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Origin of a metamorphosed lithic clast in CM chondrite Grove Mountains 021536

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Abstract–A metamorphosed lithic clast was discovered in the CM chondrite Grove Mountains 021536, which was collected in the Antarctica by the Chinese Antarctic Research Exploration team. The lithic clast is composed mainly of Fe-rich olivine (Fo_{62}) with minor diopside ($Fs_{9.7–11.1}Wo_{48.3–51.6}$), plagioclase ($An_{43–46.5}$), nepheline, merrillite, Al-rich chromite (21.8 wt% Al_2O_3; 4.43 wt% TiO_2), and pentlandite. $\Delta^{17}O$ values of olivine in the lithic clast vary from −3.9‰ to −0.8‰. Mineral compositions and oxygen isotopic compositions of olivine suggest that the lithic clast has an exotic source different from the CM chondrite parent body. The clast could be derived from strong thermal metamorphism of pre-existing chondrule that has experienced low-temperature anhydrous alteration. The lithic clast is similar in mineral assemblage and chemistry to a few clasts observed in oxidized CV3 chondrites (Mokoia and Yamato-86009) and might have been derived from the interior of the primitive CV asteroid. The apparent lack of hydration in the lithic clast indicates that the clast accreted into the CM chondrite after hydration of the CM components.

INTRODUCTION

Collisions between meteoritic parent bodies are common and important, as they are the major cause of shock metamorphism and brecciation, though mineral fragments in chondrites are also considered as collision products in the early solar system. Shock metamorphism of meteorites usually results in deformation or high-pressure transformation of meteoritic components and provides information about pressure and temperature conditions that meteorites have experienced (e.g., Sharp and DeCarli 2006). Brecciated meteorites usually contain exotic or cognate lithic clasts. They not only record fragmentation of the surface of the parent bodies of meteorites (e.g., lunar breccias and brecciated HED [howardite, eucrite, and diogenite] meteorites) and relative stratigraphy of lithic clasts to the hosts, but also provide a plethora of fragments that may contain new rock types (e.g., Bischoff et al. 2006).

Unequilibriated chondrites are mainly composed of chondrules, metal/sulfides, refractory inclusions, and a fine-grained matrix; these components are thought to have formed directly in the early solar system. Differentiated meteorites are commonly considered to be derived from chondrites by partial to complete melting. Thus, it is reasonable that preserved chondritic components have been found in differentiated meteorites (e.g., Bischoff et al. 2006; Liu et al. 2009). On the other hand, a few investigations have demonstrated that some lithic clasts in unequilibriated chondrites seem to have experienced strong thermal metamorphism (e.g., Bischoff et al. 2006; Sokol et al. 2007). These lithic clasts provide important evidence for the existence of planetesimals formed prior to accretion of chondrite parent bodies.

Numerous igneous-textured lithic clasts were discovered in ordinary chondrites (e.g., Hutchison and Graham 1975; Hutchison et al. 1988; Hutchison 1992; Bischoff et al. 1993; Bridges and Hutchison 1997; Sokol et al. 2007; Dyl et al. 2009; Terada and Bischoff 2009), but they are rare in primitive carbonaceous chondrites. A few metamorphosed clasts were described in CV3 chondrites (Cohen et al. 1983; Krot and Hutcheon 1997; Krot et al. 1998; Jogo et al. 2008; Jogo and Nakamura 2009). Krot and Hutcheon (1997) and Krot et al. (1998) described a few oxidized and metamorphosed clasts with granular or radial textures from the CV3 chondrite Mokoia, and inferred that these clasts were excavated from the interior of the CV3 parent body. However, no oxygen isotopes of these clasts were reported. More recently, Jogo et al. (2008) and Jogo and Nakamura (2009) described one oxidized and metamorphosed clast in the CV3 chondrite Yamato-86009 and reported oxygen isotopic compositions of its olivine. They precluded the possibility that the parent body material of the clast is made of R chondrites.

CM chondrites are a group of primitive carbonaceous chondrites that have experienced extensive aqueous alteration, but minimal thermal metamorphism. Chondrules in CM chondrites include type I and type IIA chondrules. Type I chondrules are extremely Mg-enriched with Mg# [≡100*Mg/(Mg + Fe)] values larger than 95, whereas type IIA chondrules commonly contain zoned olivines, with relict forsterite in the center (Brearley and Jones 1998). CM-related clasts have been found in ordinary chondrites (e.g., Grove Mountains [GRV] 050009) and in some achondrites (e.g., Jodzie howardite; Bunch et al. 1979); however, no exotic lithic clasts have been reported in CM chondrites. GRV 021536 is a newly identified CM chondrite in the Chinese Antarctic meteorite collection (Connolly et al. 2007). In this CM chondrite, a lithic clast is distinctly different from the chondrules and their fragments. This study reports its petrography, mineralogy, and oxygen isotopic compositions in olivine, and presents the petrologic implications and origin of this lithic clast.

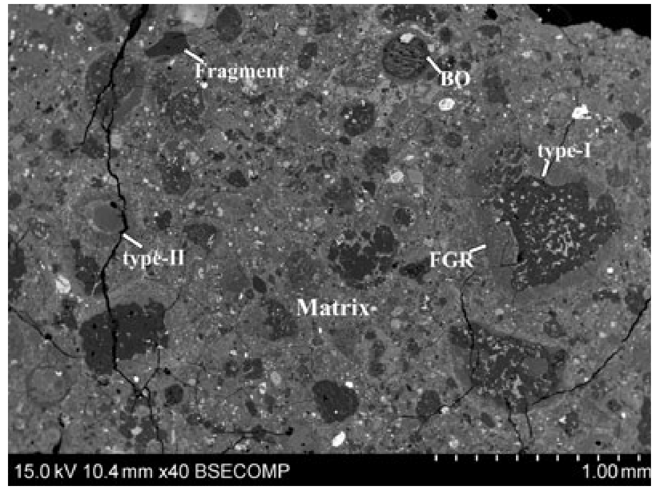

Fig. 1. Backscattered electron image of an area in Grove Mountains 021536 with type I and type II chondrules and fragments thereof set in fine-grained matrix. Chondrules usually have fine-grained rim (FGR). BO, barred olivine chondrule.

ANALYTICAL METHODS

A polished thick section of GRV 021536 was used for this study. Backscattered electron (BSE) imaging was performed with a Hitachi S-3400N II scanning electron microscope at Purple Mountain Observatory. Mineral compositions were measured using a JEOL 8100 electron microprobe (EMP) at Nanjing University and a Cameca SX100 electron microprobe at the University of Tennessee. The operating conditions were 15 kV accelerating voltage, 10–20 nA beam current, and a focused 1 μm beam for olivine, pyroxene, chromite, and phosphates, with a 5 μm beam size for plagioclase and nepheline. Natural and synthetic standards were used. Typical detection limits for oxides of most elements are 0.03 wt%. Data were reduced by ZAF and PAP procedures, for the JEOL and Cameca probes, respectively.

In situ oxygen isotope analyses of olivine grains were performed with the Cameca Nano-SIMS 50L ion microprobe at California Institute of Technology. A rastering (3 × 3 μm) Cs^+ primary beam of ~5 pA in intensity was used to sputter the gold-coated sample surface and to produce secondary ions. All $^{16}O^-$, $^{17}O^-$, and $^{18}O^-$ were simultaneously measured with electron multipliers. The $^{16}OH^-$ interference to $^{17}O^-$ was eliminated with a high-mass resolving power of ~7500. Typical errors in individual measurements were ~1 per mil (1σ) for $\delta^{18}O$ and ~2 per mil (1σ) for $\delta^{17}O$. San Carlos olivine (Fo_{89}) served as the oxygen isotope standard.

RESULTS

Petrography and Mineralogy

The GRV 021536 meteorite was collected by the Chinese Antarctic Research Exploration team during the 2002–2003 field mission. The meteorite has a mass of only 1.45 g. Part of the fusion-crust still remains. GRV 021536 is composed mainly of type I and type IIA chondrules and fragments thereof, set in a fine-grained matrix (~70 vol%) (Fig. 1). Most chondrules are small (200–300 μm in diameter); a few are up to 2 mm. Type I porphyritic olivine chondrules are the dominant type. Olivine grains in type I chondrules are homogeneous, whereas those in type IIA chondrules are usually zoned. Both type I and type II chondrules

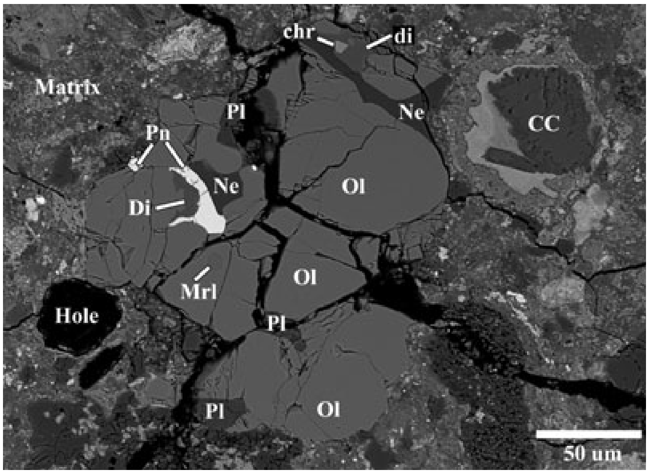

Fig. 2. Backscattered electron image of the lithic clast in GRV 021536. Ol, olivine; Di, diopside; Pl, plagioclase; Mrl, merrillite; Ne, nepheline; Pn, pentlandite; Chr, chromite; CC, calcium carbonate.

usually have the typical fine-grained rims as observed by Metzler et al. (1992). The fine-grained matrix consists mainly of phyllosilicate minerals. Several Ca, Al-rich inclusions (CAIs) were also observed. Irregular spinel-diopside inclusions are the dominant type. Spinel-hibonite spherules and other hibonite-bearing inclusions also exist, but melilite-rich CAI was not observed. A few irregular dark inclusions were also observed in the studied section. Most metal grains were altered to Fe-oxide and/or Fe-hydroxide. Hydration occurs in CAIs and the mesostasis of chondrules. Calcium carbonate is common throughout the section (Fig. 2).

The lithic clast is irregular in shape and about 200 μm in its largest dimension and has a distinct contact with the surrounding fine-grained matrix (Fig. 2). This clast is composed dominantly of subhedral to euhedral olivine grains; a few subhedral to euhedral plagioclase grains occur in contact with olivine. Anhedral diopside, nepheline, and pentlandite are interstitial to the olivine grains (Fig. 2). Diopside coexists with nepheline (or nepheline-like phase). No replacement textures were observed between nepheline and plagioclase. One euhedral chromite grain occurs as an inclusion in diopside, and a merrillite crystal is included in an olivine grain (Fig. 2). No alteration phyllosilicate minerals were observed in the lithic clast.

Representative mineral compositions in the lithic clast are given in Table 1. Olivine in this lithic clast is homogeneous and is relatively Fe-rich (Mg# = 61.9–62.4) compared to those in chondrules from GRV 021536 (see below). Al_2O_3 and Cr_2O_3 contents in olivine of the lithic clast are very low (near or below detection limits). NiO and CaO contents are generally homogeneous (0.09–0.13 and 0.26–0.30 wt%, respectively). MnO content in olivine ranges from 0.28 to 0.36 wt%, and Fe/Mn molar ratios vary from 94.7 to 114.7. Diopside grains ($Wo_{48.3-51.6}En_{38.7-40.4}$) are Fe-rich (5.84–6.77 wt% FeO) with Mg# values of 78.6–80. They contain variable amounts of Al_2O_3 (2.31–4.89 wt%) and low MnO (0.06–0.1 wt%). Chromite has high contents of Al_2O_3 (21.8 wt%) and TiO_2 (4.43 wt%). Plagioclase is weakly heterogeneous ($An_{43-46.5}$). Nepheline grains are also variable in composition, with 2.27–2.72 wt% CaO and 0.97–2.36 wt% K_2O. Merrillite contains notable contents of Na_2O (2.78 wt%), MgO (3.34 wt%), and FeO (1.69 wt%).

Chemical compositions of a few olivine grains from type I and type IIA chondrules were measured for comparison (Table 1). Olivine in type I chondrule is extremely Mg-enriched (Mg# = 98.6–98.9), with 0.03–0.13 wt% Al_2O_3, and 0.57–0.63 wt% Cr_2O_3. The contents of CaO (0.2–0.23 wt%) and NiO (0.03–0.04 wt%) are lower than those in the lithic clast. The Fe/Mn molar ratios are low (8.4–9.9). Olivines in type IIA chondrules have small forsteritic cores and Fe-rich rims. The cores are almost pure Mg_2SiO_4 (Mg# = 99.4–99.5), with Al_2O_3 and Cr_2O_3 contents of 0.46–0.77 and 0.07–0.08 wt%, respectively. CaO content is relatively high (0.67–1.01 wt%), and MnO and NiO are below detection limits (<0.03 wt%). The Al_2O_3 and Cr_2O_3 contents in the Fe-rich olivine rims (Mg# = 66.5–82.8) are 0.04–0.15 and 0.3–0.4 wt%, respectively, with variable CaO contents of 0.14–0.37 wt% and NiO contents of 0.05–0.11 wt%. The Fe/Mn molar ratios are 85.3–110.

Oxygen Isotopes in Olivine

Oxygen isotope analyses were performed on five points in olivine in the lithic clast and 10 spots on different olivine grains (four spots for forsteritic cores and six spots for Fe-rich olivine rims) in a type IIA chondrule. The results are summarized in Table 2 and plotted in Fig. 3. Oxygen isotopic compositions of olivine grains in the lithic clast plot below the carbonaceous chondrite anhydrous minerals (CCAM) line (Fig. 3), and the $\Delta^{17}O$ values vary from $-3.9‰$ to $-0.8‰$.

Oxygen isotopic compositions of olivine in the type IIA chondrule exhibit a large variation. The forsteritic core is relatively ^{16}O-rich ($\Delta^{17}O = -0.7‰$ to $+1.3‰$), whereas the more Fe-rich rim is relatively ^{16}O-poor ($\Delta^{17}O = +0.4‰$ to $+6.1‰$). Generally, oxygen isotopic compositions in olivine from the type IIA chondrule plot above the terrestrial fractionation line (TFL), and their distribution is parallel to the CCAM line (Fig. 3). The ranges of oxygen isotope compositions of olivine in type I chondrules (Leshin et al. 2000) and

Table 1. Representative mineral compositions in the lithic clast and chondrules from the GRV 021536 CM2 chondrite.

	Lithic clast							Type I	Type IIA olivine	
	Olivine	Diopside		Chromite	Nepheline	Plagioclase	Merrillite	Olivine	Core	Rim
SiO_2	36.4	51.8	49.4	0.10	44.7	57.1	0.04	43.3	43.1	37.5
TiO_2	0.05	0.73	0.67	4.43	< 0.03	0.07	< 0.03			
Al_2O_3	< 0.03	2.31	5.37	21.8	35.9	28.1	< 0.03	0.13	0.46	0.06
Cr_2O_3	< 0.03	0.65	0.67	34.6	< 0.03	< 0.03	< 0.03	0.59	0.07	0.33
MgO	30.1	13.7	13.0	5.71	< 0.03	< 0.03	3.34	55.2	56.0	32.3
FeO	32.6	6.22	5.84	32.9	0.85	0.64	1.69	1.12	0.57	29.2
MnO	0.29	0.08	0.06	0.26	< 0.03	< 0.03	< 0.03	0.13	< 0.03	0.29
CaO	0.28	23.7	24.3	0.32	2.67	9.17	47.0	0.22	0.70	0.37
Na_2O	0.03	0.49	0.40	< 0.03	13.6	5.79	2.78			
K_2O	< 0.03	< 0.03	< 0.03	< 0.03	2.35	0.07	0.04			
P_2O_5	< 0.03	< 0.03	0.04	< 0.03	< 0.03	< 0.03	45.9			
NiO	0.11							0.03	< 0.03	0.11
Total	99.9	99.7	99.8	100.1	100.1	100.9	100.8	100.7	100.9	100.2
Mg#	62.4	79.9	80	23.8				98.9	99.4	66.5
An						46.5				

Mg# = 100*Mg/(Mg + Fe) in moles. An = 100*Ca/(Ca + Na + K) in moles.

Table 2. Oxygen isotopic compositions in olivine from the lithic clast and a type IIA chondrule in GRV 021536.

	$\delta^{18}O \pm 1\sigma$ (‰)	$\delta^{17}O \pm 1\sigma$ (‰)	$\Delta^{17}O$ (‰)
Olivine in the lithic clast			
Ol_LC_1	9.1 ± 1.0	2.4 ± 2.0	−2.3
Ol_LC_2	7.0 ± 1.0	1.1 ± 2.1	−2.5
Ol_LC_3	7.8 ± 1.0	2.4 ± 2.0	−1.6
Ol_LC_4	6.5 ± 1.0	−0.5 ± 1.9	−3.9
Ol_LC_5	9.2 ± 1.0	3.9 ± 1.9	−0.8
Forsterite core in the type IIA chondrule			
Ol_Ch_4	−7.6 ± 1.0	−4.7 ± 2.0	−0.7
Ol_Ch_5	−8.1 ± 1.0	−3.9 ± 2.0	0.3
Ol_Ch_6	−7.6 ± 1.0	−4.5 ± 2.0	−0.6
Ol_Ch_7	−6.2 ± 1.0	−1.9 ± 2.0	1.3
Fe-rich olivine rim in the type IIA chondrule			
Ol_Ch_1	4.5 ± 1.0	6.1 ± 2.0	3.7
Ol_Ch_2	2.5 ± 1.0	1.7 ± 2.0	0.4
Ol_Ch_3	3.5 ± 1.0	4.3 ± 2.0	2.5
Ol_Ch_8	−1.1 ± 1.0	3.8 ± 2.0	4.4
Ol_Ch_9	−0.1 ± 1.0	3.4 ± 2.0	3.5
Ol_Ch_10	3.1 ± 1.0	7.7 ± 2.0	6.1

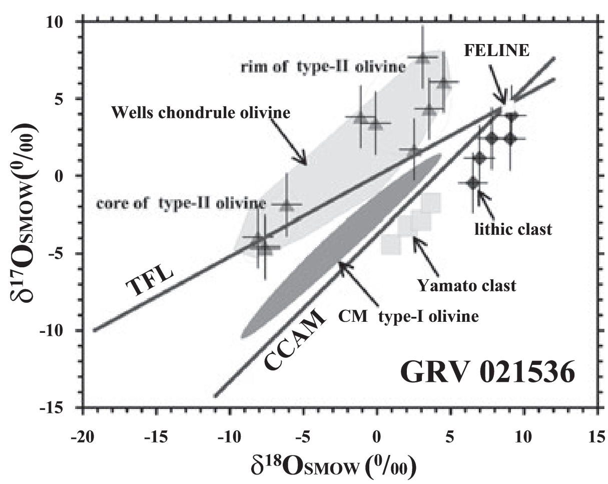

Fig. 3. Oxygen isotopic compositions of olivine in the lithic clast and a type IIA chondrule from GRV 021536. Black diamonds are data of olivine in the lithic clast. Gray triangles are data of olivine in the type II chondrule in GRV 021536. The range of oxygen isotopic compositions in olivines from CM type I chondrules (dark area, Leshin et al. 2000) and from type II chondrules in the Wells ordinary chondrite (gray area, Ruzicka et al. 2007), the bulk oxygen isotopic compositions (white square) of the FELINE clast from Parnallee (LL3.6) (Bridges et al. 1995), and the oxygen isotopic compositions (gray squares) in olivine of clast from Yamato-86009 (Jogo et al. 2008) are also shown for comparison.

of olivine in the Wells ordinary chondrite (Ruzicka et al. 2007) are also shown in Fig. 3 for comparison.

DISCUSSION

Exotic Origin of the Lithic Clast

The GRV 021536 meteorite is a newly defined CM chondrite, based mainly on high abundance of matrix, high-degree of hydration of matrix and chondrules, size distribution of chondrules (Scott 2007). Types of CAIs are also similar to other CM chondrites, e.g., dominance of spinel-diopside inclusions and lack of melilite-rich CAIs. Although chondrules were not systematically measured in GRV 021536, oxygen isotopic compositions in olivine from a type IIA chondrule generally plot above the TFL, similar to some type II chondrules in CR chondrites and to type II chondrules in ordinary chondrites (e.g., Ruzicka et al. 2007; Connolly et al. 2008). This similarity is consistent with the suggestion by Connolly et al. (2008) that some type II chondrules could be related to ordinary chondrites. Thus, its oxygen isotopic compositions of olivine in the lithic clast are not unusual. All the above observations support GRV 021536 as a typical CM chondrite.

The lithic clast in this CM chondrite has several unique characteristics distinguishing from refractory inclusions, normal chondrules, and the matrix. (1) The lithic clast has an irregular shape, without a fine-grained rim, implying that it is a lithic fragment. (2) The lithic clast consists dominantly of coarse olivine grains, which is distinct from Ca, Al-rich refractory inclusions. (3) Olivine in the lithic clast is relatively Fe-rich, compared to olivine in type I and even type IIA chondrules in CM chondrites. Olivine in the lithic clast is homogeneous in major and minor elements, whereas that in type IIA chondrules shows chemical zoning. (4) The mineral assemblage of the lithic clast is different from that of normal chondrules. Merrillite, chromite, plagioclase (An ~45), and nepheline are a rare assemblage in chondrules. (5) Minor-element compositions of olivine in the lithic clast are distinctly different from those of olivine in type I and type IIA chondrules from the CM chondrite. NiO content of olivine in the lithic clast is higher than that of olivine in chondrules, and Cr_2O_3 and Al_2O_3 contents are significantly lower than in chondrules (Table 1). (6) Oxygen isotopic compositions of olivine in the lithic clast are distinctly different from those of olivine in type I (Leshin et al. 2000) and type IIA chondrules (Fig. 3). It should be apparent from these observations that the lithic clast is distinctly different from normal components in CM chondrites, and it may have an exotic origin.

Precursor of the Lithic Clast and Its Partial Melting

Based on the apparent mineral assemblage, the precursor of the lithic clast should consist mainly of ferromagnesian silicates (e.g., olivine and diopside), plagioclase, nepheline, and sulfide. This mineral assemblage is well consistent with chondrules that have experienced low-temperature anhydrous alteration (e.g., Kimura and Ikeda 1997). During the anhydrous alteration, olivine became Fe-enriched and the mesostasis became Na-, K-enriched. Thus, chondrules that have experienced low-temperature anhydrous alteration could be the potential precursor of the lithic clast observed in GRV 021536.

Electron microprobe results show that olivine in the lithic clast is homogeneous in major and minor elements, which could be a result of strong thermal metamorphism. If assuming that chondrule olivine in unequilibriated chondrites contains high Cr_2O_3 and/or Al_2O_3 (e.g., Grossman 2004; Wang and Hsu 2009; Zhang and Hsu 2009), low Al_2O_3 and Cr_2O_3 contents (below the detection limit 0.03 wt%) in olivine from the lithic clast support this suggestion. Grossman (2004) presented statistics for the distribution of Cr_2O_3 contents in olivine from different petrologic types (corresponding to various degrees of thermal metamorphism) of carbonaceous and ordinary chondrites. He found that Cr_2O_3 content decreases with increasing petrologic types (increasing degrees of thermal metamorphism). This suggests that thermal metamorphism is a significant factor controlling the Cr concentration of olivine. Although the correlation between Al concentration in olivine and petrologic types of chondrites remains unclear, thermal metamorphism could also be a major factor controlling Al concentration in olivine. In the case of the lithic clast in GRV 021536, the precursor of the lithic clast could have experienced a prolonged heating event that caused Cr and Al to diffuse out of the olivine structure and produced Al-rich chromite (Fig. 2).

Formation of merrillite in the clast could also be related to thermal metamorphism of its precursor. A few olivine grains from the Ningqiang chondrite contain up to 4 wt% P_2O_5 (Wang et al. 2007), and thermal metamorphism could diffuse P and Ca out of olivine crystals. However, if phosphorus was indeed derived from olivine, a high-degree of thermal metamorphism is needed to form merrillite, because diffusion of P in olivine is extremely slow (Milman-Barris et al. 2008). Phosphorus concentration of 0.1–1 wt% is also common in metal grains from low-grade metamorphosed, ordinary and carbonaceous chondrites (Zanda et al. 1994). Thus, metal could be another possible source of phosphorus. However, if the P is from the metal simple, thermal metamorphism (solid-state thermal diffusion) cannot explain the inclusion of merrillite in olivine.

Based on the inclusion of euhedral Al-rich chromite in diopside, it appears that the chromite preceded the formation of the diopside. Assuming that the Al-rich chromite grain is equilibrated with olivine, the minimum equilibrium temperature is 828 °C (Ballhaus et al. 1991). However, using the high-Ca pyroxene thermometer of Kretz (1982), the composition of diopside in the lithic clast results in a maximum temperature of 679 °C. Thus, the olivine-spinel and diopside thermometers show a temperature difference of at least 150 °C, indicating that olivine and diopside are not in complete equilibrium. The disequilibrium between olivine and diopside is also supported by the large difference in terms of Mg# value (Table 1).

A partial melting model due to thermal metamorphism could explain the textural features and mineral assemblage of this lithic clast. During thermal metamorphism, some materials in its precursor were melted, whereas olivine and anorthite were preserved and rim of olivine was absorbed into melt. The absorption of rim of olivine is consistent with the rounded outline of olivine. At the same time, merrillite formed due to diffusion of P in olivine; Cr and Al diffused into the melt and formed the Al-rich chromite. Then, diopside, nepheline, and pentlandite could form simultaneously; this could explain the texture that diopside is direct contact with nepheline and the large difference of Mg# values between olivine and diopside. The presence of pentlandite could consume most iron in the melt; that buffered the partitioning of Fe into diopside crystal structure and resulted in the high Mg# value of diopside. Rout and Bischoff (2008) suggested that nepheline in CAIs from R chondrites were transformed into Ab-rich plagioclase under thermal metamorphism. However, in the case of the lithic clast, no apparent replacement or other reaction was observed between plagioclase and nepheline. In addition, if the plagioclase was transformed from nepheline, other K-bearing minerals except nepheline would occur because nepheline in the clast contains 2.35 wt% K_2O and plagioclase contains very low K_2O (0.07 wt%); however, no such minerals were observed although sampling bias cannot be completely excluded.

Comparison with Other Lithic Clasts and Meteorites and Implications

Lithic clasts with mineral assemblages similar to that of the lithic clast in GRV 021536 have been observed in two CV3 chondrites, Mokoia and Yamato-86009 (Cohen et al. 1983; Krot and Hutcheon 1997; Krot et al. 1998; Jogo et al. 2008; Jogo and Nakamura 2009). Olivine, diopside, plagioclase, and nepheline in the Mokoia clasts have compositions that are almost identical to those in GRV 021536 (Krot and Hutcheon 1997). However, the mineral assemblages and textures of the Mokoia clasts are slightly different from that in GRV 021536. These include: (1) the Mokoia clasts have granular and radial textures; (2) the granular clast in Mokoia has smaller olivines (<30 μm; Krot et al. 1998) than the GRV clast (>50 μm); (3) the Mokoia clasts have a higher abundance of pyroxene than the GRV clast; and (4) merrillite was not observed in the Mokoia clasts. The similarity of mineral compositions between these clasts in Mokoia and the lithic clast in GRV 021536 suggests a common affinity. Differences in mineral assemblage could be due to sampling bias, and differences in textural features could be a result of formation at different depths in their parent bodies. Krot et al. (1998) suggested that the Mokoia clast could represent materials from the interior of the CV3 parent body. The clast in GRV 021536 might represent a deeper material than the Mokoia clasts. However, no oxygen isotopic compositions of lithic clasts in the Mokoia CV3 chondrite were reported.

The lithic clast (olivine-rich aggregates) in Yamato-86009 (Jogo et al. 2008) is also similar to the GRV clast. The Yamato clast consists mainly of coarse-grained olivine and interstitial pyroxene and plagioclase; sulfide is large; merrillite, nepheline, and chromite were not observed. Compositions of olivine (Fa_{33-35}) and plagioclase (An_{54-60}) (Jogo and Nakamura 2009) in the Yamato clast are generally similar to those in the Mokoia and GRV clasts. Similar textures and mineral compositions of silicate minerals suggest that the Yamato clast could also have a common source with the Mokoia and GRV clasts. Jogo et al. (2008) reported oxygen isotopes of olivine in the Yamato clast of lower $\delta^{18}O$ values (~1–4‰) than that in the GRV clast (6.5–9.2‰), but both clasts plot along and below the CCAM line (Fig. 3). If the Yamato clast came from the same parent body as those in GRV and Mokoia, the oxygen isotope diversity might suggest that their source regions were not completely homogenized in oxygen isotopic compositions.

A feldspar-nepheline clast (referred as FELINE) was reported in Parnallee (LL3.6) by Bridges et al. (1995). The FELINE is composed of plagioclase (An_{83-87}) and nepheline (0.01–0.44 wt% K_2O), which are different from those in the GRV, Mokoia, and Yamato clasts. However, the bulk oxygen isotopes ($\delta^{17}O = +4.5$‰ and $\delta^{18}O = +8.9$‰) of the FELINE clast are similar to those of olivine in the GRV clast (Fig. 3), within analytical errors. Due to the similarity in oxygen isotopes, we cannot completely exclude the possibility that the FELINE and the GRV clast may have a common origin.

Based on petrographic texture and high abundances of chondrules (~5 vol%), Krot et al. (1998) suggested that the Mokoia clast could be derived from the interior of the CV3 asteroid. Similarities between the Mokoia and GRV clasts might imply that the GRV clast was also derived from the CV asteroid. Several other groups of chondrites (e.g., H, L, LL, CR, CK, and R) contain Fe-rich olivine and have experienced strong thermal metamorphism. However, these chondrites could not be the source of the Mokoia, GRV, and Yamato clasts. Olivines in LL6 chondrites ($Fa_{<35}$, Sears and

Dodd 1988; Krot and Hutcheon 1997) have lower Fa contents than those in the GRV clast. Chromite in metamorphosed ordinary chondrites are usually Al-poor (Bunch et al. 1967), different from that in the lithic clast (Table 1). Olivine in the lithic clast is also more Fe-rich than those in CK6 (Fa_{29-33}, Krot et al. 2003) and in CR6 chondrites (Fa_{29}, Bourot-Denise et al. 2002). Fe-rich olivine was reported in Rumuruti (R) chondrites, where olivine is abundant (70 vol%, Schulze et al. 1994; Bischoff et al. 1994; Rubin and Kallemeyn 1994). The Fa contents (Fa_{39}) in olivine from R chondrites are identical to that in the Mokoia and GRV clasts, and the former also contains high NiO (0.19 wt%). However, olivines in R chondrites have lower CaO (< 0.1 wt%) contents than those in the GRV clast. In addition, high-Ca pyroxene ($En_{42}Fs_{11}Wo_{47}$) and plagioclase (An_{7-12}) in R chondrites are also different in chemistry from those in the GRV clast. Oxygen isotopic compositions of olivine in the GRV clast are also significantly different from those of olivine in R chondrites (Greenwood et al. 2000).

If the lithic clast described in this study was indeed derived from the CV asteroid, its occurrence in a CM chondrite indicates that the primitive CV asteroid would have accreted earlier than the CM chondrite. In such a scenario, a later impact event disrupted the primitive CV asteroid, and some clasts accreted into late CV asteroid and the CM asteroid. This model could explain why similar clasts were observed in two CV chondrites (e.g., Mokoia and Yamato-86009, Cohen et al. 1983; Krot and Hutcheon 1997; Krot et al. 1998; Jogo et al. 2008; Jogo and Nakamura 2009) and a CM chondrite in this present study. CM chondrites including GRV 021536 are extensively hydrated rocks. However, no alteration products (e.g., phyllosilicate, iron oxide/hydroxide) were observed in the lithic clast. The apparent lack of hydration in this lithic clast suggests its late addition into the CM parent body after hydration of most CM components.

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