CM chondrules (Inoue *et al.*, 1994) and the chemical compositions of interstitial phases are also similar to those of mesostasis in altered Murchison chondrules (Table 2). Judging from the texture and mesostasis compositions, the degree of melting in the section A of MC-27 is considered to be relatively small. In analogy to the fusion crust of Orgueil, abundant fine grained Fe-oxide in the groundmass may be Fe_3O_4 (magnetite) crystallized from the Fe-rich melts in chondrules.

The presence of magnetite indicates relatively higher oxygen fugacity during reheating. The peak temperature and f_{O_2} during the atmospheric entry of Murchison chondrite were estimated to be >2000 K and >~10^{-3} atm, respectively, using f_{O_2} (atm)–1/T (K) diagram (Huebner, 1971) of FeO/Fe_3O_4 buffer (assumed equilibrium melting).

It is considered that high iron melts were produced by the reaction of altered high-iron groundmass of chondrules such as phyllosilicate (or PCP) and porphyritic olivine. Because of short period of (flash) heating, disequilibrium melting and reaction may have

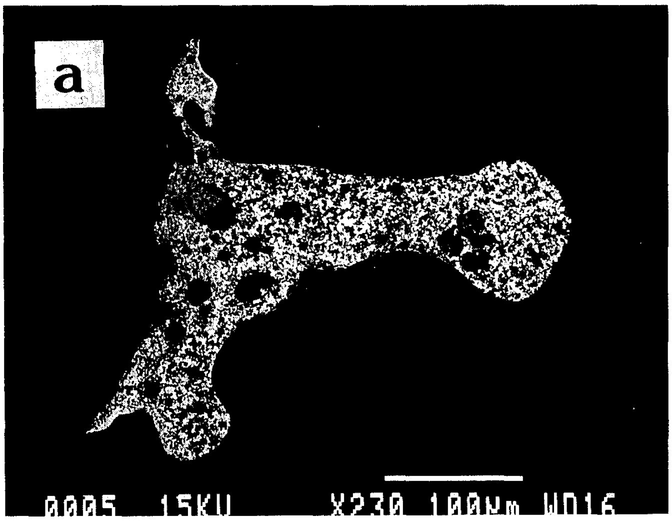

Fig. 1a. Back scattered electron image (SEM-BSE) of section A of "dehydrated" Murchison (CM) chondrule, MC-5. The section contains relict olivine [Fo=95.0] and pyroxene [En=96.0, Wo=1.4], recrystallized olivine, and interstitial glass carrying numerous Fe (rarely Cr) oxide grains.

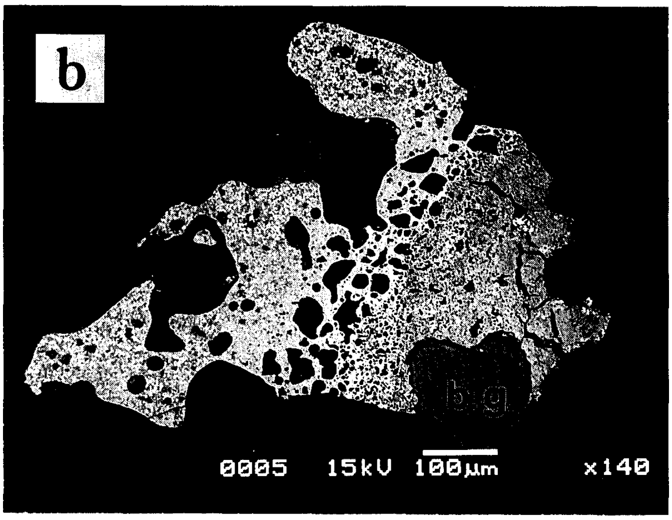

Fig. 1b. Section B of MC-5. Vesicular texture consists of minor relict olivine, recrystallized olivine [Fo=82.3–91.0] and glass with iron oxide grains (b.g.=bed glass).

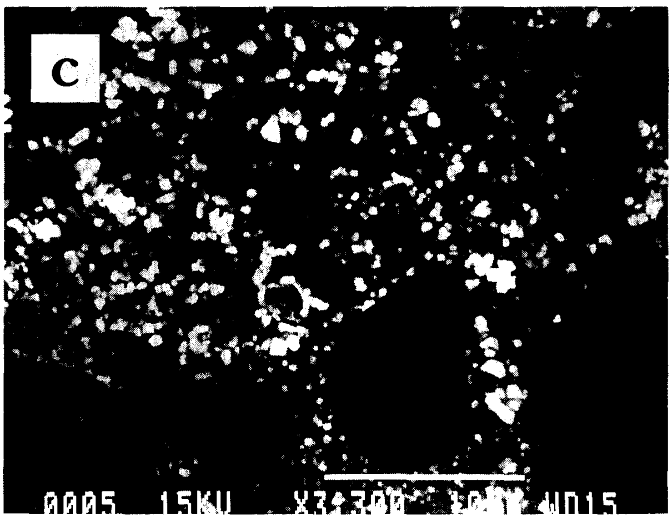

Fig. 1c. Enlarged view of MC-5 (section A). The micrometer-sized reflective grains are iron oxide, the angular grains are recrystallized olivine, rounded grains are relict olivine (pyroxene), and large dark portions are vesicles. The filling material between olivine grains is glass.

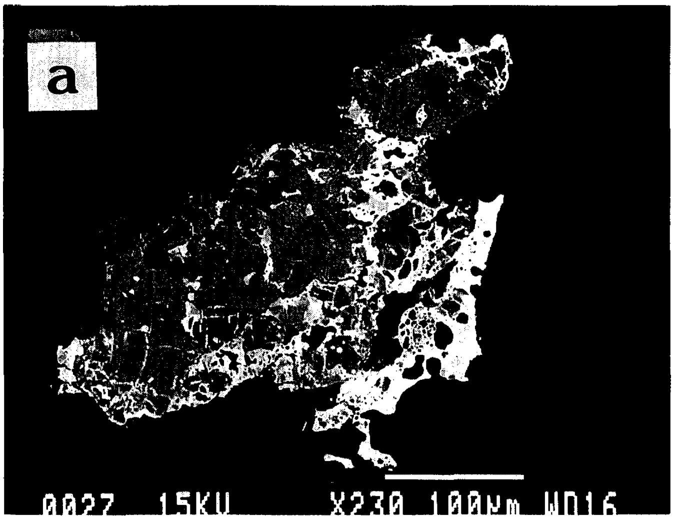

Fig. 2a. BSE image of section A of Murchison chondrule, MC-27. Olivine [Fo=98.2] and Ca-poor pyroxene [En= 96.6, Wo=1.6] phenocrysts are enclosed with interstitial materials.

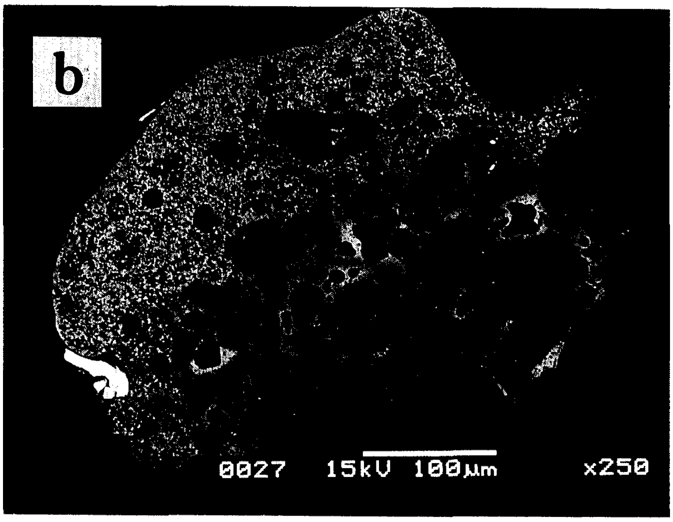

Fig. 2b. Section B of MC-27. Relict and recrystallized olivine [Fo=67.9–88.4] grains are surrounded by glass containing abundant iron oxide grains, showing a texture similar to MC-5 (on the left side).

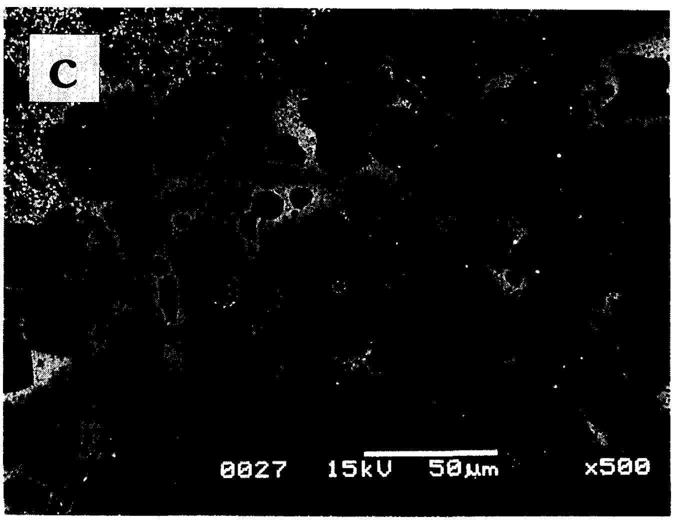

Fig. 2c. Enlarged view of MC-27 (section B) consisting of relict olivine, recrystallized olivine [Fo=67.9–88.4] and interstitial glass including irregular Fe (or Cr) oxide grains.

Table 2. Representative chemical compositions (wt%) of "dehydrated" chondrules, MC-5 and MC-27.

	MC-5		MC-27					Murchison chondrules		
	Section B		Section A		Section B					
	Rcry* ol	gls*	mesostasis**		Rcry* ol		gls*	phyllosilicate***		
Na_2O	–	1.42	0.00	0.00	0.32	–	1.40	0.00	0.00	0.00
MgO	40.43	7.71	12.11	11.77	31.31	43.27	8.74	11.43	12.43	6.44
Al_2O_3	0.14	5.44	5.43	5.84	2.11	0.06	5.24	6.23	2.36	3.51
SiO_2	39.07	43.29	33.43	30.06	44.72	41.04	40.75	22.70	24.74	23.60
P_2O_5	0.02	0.36	–	–	0.43	0.07	0.26	0.03	–	–
SO_3	–	0.24	–	–	0.24	0.03	–	1.88	0.27	0.18
K_2O	0.09	0.00	0.03	0.03	0.07	0.01	0.12	0.04	0.04	0.04
CaO	0.35	6.01	3.97	1.84	2.13	0.25	5.58	0.20	0.16	0.15
TiO_2	–	0.24	0.40	0.22	0.25	0.02	0.28	0.14	0.13	0.25
Cr_2O_3	0.41	0.08	0.36	0.42	0.13	0.03	0.14	0.29	0.22	0.23
MnO	0.25	0.34	0.23	0.22	0.21	–	0.48	0.07	0.35	0.35
FeO	15.54	26.41	39.03	45.37	15.47	10.09	27.62	36.38	44.54	52.46
NiO	1.75	0.07	0.44	0.50	1.48	2.23	0.44	0.22	0.40	0.58
Total	98.06	91.61	95.44	96.25	98.88	97.11	91.05	79.62	85.62	87.80
Fo	82.3				78.3	88.4				

"–" denotes "not determined" or "undetectable".
Because of their small grain sizes (~1 μm), the chemical compositions were not precisely determined for individual magnetite grains.
*Rcry ol=Recrystallized olivine, and gls=interstitial glass.
**Interstitial phase of olivine or pyroxene phenocrysts in MC-27.
***Interstitial phyllosilicate in three porphyritic chondrules from Murchison.

occurred and then olivine and magnetite grains should have crystallized from such high-iron melts.

3.2. Bulk chemical composition

3.2.1. EPMA analysis

Bulk chemical compositions of MC-5, MC-27 and aqueously altered chondrules (MC-7, MC-26 and MC-28) obtained by defocused beam analysis of EPMA are shown in Table 3. Bulk compositions of CM chondrules show wide variations (GROSSMAN and WASSON, 1983). For MC-5 and MC-27 as well as MC-7, MC-26 and MC-28, Fe contents are obviously high and Mg contents are low, and also Al, Si and K tend to be low relative to least altered Murray (CM) chondrules (RUBIN and WASSON, 1986) (Table 3). Such chemical features can be explained by alteration effects (IKEDA, 1983; KOJIMA *et al.*, 1984) as like other CM chondrules. Although the leaching effects of Na and Ca are not clearly noted in Table 3, it is possible that the leaching of these elements from MC-5 and MC-27 may have occurred (RUBIN and WASSON, 1987, 1988).

Bulk compositions of MC-5 and MC-27 are in a similar range to those of altered Murchison chondrules (Table 3). Relatively high Fe and low Mg contents of MC-5 are also within abundance ranges of Fe and Mg for Murchison chondrules (unpublished IDMS data). It is considered that melting and crystallization of MC-5 and MC-27 have

Table 3. Bulk chemical compositions (wt%) of Murchison chondrules, MC-5 and MC-27, compared with typical chondrules (MC-7, MC-26 and MC-28) from Murchison. Data obtained by defocused beam analyses of EPMA after correction by the method of IKEDA *(1980) and adjusted to 100%.*

	MC-5	MC-27	MC-7* (PO)	MC-26* (POP)	MC-28* (PP)	Murray porphyritic** chondrules	(range)
Number of analyses	16	23	32	36	22		
Na_2O	0.56	0.10	0.05	0.06	0.11	<0.04	
MgO	27.13	39.46	48.29	44.79	34.32	44.2	(40.2 -55.8)
Al_2O_3	1.77	0.99	1.77	2.35	1.32	2.1	(0.70- 4.5)
SiO_2	34.96	46.81	39.02	39.84	48.46	48.4	(41.4 -53.2)
P_2O_5	–	–	–	–	–	0.08	
K_2O	0.05	0.02	0.02	0.03	0.08	0.06	
CaO	1.90	0.82	1.31	2.24	1.43	0.74	(0.44–1.1)
TiO_2	0.14	0.13	0.19	0.24	0.26	0.08	
Cr_2O_3	1.00	0.80	0.72	0.79	1.08	0.53	
MnO	0.31	0.13	0.20	0.19	0.19	0.14	
FeO	32.18	10.75	8.44	9.48	12.74	3.2	(0.61–6.8)
S	–	–	–	–	–	0.16	
Cl	–	–	–	–	–	0.08	
Ni	–	–	–	–	–	0.19	

* Aqueously altered porphyritic chondrules with phyllosilicate mesostasis.

** Average value of least altered 11 chondrules in the Murray (CM) chondrite (RUBIN and WASSON, 1986).

occurred in a closed system during heating and cooling. For example, iron in metal oxide was probably supplied from interstitial phyllosilicates, and felsic components (such as Al, Ca and Na) concentrated in the interstitial glass may have come from Ca-rich pyroxene and mesostasis materials.

3.2.2. Lithophile trace element abundances

The results of isotope dilution analyses for MC-5, MC-27 and a whole rock sample are given in Table 4 and Fig. 3. The whole rock specimen shows an unfractionated REE-Ba-Sr pattern (~1.5 × CI) and relatively lower alkali abundances (~0.8 × CI). These data are consistent with previous results reported for the Murchison whole rock (NAKAMURA, 1974; EVENSEN *et al.*, 1978).

In "dehydrated" chondrules, MC-5 and MC-27, abundances of K, Rb (0.2–0.4 × CI), Sr and Ba (0.4 –1.0 × CI) are lower than those in CI chondrite, Orgueil (ANDERS and EBIHARA, 1982), but still within a range of CM chondrules (unpublished data). In addition, the degrees of depletion of K and Rb, for MC-5 and MC-27, relative to more refractory alkaline earths (CI normalized K (Rb)/Sr (Ba) ratios=~0.5) are also in the same range of altered CM chondrules (K (Rb)/Sr (Ba)=0.2–0.8). Under such oxidation state ($f_{O_2} > 10^{-3}$), vaporization loss of alkalies may not have been significant. This condition may be similar to the case of the fusion crust of the Nakhla meteorite which showed no alkali loss (BUNCH and REID, 1975).

The results of REE analyses indicate light-REE depleted, smoothly fractionated pattern with a large negative Eu anomaly. The REE absolute abundances (1.2–3.9 × CI) and fractionations of MC-5 and MC-27 are similar to those of many altered chondrules from Murchison (INOUE and NAKAMURA, 1995) (Fig. 3). It is suggested that reheating probably did not affect the chemical compositions (even in moderately volatile elements,

Table 4. Chemical compositions of MC-5, MC-27 and whole rock sample (W. R.) from the Murchison (CM) chondrite determined by the isotope dilution method.

	MC-5	MC-27	W. R.
wt (mg)*	0.466	0.260	
	(0.370)	(0.184)	(32.6)
Mg (%)	11.6	19.7	9.55
Ca (%)	3.15	0.991	0.902
Fe (%)	18.4	8.97	18.5
K (ppm)	223	162	569
Rb (ppm)	0.838	0.445	2.30
Sr (ppm)	7.81	3.3	7.91
Ba (ppm)	1.88	1.3	2.27
La (ppm)	0.35	0.39	0.253
Ce (ppm)	1.11	1.06	0.645
Nd (ppm)	1.32	0.805	0.476
Sm (ppm)	0.518	0.304	0.154
Eu (ppm)	0.0864	0.0698	0.0587
Gd (ppm)	0.703	0.405	0.204
Dy (ppm)	0.934	0.588	0.252
Er (ppm)	0.653	0.41	0.166
Yb (ppm)	0.624	0.47	0.168
Lu (ppm)	0.0791	0.062	0.0253

*Total weights (in mg) of MC-5 and MC-27 (values in parentheses: weights used for isotope dilution). Rim materials adhering to chondrules are considered to have been mostly removed from the specimens during sample processing.

The uncertainties of concentrations due to mass spectrometric measurements were better than ~3% for alkalies and were better than ~10% (except for a few cases) for REE. The contributions of blanks to K, Rb, Sr and Ba were <2%, <2%, ~5% and ~20%, respectively. The REE blank were <1%, except for La and Ce (~3%).

All concentration data are blank corrected.

such as K, Rb) except for highly volatile constituents (*e.g.*, H_2O). The highly fractionated REE pattern and alkali depletion suggest that these chondrules were not homogenized with the surrounding matrix material which has relatively high alkali (*e.g.*, K; 1.9 × CI) (MCSWEEN and RICHARDSON, 1977) and unfractionated REE.

We, therefore, suggest that the original chemical compositions have been preserved in two reheated chondrules, and most Murchison chondrules including these two are considered to preserve records of the conditions of the aqueous alteration process probably in the parent body.

4. Conclusions

(1) The "dehydrated" chondrules, MC-5 and MC-27, from the Murchison (CM)

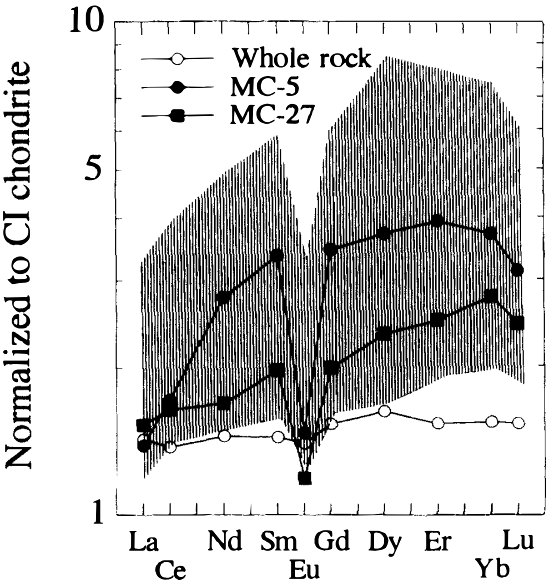

Fig. 3. CI (Orgueil; NAKAMURA, 1974) normalized REE abundance patterns of MC-5, MC-27 and a whole rock. The shaded area indicates the range of Murchison (CM) chondrules (INOUE and NAKAMURA, 1995).
The light-REE depleted pattern with a negative Eu anomaly is obvious for MC-5 (Sm/La=2.4 and Eu/Eu=0.57) and MC-27 (Sm/La=1.3 and Eu/Eu*=0.40), and these features are similar to majority of CM chondrules data. Here, Eu* is the normal value interpolated from abundances of Sm and Gd.*

chondrite contain relict olivine (pyroxene), recrystallized olivine and interstitial glass carrying abundant micrometer-sized iron oxide instead of olivine and pyroxene phenocrysts with interstitial phyllosilicate. This texture is considered to have formed by partial melting and dehydration during the atmospheric entry of the meteorite.

(2) Major element and lithophile trace element abundances in the two chondrules are in the same range of those in aqueously altered Murchison chondrules. REE and alkali abundances seem to have preserved the aqueous alteration signature and have not been significantly affected by flash heating.

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