An unusual lithic clast in the Grove Mountains 021536 CM2 chondrite: Petrography, mineralogy, and oxygen isotopes. A. Zhang[1,2], Y. Guan[3], W. Hsu[1], Y. Liu[2], A. D. Patchen[2], and L. A. Taylor[2]. [1]Purple Mountain Observatory, Nanjing 210008, China, (aczhang@pmo.ac.cn); [2]Planetary Geosciences Institute, Department of Earth & Planetary Sciences, University of Tennessee, Knoxville TN 37996; [3]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena CA 91125.

Introduction: Equilibrated lithic clasts in unequilibrated chondrites probably represent thermal metamorphism in the early solar system before or during accretion of chondritic parent bodies. Lithic clasts with equilibrated features are rare in unequilibrated chondrites and their origins are not well-understood [1]. Recently, we observed an unusual lithic clast with thermal-metamorphosed features in Grove Mountains (GRV) 021536, a new CM2 chondrite found by the Chinese Antarctic Meteorite Exploration Team [2]. Here, we report its petrography, mineralogy, oxygen isotopes, and discuss their implications.

Analytical methods: Back-scattered electron (BSE) images of the equilibrated lithic clast were taken with a Hitachi 3400N scanning electron microscope. Mineral compositions were measured using JEOL 8100 and Cameca SX100 electron microprobes. Oxygen isotope analyses of olivine grains were performed with the Cameca Nano-SIMS 50L ion microprobe at Caltech. A rastering (3x3 μm) Cs^+ beam of ~5 pA in intensity was used to sputter the gold-coated sample surface and to produce secondary ions. The $^{16}OH^-$ interference to $^{17}O^-$ was eliminated with a high mass resolving power of ~7500. All $^{16}O^-$, $^{17}O^-$, and $^{18}O^-$ were simultaneously measured with electron multipliers. Five spots on olivine grains in the equilibrated lithic clast and ten spots on olivine grains in a type-II chondrule were analyzed; 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 (Fa_{11}) was used as a standard.

Results: The ~200 μm lithic clast observed in GRV 021536 is irregular in shape and consists dominantly of subhedral-euhedral olivine grains (Fig. 1). Plagioclase grains are also subhedral to euhedral and only occur in contact with olivine. Diopside, nepheline, and pentlandite occur as interstitial phases among olivine grains, and diopside and nepheline coexist with each other. No replacement textures were observed between nepheline and plagioclase. One euhedral Al,Ti-rich chromite grain occurs as an inclusion in a diopside grain, and an anhedral merrillite grain is included in an olivine grain (Fig. 1).

Representative compositions of minerals in the lithic clast are given in Table 1. Olivine grains are homogeneous and are Fe-rich (Fo_{62}) compared to olivine grains in chondrules. Diopside grains are Fe-rich (5.84–6.22 wt% FeO) and contain variable Al_2O_3 (2.31–5.37 wt%). The chromite grain contains high Al_2O_3 (21.8 wt%) and TiO_2 (4.43 wt%). Plagioclase grains (andesine) show slight compositional variations ($An_{43–46.5}$). Nephelines are also variable in composition, with CaO of 2.27–2.67 wt% and K_2O of 0.97–2.35 wt%. Merrillite contains noteable contents of Na_2O, MgO, and FeO (Table 1). Chondrule olivines for oxygen isotopic comparison are zoned with forsteritic cores (Fo_{100}) and Fe-rich rims (Fo_{67}).

Oxygen isotopic compositions of olivine grains from the lithic clast and those of olivines in a type-II chondrule from GRV 021536 and in type-I chondrules in other CM2 chondrite [3] are shown in Fig. 2. The $\delta^{18}O$ and $\delta^{17}O$ values of olivine grains from the lithic clast vary from +6.5 to +9.2 ‰ and -0.5 to +3.9 ‰, respectively. Oxygen isotopes of olivine grains from the type-II chondrule have a large variation. The forsteritic core is relatively ^{16}O-rich ($\delta^{18}O$ = -6.2 ‰ to -8.1 ‰ with $\delta^{17}O$ = -1.9 ‰ to -4.7 ‰), while the Fe-rich rim is relatively ^{16}O-poor ($\delta^{18}O$ = -1.1 ‰ to +4.5 ‰ with $\delta^{17}O$ = +1.7 ‰ to +7.7 ‰).

Discussion: There are several lines of evidence supporting the fact that the lithic clast in GRV 021536 has experienced thermal metamorphism: 1) Olivine and diopside grains are homogeneous; 2) The sulfide grain occurs as an interstitial phase, whereas sulfide grains in chondrules commonly occur as spheres due to liquid immiscibility between silicate melt and FeNi-sulfide melt; 3) The occurrence of merrillite and Al,Ti-rich chromite is an obvious result of strong thermal metamorphism; and 4) Nepheline is not in contact with plagioclase, indicating that nepheline is not an alteration product of plagioclase or *vice versa*. Instead, the formation of nepheline probably resulted from the thermal metamorphism. All this is in contrast to the observations that most materials in CM chondrites have not experienced a high degree of thermal metamorphism. Thus, the petrography and mineralogy suggest that the lithic clast in GRV 021536 is of some exotic origin.

Oxygen isotopic compositions of olivine grains in the lithic clast are different from those of olivine grains in the type-II chondrule from the same chondrite and from those of olivines in type-I chondrules in other CM chondrite [3]. These differences suggest that the lithic clast has a different source from those in normal chondrules from CM chondrites. An exotic origin is very likely. Similar equilibrated lithic clasts have been described in the Mokoia CV3 chondrite [4, 5]. The Mokoia clasts contain some rare Ni-rich taenite, but no merrillite grain was reported. However, minerals in the lithic clast from GRV 021536 have similar chemical compositions. This might suggest a common affinity for these two suites of clasts. A feldspar-nepheline clast (FELINE) was reported in Parnallee (LL3.6) [6]. FELINE has a different mineral assemblage and composition from the GRV 021536 and Mokoia lithic clasts. However, the bulk oxygen isotopes ($\delta^{17}O$ = +4.5 ‰ and $\delta^{18}O$ = +8.9 ‰) of the FELINE clast are close to those of olivine grains in the lithic clast from GRV 021536 (Fig. 2), within analytical errors. The possibility exists that the FELINE clast also has a source similar to that of the lithic clast from GRV 021536.

The occurrence of abundant olivine and nepheline suggests that the precursor could have been SiO_2-unsaturated; if the precursor was SiO_2-saturated, nepheline would be unstable, and some back-reaction low-Ca pyroxene would have been observed on the olivine grains. In fact, no low-Ca pyroxene grain was observed in the clast. At the same time, the existence of Fe-rich olivine, Fe-rich diopside, chromite, merrillite, nepheline, and andesine implies that the precursor is enriched in the moderately volatile elements (Fe, Cr, P and Na).

Cohen et al. [4] and Krot and Hutcheon [5] proposed two models (nebular and asteroidal) to interpret the origin of the Mokoia clasts. If the lithic clast in GRV 021536 has a nebular origin (formed by recrystallization of fine-grained dust aggregates during sintering in the solar nebula) [4, 5], one candidate for its precursor might be related to amoeboid olivine aggregates that have experienced low-temperature alteration, which usually results in formation of Fe-rich or alkali-rich secondary phases [7]. If an asteroidal origin is considered, the mineralogy of the lithic clast in GRV 021536 does not match any known metamorphosed ordinary or carbonaceous chondrites, as well as achondrites [5]. This unusual lithic clast might represent a fragment from a previously unsampled asteroid.

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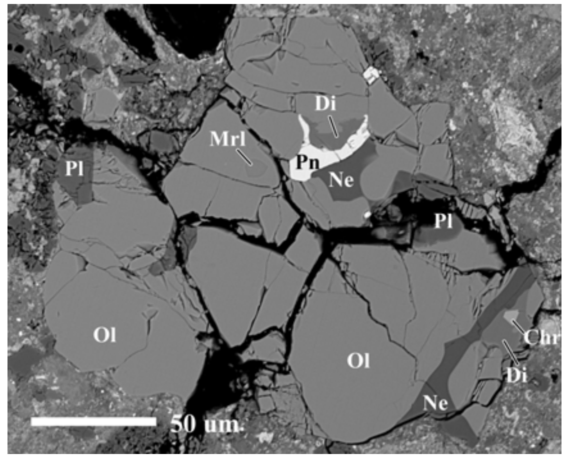

Figure 1. BSE image of the equilibrated lithic clast in GRV 021536. Ol-olivine; Di-diopside; Pl-plagioclase; Mrl-merrillite; Ne-nepheline; Pn-pentlandite; Chr-chromite.

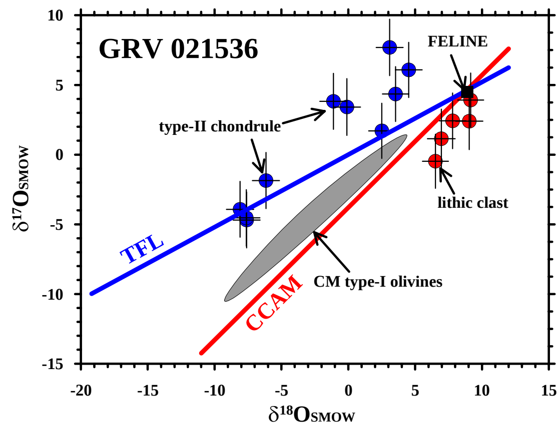

Figure 2. Oxygen isotopic compositions of olivines in the equilibrated lithic clast (red dots) and a type-II chondrule (blue dots) from GRV021536. An oxygen isotopic range of CM olivines from type-I chondrules [2] and the bulk oxygen isotopes of FELINE clast from Parnallee (LL3.6) are also shown [5].

Table 1. Representative compositions of minerals in the equilibrated lithic clast from the GRV 021536 CM2 chondrite.

	Ol	Di	Chr	Ne	Pl	Mrl
SiO_2	36.4	51.8	0.10	44.7	57.1	0.04
TiO_2	0.05	0.73	4.43	<0.03	0.07	<0.03
Al_2O_3	<0.03	2.31	21.8	35.9	28.1	<0.03
Cr_2O_3	<0.03	0.65	34.6	<0.03	<0.03	<0.03
MgO	30.1	13.7	5.71	<0.03	<0.03	3.34
FeO	32.6	6.22	32.9	0.85	0.64	1.69
MnO	0.29	0.08	0.26	<0.03	<0.03	<0.03
CaO	0.28	23.7	0.32	2.67	9.17	47.0
Na_2O	0.03	0.49	<0.03	13.6	5.79	2.78
K_2O	<0.03	<0.03	<0.03	2.35	0.07	0.04
P_2O_5	<0.03	<0.03	<0.03	<0.03	<0.03	45.9
NiO	0.11	n.a.	n.a.	n.a.	n.a.	n.a.
Total	99.86	99.68	100.1	100.1	100.9	100.8
Mg#	0.62	0.80	0.24			

n.a.: not analyzed; Mg#: Mg/(Mg+Fe) in moles. Mineral abbreviations are the same as in Figure 1.