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Evidence for a multilayered internal structure of the chondritic acapulcoite-lodranite parent asteroid

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Abstract

We report a petrography, mineral chemistry, oxygen and chromium isotopic study of Grove Mountains (GRV) 020043 together with a subset of other acapulcoites and lodranites. GRV 020043 is a petrologic type 4 chondrite, with chondrules of diverse types and sizes, and is composed of low-Ca pyroxene (40 vol.%), olivine (24 vol.%), diopside (8 vol.%), plagioclase (10 vol.%), Fe-Ni metal (kamacite and taenite), troilite and some accessory minerals (chromite and apatite). The olivine in GRV 020043 has an average fayalite content (Fa) of 10.7 mol.% with the low-Ca pyroxene having an average ferrosilite content (Fs) of 10.8 mol.%. The whole rock oxygen isotopic composition of GRV 020043 is +3.226 ± 0.267‰, +0.797 ± 0.131‰, and −0.927 ± 0.017‰ for $\delta^{18}O$, $\delta^{17}O$, and $\Delta^{17}O$, respectively, with a bulk chromium isotopic compositions of $\varepsilon^{54}Cr = -0.48 \pm 0.10$. These characteristics of GRV 020043 are different from all established or ungrouped chondrites but agree with those of the acapulcoite-lodranite clan. We therefore suggest that GRV 020043 represents the chondritic precursor of acapulcoite-lodranite parent body.

The similarity of bulk oxygen and chromium isotopic compositions among GRV 020043, Acapulco, Northwest Africa (NWA) 468 (metal-rich lodranite), NWA 8118 (lodranite), NWA 8287 (acapulcoite), and NWA 8422 (lodranite) indicates that they originated from a common oxygen and chromium reservoir in the protoplanetary disk or may have derived from a parent body with a differentiated multilayer structure.

Keywords: GRV 020043; Acapulcoite; Lodranite; Oxygen isotope; Chromium isotope

1. INTRODUCTION

Grove Mountains (GRV) 020043 petrographically resembles a CR-type chondrite and has many chemical

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affinities to that of the acapulcoite-lodranite clan. Therefore, it is an ideal sample to examine the genetic relationships predicted by Rubin (2007). GRV 020043 was collected during the Chinese Antarctic Research Expedition in 2002 from the surface of a blue ice field in the Grove Mountains, Antarctica. This meteorite was originally classified as an ordinary chondrite (type H4) according to its petrographic and mineralogical composition (Meteoritical Bulletin No. 93), and later re-classified as a transitional type between H and E chondrites (Li et al., 2011a). In this study, we show that neither classification is correct, and that this meteorite rather documents the chondritic precursor of the acapulcoite-lodranite clan. Diverse petrological variations in the acapulcoite-lodranite clan might suggest a multi-layer structure of its parent body beyond the two-layer asteroid previously proposed by Eugster and Lorenzetti (2005).

We report detailed petrographic and mineralogical observations of GRV 020043 (the first petrologic type 4 "Acapulco" chondrite), and the oxygen and Cr isotopic compositions of GRV 020043, GRV 021663 (acapulcoite), Northwest Africa (NWA) 468 (ungrouped iron), NWA 8054 (ungrouped achondrite), NWA 8118 (lodranite), NWA 8422 (lodranite), Acapulco, and NWA 8287 (acapulcoite). Oxygen isotopes when combined with Cr isotopes provide a new robust tool for meteorite classification (Yin et al., 2009; Warren, 2011a,b; Sanborn et al., 2013; Sanborn et al., 2014a, 2014b; Sanborn and Yin, 2014; Schmitz et al., 2016).

The acapulcoite-lodranite clan is composed of two groups of achondrites, acapulcoites and lodranites, with a couple of transitional acapulcoite/lodranite meteorites (Kimura et al., 1992; Patzer et al., 2004; Eugster and Lorenzetti, 2005; Rubin, 2007; Crowther et al., 2009; Dhaliwal et al., 2017). These meteorites were proposed to come from a common parent asteroid based on oxygen isotopic compositions, mineral chemistry, as well as cosmic-ray exposure ages (Nagahara, 1992; McCoy et al., 1996; Clayton and Mayeda, 1996; McCoy et al., 1997a,b; El Goresy et al., 2005; Dhaliwal et al., 2017). El Goresy et al. (1995) reported that the Acapulco meteorite contains isotopically heterogeneous graphite material, indicating that its parent body was not homogenized, although it experienced pervasive heating and partial melting. Eugster and Lorenzetti (2005) suggested a two-layer structure for the acapulcoite-lodranite parent asteroid, where acapulcoites comprised the outer layer and lodranites the inner layer, while Dhaliwal et al. (2017) inferred melt-pool domains in the interior. Acapulcoites are similar to ordinary chondrites in mineral assemblage and modal abundances, despite a distinct oxygen isotopic composition between the two groups (Clayton and Mayeda, 1996; Irving et al., 2007). A few relict chondrules have been observed in several acapulcoites (e.g. Allan Hills (ALHA) 77081, Schultz et al., 1982; Yamato (Y-)74063, Yanai and Kojima, 1991; Monument Draw, McCoy et al., 1996; Graves Nunataks (GRA) 98028, Dhofar 1222, Benedix and Lauretta, 2006; Rubin, 2007). Compared with acapulcoites, lodranites are coarser grained and more depleted in troilite and/or plagioclase, and exhibit higher variability in metal abundance (Mittlefehldt et al., 1996; McCoy et al., 1996, 1997a, 1997b; Rubin, 2007). There is evidence suggesting that basaltic melts were present and migrated in lodranites (McCoy et al., 1996; Patzer et al., 2004; Floss, 2000). Transitional acapulcoite/lodranite samples spanning both groups (e.g. GRA 95209, ALHA 81187, and Elephant Moraine (EET) 84302) have also been reported (Floss, 2000; Eugster and Lorenzetti, 2005). The metal-rich lodranite GRA 95209 was previously proposed to hold information on the earliest stages of the core formation process on asteroids (McCoy et al., 2006). The characteristics of the acapulcoite-lodranite clan indicate they might record the entire evolutionary process from chondritic precursor material to the early stages of core formation.

Although it has been suggested that the acapulcoite-lodranite clan originated from the partial melting and thermal metamorphism of chondritic material (Palme et al., 1981; Nagahara, 1992; Zipfel et al., 1995; McCoy et al., 1996, 1997a, 1997b; Mittlefehldt et al., 1996; Floss et al., 2000; Patzer et al., 2004; Krot et al., 2005; Rubin, 2007), the nature of the precursor chondritic material remains elusive. However, Rubin (2007) proposed that the chondritic precursor of acapulcoites might be similar to the CR chondrites. Based on the measurements in this study and published data we discuss the possible interior structure of the acapulco-lodranite parent body.

2. SAMPLES AND ANALYTICAL TECHNIQUES

2.1. Sample descriptions

Eight meteorites were analyzed within this study: GRV 020043, GRV 021663, NWA 468, NWA 8054, NWA 8118, NWA 8287, NWA 8422, and NWA 11187. These eight samples encompass both typical acapulcoite and lodranites, as well as ungrouped achondrites that show strong similarities, but exhibit minor mineralogical or chemical differences to, typical acapulcoites and lodranites. Petrography descriptions of GRV 020043 and NWA 8118 are discussed in the results section. Here, we briefly provide overview descriptions of GRV 021663, NWA 468, NWA 8054, NWA 8287, NWA 8422, and NWA 11187.

(1) Northwest Africa 468 is an ungrouped iron originally proposed to be a silicate-rich member of the IAB iron meteorite complex by Rubin et al. (2002).
(2) Northwest Africa 8054 (ungrouped achondrite) is a relatively coarse-grained achondrite composed of olivine, orthopyroxene and clinopyroxene with sporadic plagioclase and Cr-troilite phases (Irving et al., 2014).
(3) Northwest Africa 8287 is a fine-grained acapulcoite with a silicate fraction composed of predominantly orthopyroxene (~95%) and lesser amounts of plagioclase (~3%), and clinopyroxene (~2%) with no observed olivine and a sizable portion of the sample (~25%) being kamacite and troilite (Keil and McCoy, 2018 and Meteoritical Bulletin No. 103).
(4) Northwest Africa 8422 (along with paired stone NWA 8410) is a coarse-grained lodranite composed

of olivine, high- and low-Ca pyroxene, and Cr-bearing troilite (Kuehner et al., 2015).

(5) Northwest Africa 11187 (ungrouped achondrite) is a coarse-grained achondrite with large low-Ca pyroxene grains encasing chadacrysts of olivine.

(6) GRV 021663 (acapulcoite) was originally classified as an acapulcoite based on the mineralogical and chemical composition (Meteoritical Bulletin No. 95). However, subsequent oxygen isotopic analyses instead suggest GRV 021663 should be classified as a winonaite (Li et al., 2011b). GRV 021663 is primarily composed of olivine, orthopyroxene, high-Ca pyroxene, troilite, and kamacite, a similar mineralogical assemblage to that seen in acapulcoites (Li et al., 2011b).

2.2. Analytical techniques

One polished thin section with a standard thickness of 30 microns and a polished section, labeled GRV 020043-2 and GRV 020043-3 (Fig. 1a and b), respectively, were prepared for mineralogical and petrographic investigation. One polished section of NWA 8118 labeled "NWA 8118-1" was also prepared for mineral chemistry measurements and texture characterization.

Petrographic characterization and micro-imaging was carried out using an OLYMPUS-BX51 polarizing microscope and a JSM-6460LV scanning electron microscope equipped (SEM) with an EDAX energy-dispersive X-ray spectrometry at the State Key Laboratory of Environmental Geochemistry, Chinese Academy of Sciences (SKLEG, CAS). A Scios-FIB field emission scanning electron microscope (at the Institute of Geochemistry, CAS) was used for NWA 8118 petrographic investigation and to obtain backscattered electron (BSE) images. In situ analyses of mineral compositions (except plagioclase) were made using a Shimadzu EPMA-1600 electron microprobe at the State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences (SKLODG, CAS). Plagioclase chemical composition measurements were performed using a CAMECA SXFiveFE EPMA at the Institutions of Geology and Geophysics, Chinese Academy of Sciences. Whole rock elemental concentration measurements were made using a combination of a Varian Vista-MPX inductively coupled plasma-optical emission spectrometer, a Perkin-Elmer 5100-PC atomic absorption spectrometer, and a Perkin Elmer Elan DRC-e inductively coupled plasma mass spectrometer at SKLEG, CAS. The bulk oxygen isotopic compositions of GRV 020043 and GRV 021663 was measured at Louisiana State University (LSU) and University of New Mexico (UNM), while the bulk oxygen isotopic composition of NWA 8118 was measured at UNM. Eight samples were analyzed for Cr isotopic composition: GRV 020043, GRV 021663, NWA 468, NWA 8054, NWA 8118, NWA 8287, NWA 8422, and NWA 11187. All of the eight samples were measured using a Thermo *Triton Plus* thermal ionization mass spectrometer at the University of California at Davis. Detailed analytical information is available in the on-line supplementary information.

3. RESULTS

3.1. Petrography

The GRV 020043 main mass is an irregular spheroid, with a total mass of 56.9 g and dimensions of 5.5 × 5 × 4.5 cm. Approximately 95% of the surface was covered with black fusion crust. GRV 020043 is a typical chondrite composed of about 62 vol.% (GRV 020043-2: 61 vol.%; GRV 020043-3: 62 vol.%) of well-defined chondrules and chondrule fragments and approximately 38 vol.% matrix (Fig. 1a and b). Some smaller chondrule fragments and mineral fragments are difficult to distinguish from the surrounding matrix. Fig. 2 shows the distributions of chondrule sizes in GRV 020043. The apparent diameter of 81 chondrules in two sections ranged from 0.2 mm to 2.7 mm (mainly between the range of 0.3–0.9 mm, the

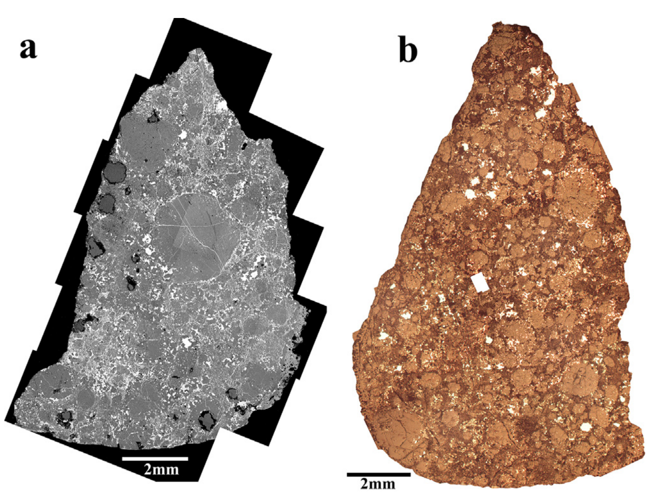

Fig. 1. Overview of the two GRV 020043 sections. (a) Back-scattered electron image (BSEI) of section GRV 020043-2. (b) Polished section GRV 020043-3 in reflected light, a white rectangle in the middle of the image is a void.

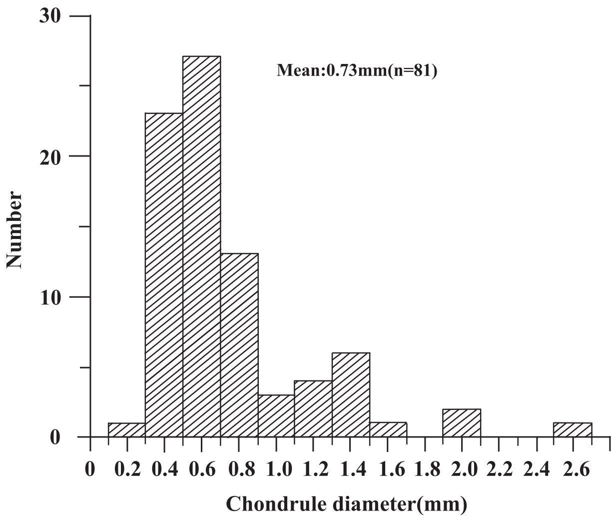

Fig. 2. Histogram showing the distributions of chondrule sizes in GRV 020043.

median is 0.61 mm) with an average of 0.73 mm. The average chondrule diameter in GRV 020043 is similar to the mean diameter in CR chondrites (Scott and Krot, 2004). Nearly 80% of the chondrules in GRV 020043 are porphyritic, the majority of which are porphyritic olivine-pyroxene (POP). The porphyritic chondrules are composed mainly of low-Ca pyroxene, diopside and minor olivine, as well as mesostasis (Fig. 3a and b). The largest chondrule in section GRV 020043-2 is a radial pyroxene chondrule with a diameter of 2.7 mm (Fig. 3c). A few chondrules with complex structure are also observed in the sections, for example one with a mat-like texture (Fig. 3d). No cryptocrystalline, barred olivine, or granular chondrules were observed within the two sections in this study. A noteworthy feature is that almost all chondrules in GRV 020043 contain troilite and Fe-Ni metal. This is very similar to CR chondrites (Leitner et al., 2012; Wasson and Rubin, 2013). The matrix in GRV 020043 is moderately recrystallized with mineral grain sizes ranging between 3 µm and 40 µm (Fig. 4a). The meteorite is composed mainly low-Ca pyroxene (40 vol.%), olivine (24 vol.%), diopside (8 vol.%), plagioclase (10 vol.%), Fe-Ni metal (mainly kamacite), troilite and some minor minerals (e.g., chromite and apatite). The abundance of Fe-Ni metal and troilite unaltered by weathering is about 3 vol.% and 4 vol.%, respectively. The modal abundance of Fe-Ni metal weathering products is about 10 vol.%. Fe-Ni metal in matrix of GRV 020043 is more extensively weathered when compared to the metal distributed within and around the chondrules. More than 90% of Fe-Ni metal in matrix of GRV 020043 is altered to limonite (Fig. 4a). Apatite is distributed heterogeneously in GRV 020043 with some grains concentrated in a small area (Fig. 4b).

Planar fractures, undulatory extinction and irregular fractures are seen in most olivine grains of GRV 020043, which indicate the shock stage of this meteorite is S3 according to the criteria of Stöffler et al. (1991).

The total mass of NWA 8118 is 955 g. The surface of the stone is reddish-brown and the stained clasts and the green diopside clasts (up to 1 cm) can be readily seen on the cut surface of NWA 8118 (Fig. 5a). The most remarkable characteristics of NWA 8118 is its fragmental breccia texture (Fig. 5b). The stone is composed of mainly olivine, orthopyroxene, chrome diopside, troilite, Fe-Ni metal, and trace amount of chromite and whitlockite (Fig. 5c). Exsolution of laminar orthopyroxene in chrome diopside is very common in the observation section of NWA 8118 (Fig. 5b and c).

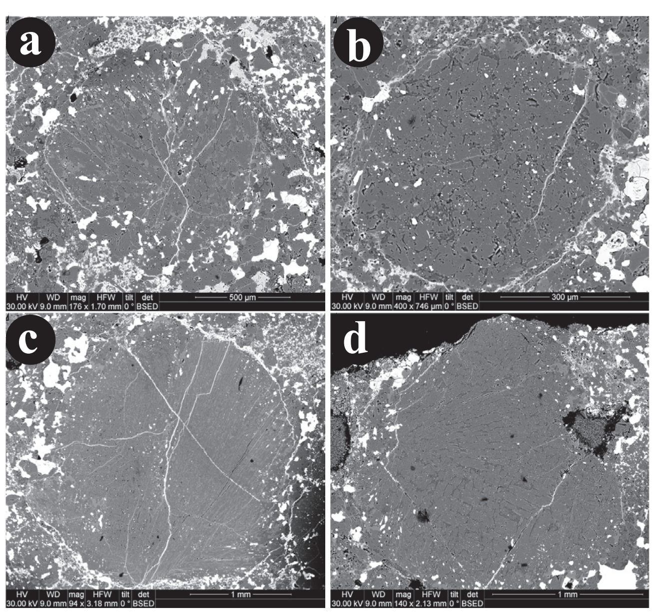

Fig. 3. BSEIs of representative chondrule types in GRV 020043, all the chondrules contain variable amount of Fe-Ni metal and troilite. (a) Porphyritic chondrule composed mainly of low-Ca pyroxene and diopside. (b) Low-Ca pyroxene rich POP. (c) Radial pyroxene chondrule with a diameter of ~2.7 mm. (d) Complex structure chondrule with a mat-like structure.

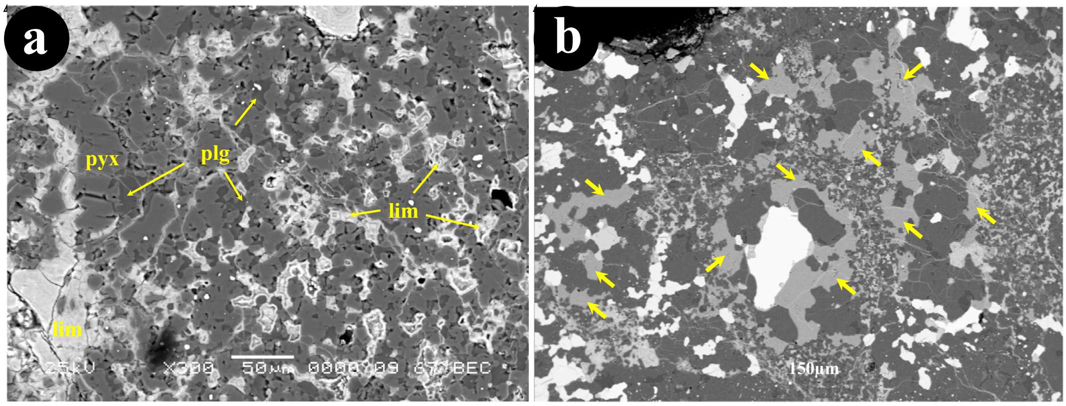

Fig. 4. (a) Matrix in GRV 020043. (b) An area enriched with apatite in GRV 020043. Apatite marked by arrows, other areas of light gray are limonite formed during weathering, white areas are Fe-Ni metal and troilite, gray areas are silicate minerals.

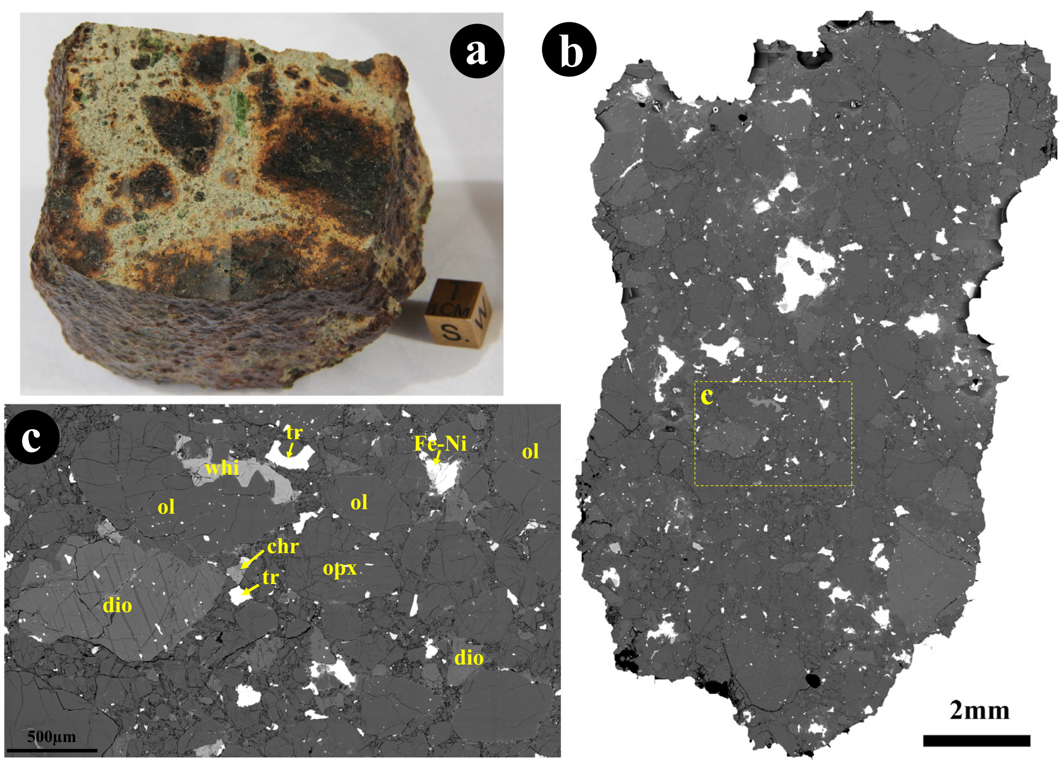

Fig. 5. NWA 8118 meteorite. (a) photograph of NWA 8118. (b) BSE image of polished section NWA 8118. The rectangular outline shows the position of Fig. 5c. (c) The magnification BSE image of NWA 811. ol = olivine, opx = orthopyroxene, dio = diopside, Fe-Ni = Fe-Ni metal, tr = troilite, chr = chromite, whi = whitlockite.

3.2. Mineral compositions and chemistry

Electron Probe Microanalysis (EPMA) data for olivine, low-Ca pyroxene, diopside, plagioclase, and chromite in GRV 020043 and NWA 8118 are reported in Table 1.

In GRV 020043, fayalite content (Fa) of olivine varies between 9.9 mol.% and 12.2 mol.% (avg. = 10.7 ± 0.3 mol.%) based on measurement of 51 olivine grains; chemical zoning in olivine has not been observed. Low-Ca pyroxene is the most abundant mineral in this meteorite. The ferrosilite content (Fs) ranges from 10.0 mol.% to 12.1 mol.% (avg. = 10.8 ± 0.4 mol.%) among the 51 grains used in analysis, while the wollastonite content (Wo) varies between 0.7 mol.% and 1.4 mol.% (avg. = 1.2 ± 0.1 mol.%). Histograms of olivine and low-Ca pyroxene compositions are shown in Fig. 6a and b, respectively, which illustrates sharp peaks in the distributions and average compositions that are more FeO-poor than H chondrites. The composition of diopside is also as homogeneous as olivine and low-Ca pyroxene in this meteorite; average values of En (enstatite), Fs, and Wo are 49.3 ± 0.3, 4.0 ± 0.2, and 46.6 ± 0.4 mol.%, respectively. Average Cr content in 6 diopside grains of this meteorite is 0.60 ± 0.04 wt.% Cr_2O_3. Two-pyroxene thermometry indicates an equilib-

Table 1
EPMA analysis Mean composition (wt.%) of olivine, low-Ca pyroxene, plagioclase, diopside, and chromite in GRV 020043 and NWA 8118.

Mineral	GRV 020043					NWA 8118			
	Ol(51)	Low-Ca Px(51)	Dio(6)	Pl(16)	Chr(7)	Ol(11)	Low-Ca Px(15)	Dio(15)	Chr(9)
Na_2O	n.a.	n.a.	n.a.	9.6 ± 0.1	n.a.	n.a.	n.a.	n.a.	n.a.
SiO_2	40.7 ± 1.0	58.3 ± 1.2	56.5 ± 0.6	63.6 ± 0.9	0.11 ± 0.16	41.3 ± 0.3	57.9 ± 0.3	55.7 ± 0.7	n.a.
TiO_2	0.01 ± 0.02	0.15 ± 0.04	0.47 ± 0.06	0.04 ± 0.01	1.9 ± 0.5	0.01 ± 0.01	0.07 ± 0.04	0.16 ± 0.05	0.46 ± 0.07
Al_2O_3	b.d.	0.15 ± 0.08	0.60 ± 0.07	22.1 ± 0.2	5.0 ± 0.8	b.d.	0.42 ± 0.10	0.84 ± 0.15	4.9 ± 1.4
Cr_2O_3	0.01 ± 0.02	0.09 ± 0.02	0.60 ± 0.04	0.01 ± 0.20	60.9 ± 1.3	0.03 ± 0.04	0.56 ± 0.14	0.96 ± 0.10	64.1 ± 1.8
V_2O_3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.95 ± 0.13
FeO	10.2 ± 0.3	7.2 ± 0.27	2.46 ± 0.1	0.59 ± 0.17	22.8 ± 1.0	11.7 ± 0.20	8.4 ± 1.0	3.8 ± 0.5	25.1 ± 1.8
MnO	0.55 ± 0.31	0.61 ± 0.03	0.29 ± 0.03	0.02 ± 0.01	1.5 ± 0.3	0.47 ± 0.03	0.52 ± 0.07	0.06 ± 0.07	0
MgO	47.6 ± 0.7	33.1 ± 0.7	16.9 ± 0.2	0.01 ± 0.01	5.1 ± 1.0	47.5 ± 0.2	31.6 ± 0.6	17.7 ± 0.8	4.8 ± 0.9
CaO	0.02 ± 0.02	0.63 ± 0.07	22.2 ± 0.3	3.0 ± 0.1	0.03 ± 0.03	0.04 ± 0.02	1.5 ± 0.7	21.5 ± 1.2	0
ZnO	n.a.	n.a.	n.a.	n.a.	1.02 ± 0.22	n.a.	n.a.	n.a.	0.01 ± 0.02
K_2O	n.a.	n.a.	n.a.	0.60 ± 0.05	n.a.	n.a.	n.a.	n.a.	n.a.
Total	99.1 ± 1.1	100.3 ± 1.1	100.1 ± 0.8	99.7 ± 0.9	98.3 ± 1.0	101.1 ± 0.5	100.9 ± 0.6	100.8 ± 1.4	100.4 ± 2.0
Fa/Fs	10.7 ± 0.3	10.8 ± 0.4	4.03 ± 0.2	n.a.	n.a.	12.2 ± 0.2	12.5 ± 1.5	5.9 ± 0.9	n.a.
En	n.a.	n.a.	49.3 ± 0.3	n.a.	n.a.	n.a.	n.a.	49.5 ± 1.7	n.a.
Wo	n.a.	1.2 ± 0.1	46.6 ± 0.4	n.a.	n.a.	n.a.	2.8 ± 1.3	43.2 ± 2.0	n.a.
Ab	n.a.	n.a.	n.a.	82.2 ± 0.6	n.a.	n.a.	n.a.	n.a.	n.a.
An	n.a.	n.a.	n.a.	14.4 ± 0.6	n.a.	n.a.	n.a.	n.a.	n.a.
Or	n.a.	n.a.	n.a.	3.4 ± 0.3	n.a.	n.a.	n.a.	n.a.	n.a.

The detection limits of MgO, Al_2O_3, CaO, and SiO_2 are all 0.01%, of Cr_2O_3, FeO, and MnO are 0.02%, and of TiO_2 is 0.05%. b.d. = below detection limit; n.a. = not analysis. Ol = olivine, Px = pyroxene, Dio = diopside, Pl = plagioclase, Chr = chromite.

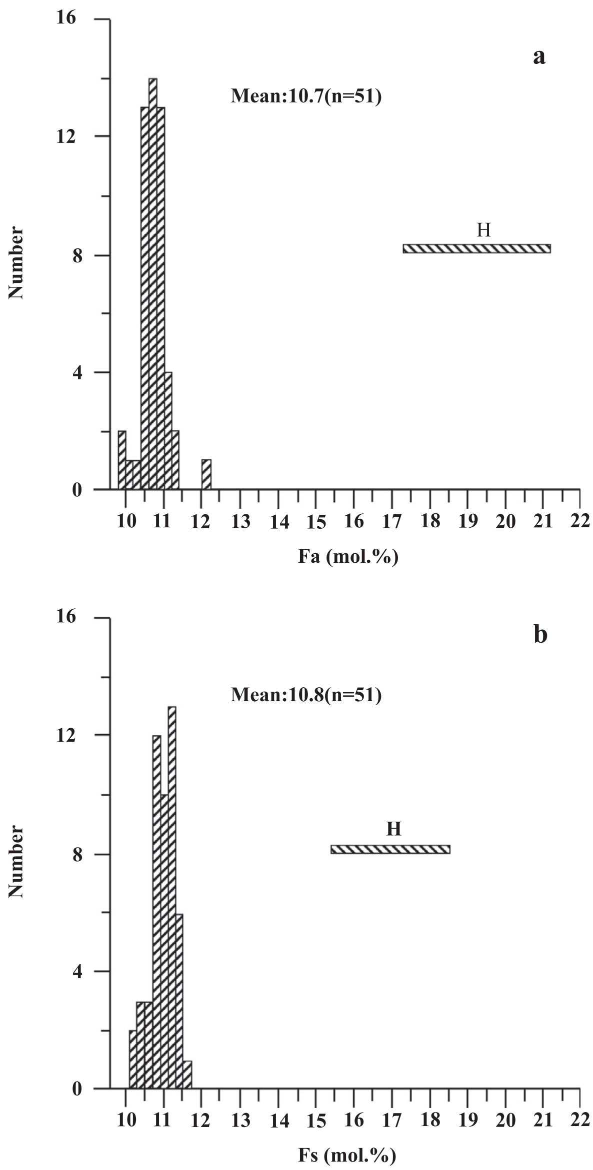

Fig. 6. Olivine (a) and low-Ca pyroxene (b) compositions of GRV 020043. The sharp peaks in composition indicate GRV 020043 is equilibrated. Olivine and pyroxene in GRV 020043 are more FeO-poor than the same phases in H chondrites.

rium metamorphic temperature of 861 ± 27 °C based on the QUILF95 program (Andersen et al., 1993). Mean FeO/MnO ratios in olivine, low-Ca pyroxene, and diopside are 18.7 ± 1.3, 11.8 ± 0.8, and 8.5 ± 1.1 mol.%, respectively. The measurement of 18 grains indicates that the composition of plagioclase is not homogeneous when compared with olivine and pyroxene. The values of Ab (albite), Or (orthoclase), and An (anorthite) are 82.2 ± 0.6, 3.4 ± 0.3, and 14.4 ± 0.6 mol.%, respectively.

For NWA 8118, Fa values of 11 olivine grains vary between 11.9 and 12.5 mol.% (avg. = 12.2 ± 0.2 mol.%). Fs values of 15 orthopyroxene grains range from 10.8 mol.% to 15.2 mol.% with the average of 12.5 ± 1.5 mol.%, and the Wo values vary from 0.9 mol.% to 4.8 mol.% (avg. = 2.8 ± 1.3 mol.%). The average En, Fs, and Wo values of chrome diopside are 49.5 ± 1.7, 5.9 ± 0.9, and 43.2 ± 2.0 mol.%, respectively. Average Cr_2O_3 content of 15 diopside grains of NWA 8118 is 0.96 ± 0.10 wt.%.

The EPMA data of kamacite, taenite, and troilite are listed in Table 2. Except for one tetrataenite grain that was observed, the metal phases in GRV 020043 are all kamacite and taenite. Kamacite is the major metal phase with the average composition of Fe = 90.8 ± 0.6 wt.%, Ni = 6.6 ± 0.1 wt.%, Co = 0.57 ± 0.03 wt.%, and Si = 0.017 ± 0.005 wt.%. The abundance of taenite is much lower than kamacite, with the average composition of Fe = 75.0 ± 3.0 wt.%, Ni = 22.3 ± 2.8 wt.%, Co = 0.22 ± 0.04 wt.%, Si = 0.018 ± 0.006 wt.%, Cr = 0.274 ± 0.051 wt.%, and Cu = 0.146 ± 0.038 wt.%. The chemical composition of troilite is more homogenous than kamacite and taenite. Troilite in GRV 020043 contains 63.9 ± 0.4 wt.% Fe, 35.1 ± 0.2 wt.% S, and 0.041 ± 0.011 wt.% Cr, respectively, distributed in both chondrules and matrices.

Chromite, similar to olivine and low-Ca pyroxene, has different composition in different meteorite groups (Bunch et al., 1967; Bunch and Keil, 1971). In order to classify GRV 020043 more accurately, the chemical compositions of seven chromite grains were analyzed using EPMA and listed in Table 1 and shown in Fig. 7, as a plot of Cr/(Cr + Al) versus Fe/(Fe + Mg). Chromite in GRV 020043 is significantly more Fe-poor and Mn-rich than those in ordinary chondrites (Bunch et al., 1967; Nehru et al., 1997). The overall chemical composition of chromite in GRV 020043 is similar to chromite in acapulcoites and lodranites (Mittlefehldt et al., 1996).

The chemical composition of chromite in NWA 8118 is similar to that in GRV 020043 (Table 1, Fig. 7).

3.3. Bulk chemistry

The bulk chemical composition (major and trace elements) in GRV 020043 is reported in Table 3. Magnesium and CI chondrite (Lodders, 2003) normalized elemental distribution patterns of GRV 020043, LEW 87232 (K chondrite) (Weisberg et al., 1996), Kakangari (K3 chondrite) (Weisberg et al., 1996), average H chondrite (Lodders and Fegley,1998), average L chondrite (Lodders and Fegley,1998), and acapulcoites (Mittlefehldt et al., 1996; Patzer et al., 2004) are shown in Fig. 8. For most of the elements in GRV 020043, the abundances are similar to Kakangari, H chondrites, and acapulcoites. However, there are some noted deviations in certain elements. Potassium is lower in GRV 020043 than in Kakangari, H and L ordinary chondrites, while higher than that in LEW 87232 and acapulcoite. Scandium and Ca are lower in GRV 020043 than that in Kakangari, H and L ordinary chondrites, and the acapulcoites. Antimony is remarkably abundant in GRV 020043 but depleted in H and L chondrites, the K chondrite grouplet, and acapulcoites.

3.4. Bulk oxygen isotopic composition

Bulk oxygen isotopic compositions for GRV 020043 are shown in Table 4 and are plotted on a three-isotope dia-

Table 2
EPMA analysis mean composition (wt.%) of kamacite, taenite and troilite in GRV 020043.

Grain	S	Fe	Co	Ni	Cu	Si	Cr	Total
kam1	n.a.	90.1	0.52	6.57	0.047	0.009	0.171	97.4
kam2	n.a.	90.2	0.57	6.78	b.d.	0.023	0.136	97.7
kam3	n.a.	91.3	0.59	6.60	b.d.	0.018	0.145	98.7
kam4	n.a.	90.6	0.58	6.62	b.d.	0.019	0.156	97.9
kam5	n.a.	91.7	0.58	6.63	0.018	0.018	0.132	99.0
kam6	n.a.	91.0	0.58	6.61	b.d.	0.016	0.187	98.4
T1	n.a.	70.2	0.16	26.1	0.088	0.01	0.155	96.7
T2	n.a.	77.3	0.25	20.1	0.043	0.017	0.279	98.0
T3	n.a.	77.1	0.22	20.9	0.103	0.023	0.255	98.6
T4	n.a.	73.8	0.23	24.3	0.074	0.026	0.262	98.7
T5	n.a.	76.5	0.27	19.9	0.146	0.016	0.274	97.1
tro1	63.4	35.0	0.056	n.a.	n.a.	0.005	0.055	98.5
tro2	63.7	35.3	0.042	n.a.	n.a.	b.d.	0.044	99.0
tro3	64.4	35.0	0.049	n.a.	n.a.	b.d.	0.037	99.5
tro4	64.1	35.2	0.076	n.a.	n.a.	b.d.	0.026	99.5
tro5	63.9	35.0	0.048	n.a.	n.a.	0.003	0.042	98.9

Kam = kamacite; T = taenite; tro = troilite; b.d. = below detection limit; n.a. = not analyzed.

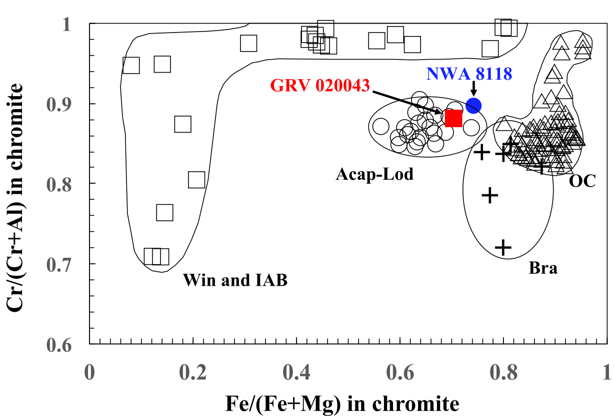

Fig. 7. Cr/(Cr + Al) versus Fe/(Fe + Mg) in chromite. The figure modified from the Fig. 7c of Folco et al. (2006) and the ordinary chondrite data from Bunch et al. (1967) and Nehru et al. (1997).

gram (Fig. 9). Analyses of three aliquots of the finely ground samples of GRV 020043 at LSU by laser fluorination yield average values for the $\delta^{18}O$ and $\delta^{17}O$ of $+3.266 \pm 0.267‰$ and $+0.797 \pm 0.131‰$, respectively, plotting below the terrestrial fractionation line with an average $\Delta^{17}O$ value of $-0.927 \pm 0.017‰$. The triplicate analyses performed at UNM give an average $\delta^{18}O = +3.40 \pm 0.17‰$ and $\delta^{17}O = +0.778 \pm 0.200‰$, with average $\Delta^{17}O$ value of $-1.018 \pm 0.041‰$. Based on the oxygen isotopic data alone, GRV 020043 is similar to the K chondrite grouplet and CR type chondrites, and different from other chondrite groups (Clayton et al., 1991; Clayton and Mayeda 1996, 1999).

3.5. Bulk chromium isotopic composition

The results of the Cr isotopic analyses are shown in Table 5 and plotted in Fig. 10 together with $\Delta^{17}O$ values. Six of the analyzed samples: GRV 021663, GRV 020043, NWA 468, NWA 8118, NWA 8287, and NWA 8422 exhibit $\varepsilon^{54}Cr$ values that are indistinguishable from one another. NWA 8054 plots slightly to the right of these five samples, but only marginally outside of error of NWA 8422 and NWA 8287. However, all of these samples are within the compositional range observed in previously analyzed acapulcoite, lodranite, and winonaite meteorites. In contrast, NWA 11187 has an $\varepsilon^{54}Cr$ value most similar to that measured in ureilites, plotting within the compositional field of ureilites and only slightly overlapping $\varepsilon^{54}Cr$ values seen in acapulcoites. The position of GRV 020043 is well resolved from E and H ordinary chondrites (Li et al., 2011a), as well as from CR chondrite (Rubin 2007), instead plotting near acapulcoite and lodranite meteorites (Fig. 10).

4. DISCUSSION

4.1. Classification of GRV 020043

The texture of GRV 020043 is partially recrystallized with ubiquitous well-defined chondrules (Fig. 1). Relatively homogeneous compositions are observed for olivine (percent mean deviation (PMD) value is 3.2) and pyroxene (PMD value is 3.4) within the chondrules and matrix. These characteristics fit the criteria for petrologic type 4 chondrites given by Van Schmus and Wood (1967), i.e., PMDs less than 5%, well-defined chondrules, and transparent micro-crystalline matrix. Some secondary plagioclase grains in GRV 020043 are larger than 2 μm, which fits the plagioclase grain size for petrologic type 5 used in many references (e.g., Van Schmus and Wood, 1967; Krot et al., 2005; Huss et al., 2006). However, plagioclase grains >50 μm in petrologic type 4 H and LL chondrites have also been reported (Kovach and Jones, 2010). Therefore, we propose a petrologic type 4 classification for GRV 020043. GRV 020043 is similar to H ordinary chondrites in texture, mineral assemblage, and bulk chemical composition (Li et al., 2011a), but with different mineral abun-

Table 3
Whole rock chemical composition of GRV 020043.

Element	Concentration	Unit	Method	Element	Concentration	Unit	Method
Li	1.62	μg/g	ICP-MS	Ce	891	ng/g	ICP-MS
Na	5816	μg/g	ICP-OES	Pr	112	ng/g	ICP-MS
Mg	14.1	wt.%	ICP-OES	Nd	548	ng/g	ICP-MS
K	603	μg/g	ICP-OES	Sm	186	ng/g	ICP-MS
Ca	1.14	wt.%	ICP-OES	Eu	84	ng/g	ICP-MS
Sc	5.5	μg/g	ICP-MS	Gd	201	ng/g	ICP-MS
V	74.1	μg/g	ICP-MS	Tb	51	ng/g	ICP-MS
Cr	2390	μg/g	ICP-MS	Dy	338	ng/g	ICP-MS
Mn	2723	μg/g	ICP-OES	Ho	69	ng/g	ICP-MS
Fe	24.5	wt.%	AAS	Er	213	ng/g	ICP-MS
Co	687(*740*)	μg/g	ICP-MS (*AAS*)	Tm	29	ng/g	ICP-MS
Ni	17273.7(*17200*)	μg/g	ICP-MS (*AAS*)	Yb	223	ng/g	ICP-MS
Cu	85.8	μg/g	ICP-MS	Lu	38	ng/g	ICP-MS
Zn	171.4	μg/g	ICP-MS	Hf	190	ng/g	ICP-MS
Ga	7.8	μg/g	ICP-MS	Ta	85	ng/g	ICP-MS
Ge	26.4	μg/g	ICP-MS	W	408	ng/g	ICP-MS
As	1.5	μg/g	ICP-MS	Tl	4	ng/g	ICP-MS
Rb	301	ng/g	ICP-MS	Pb	680	ng/g	ICP-MS
Sr	13.4(*13.1*)	μg/g	ICP-MS (*ICP-OES*)	Bi	7	ng/g	ICP-MS
Y	1.97	μg/g	ICP-MS	Th	44	ng/g	ICP-MS
Zr	6.32	μg/g	ICP-MS	U	22	ng/g	ICP-MS
Nb	477	ng/g	ICP-MS	Ru	656.8	ng/g	ICP-MS
Mo	3.87	μg/g	ICP-MS	Pd	703.8	ng/g	ICP-MS
Sb	221	ng/g	ICP-MS	Ir	574.5	ng/g	ICP-MS
Cs	10	ng/g	ICP-MS	Pt	928.7	ng/g	ICP-MS
Ba	3.33	μg/g	ICP-MS	Rh	86.5	ng/g	ICP-MS
La	339	ng/g	ICP-MS				

The uncertainties of Na, Mg, K, Ca, Fe, Co, and Ni are lower than 0.1%, the uncertainties of trace elements are about 10%.

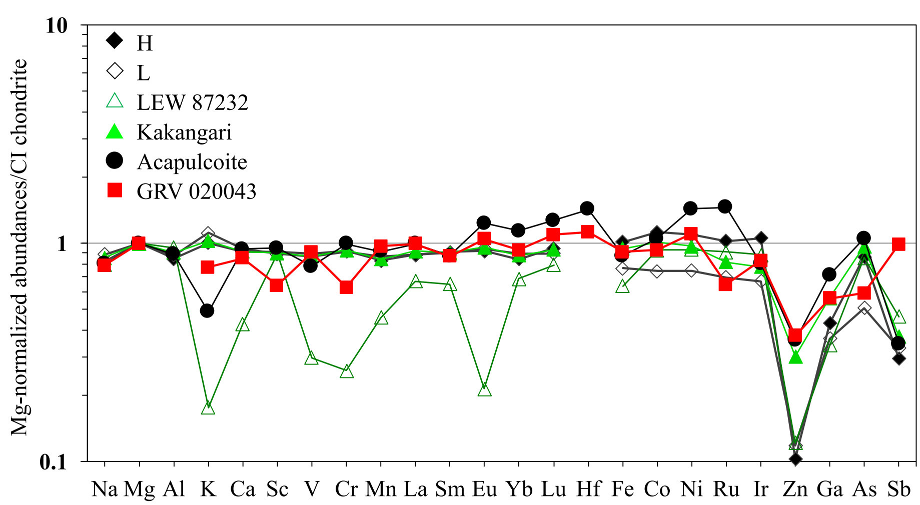

Fig. 8. The elemental distribution patterns of GRV 020043, H chondrite, L chondrite, two K chondrite grouplet chondrites (LEW 87232 and Kakangari), and acapulcoites. The CI chondrite data are from Lodders (2003), H and L values from Lodders and Fegley (1998) while Lu data from Bunch et al. (1967), data of LEW 87232 and Kakangari from Weisberg et al. (1996), data of acapulcoites from Patzer et al. (2004) and Mittlefehldt et al. (1996).

dances. Low-Ca pyroxene (~40 vol.%) is the most abundant mineral in this meteorite, and low-FeO content in low-Ca pyroxene, olivine, and chromite, implies this meteorite might have formed in more reducing conditions than that of H chondrites. Additionally, the combined Δ^{17}O-ε^{54}Cr plot of GRV 020043 precludes an origin from a source with isotopic characteristics similar to any established chondrite group, as well as any previously identified ungrouped chondrites (Fig. 10).

In the plot of Fa content in olivine versus Fs content in low-Ca pyroxene, GRV 020043 plots between the K chondrite grouplet and H chondrite group, but also within the

Table 4
Oxygen isotope compositions of GRV 020043, GRV 021663 and NWA 8118.

Sample	$\delta^{17}O$	1σ	$\delta^{18}O$	1σ	$\Delta^{17}O$	1σ
LSU Oxygen Data						
GRV 020043	0.857		3.417		−0.947	
	0.646		2.957		−0.915	
	0.888		3.423		−0.919	
Average	0.797	0.131	3.266	0.267	−0.927	0.017
GRV 021663	3.550		7.546		−0.434	
	3.466		7.377		−0.429	
	3.532		7.506		−0.424	
Average	3.516	0.045	7.476	0.088	−0.431	0.003
UNM Oxygen Data						
Sample	$\delta^{17}O'$	1σ	$\delta^{18}O'$	1σ	$\Delta^{17}O'$	1σ
GRV 020043	0.754		3.44		−1.063	
	0.887		3.54		−0.984	
	0.682		3.21		−1.007	
Average	0.778	0.100	3.40	0.17	−1.018	0.041
GRV 021663	3.85		7.97		−0.351	
NWA 8118	−0.366		1.84		−1.340	
	−0.354		1.93		−1.373	
Average	−0.360	0.008	1.89	0.06	−1.346	0.023

$\Delta^{17}O$ calculated using the formula $\Delta^{17}O' = \delta^{17}O' - 0.528 \times \delta^{18}O'$.

Table 5
Cr isotopic composition of GRV 020043, GRV 021663, acapulcoites, lodranites, and winonaites.

Sample	Meteorite Type	$\varepsilon^{54}Cr$ (±2SE)*
GRV 020043	"Acapulco" chondrite	−0.48 ± 0.10
NWA 11187	Ureilite	−0.85 ± 0.11
Acapulco	Acapulcoite	−0.70 ± 0.10[a]
NWA 8287	Acapulcoite	−0.62 ± 0.10
NWA 8054	Lodranite	−0.44 ± 0.08
NWA 8118	Lodranite	−0.59 ± 0.09
NWA 8422	Lodranite	−0.70 ± 0.09
NWA 468 (silicate inclusion)	Metal-rich lodranite	−0.59 ± 0.09
GRV 021663	Winonaite	−0.52 ± 0.08
NWA 725	Winonaite	−0.54 ± 0.08[b]
Villalbeto de la Peña (clast)	Winonaite	−0.52 ± 0.10[b]

* $\varepsilon^{54}Cr$ is a part per 10,000 deviation of $^{54}Cr/^{52}Cr$ ratio of the samples relative to standard.
[a] Reported in Goodrich et al. (2017).
[b] Reported in Schmitz et al. (2016).

range of the acapulcoite-lodranite clan (Fig. 11a). Fig. 7 shows that the composition of chromite in GRV 020043 is clearly different from those in ordinary chondrites. Plagioclase in GRV 020043 has an Or value of 3.4 ± 0.3 mol.%, while the Or value is about 6 mol.% in H ordinary chondrites (Van Schmus and Ribbe, 1968; Kovach and Jones, 2010). The Co content in kamacite of H chondrites ranges from 4.4 to 5.1 mg/g (Rubin, 1990) with average of 4.5 mg/g. Cobalt content in kamacite of GRV 020043 is 5.7 ± 0.3 mg/g, slightly higher than the kamacite of H chondrites (Rubin, 1990). Low-Ca pyroxene (~40 vol.%) is the most abundant mineral in GRV 020043, which is not typical of H chondrites (with olivine the most abundant mineral in H chondrites [McSween et al., 1991]). Petrographic studies (Scott and Krot, 2004 and references therein) have revealed that different chondrite groups usually have different average chondrule sizes. The average chondrule radius is 0.3 mm for H chondrites. However, the average radius of 81 chondrules in GRV 020043 is 0.73 mm, much larger than that of H ordinary chondrites.

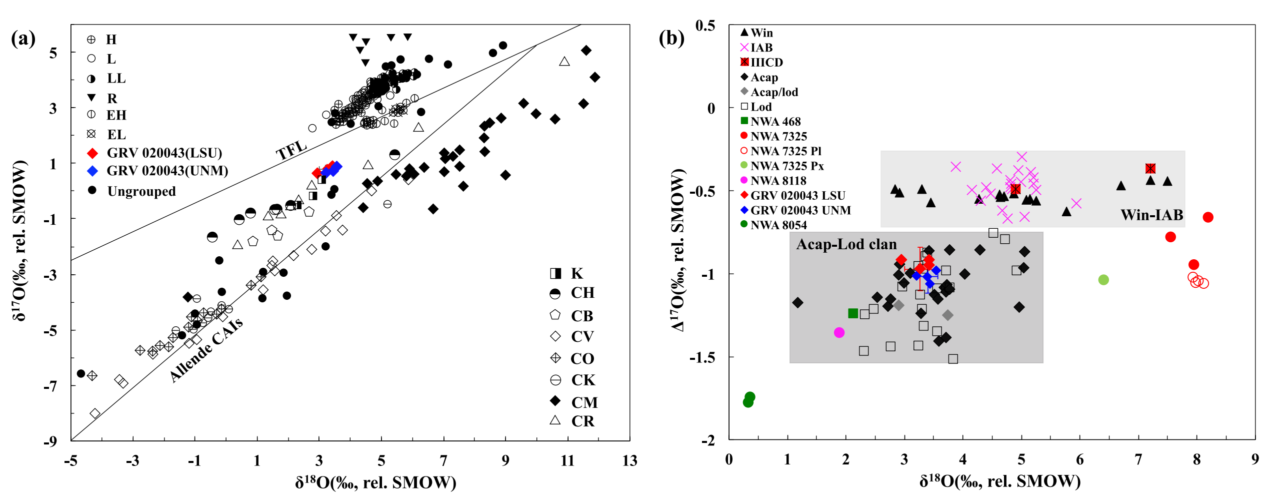

Fig. 9. (a) Bulk oxygen isotopic composition of GRV 020043 compared with that of established chondrite groups and select ungrouped chondrites. All the data except GRV 020043 and some ungrouped chondrites are from Krot et al. (2003) and references therein. Data for some ungrouped chondrites are from Bevan and Bmmis (1989), Weisberg et al. (2001, 2008), Bunch et al. (2008), Bridges et al. (1997), Bischoff et al. (1997), Sexton (1998), and Connolly et al. (2007). TFL is the terrestrial fractionation line. (b) Whole rock oxygen isotopic composition of GRV 020043 compared with those of the acapulcoite-lodranite clan, winonaite-IAB-IIICD clan, and NWA 468 and NWA 7325 (including its plagioclase and pyroxene data). Data for IAB and IIICD are from Clayton and Mayeda (1996). Data for acapulcoite-lodranite and winonaites are from Greenwood et al. (2012). Data of NWA 468 is from Rubin et al. (2002). Whole rock, plagioclase, and pyroxene data of NWA 7325 are from Irving et al. (2013), Jabeen et al. (2014), and Weber et al. (2016).

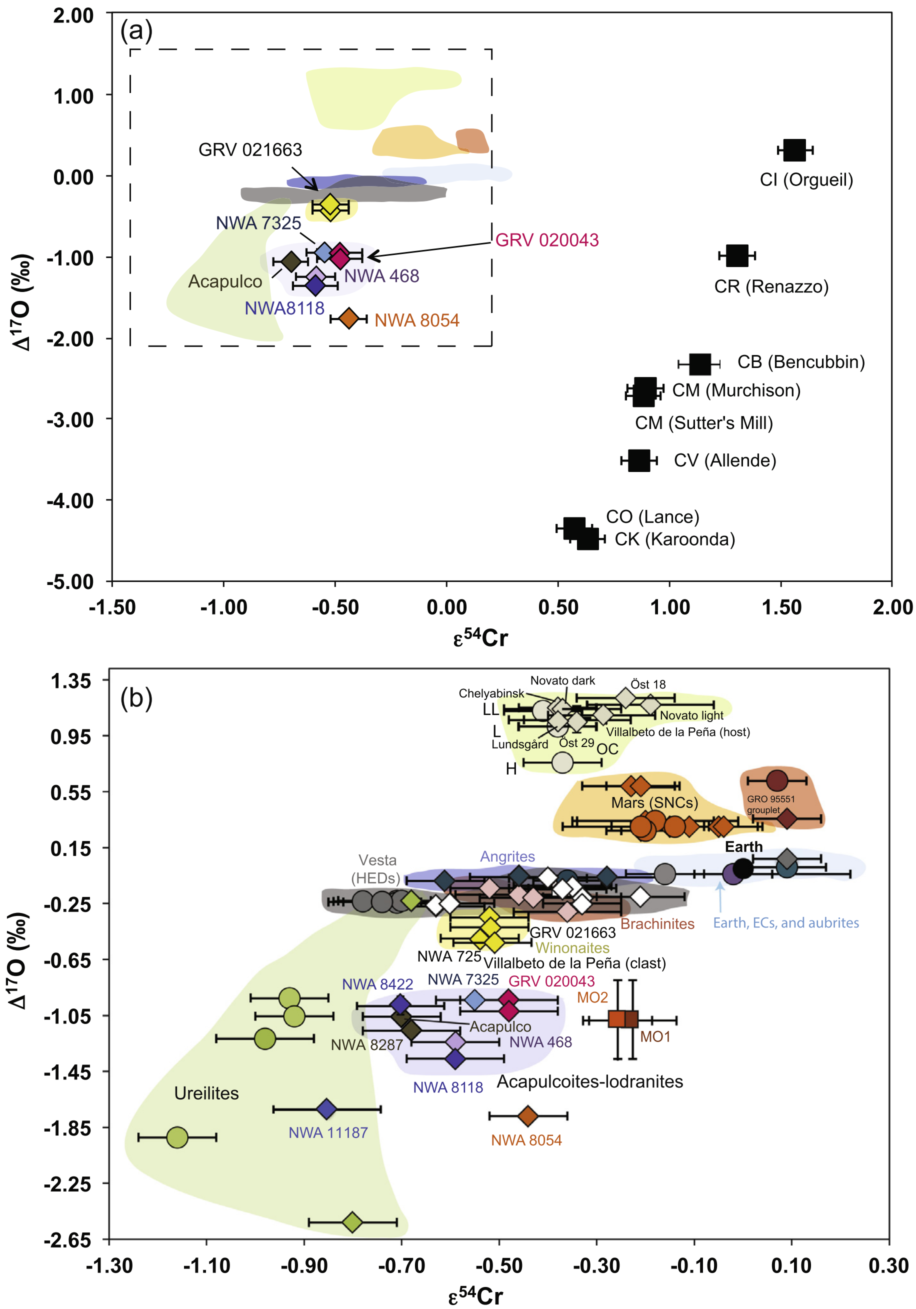

Fig. 10. (a) $\Delta^{17}O$ - $\varepsilon\ ^{54}Cr$ composition of GRV 021663, GRV 020043, NWA 8118, and Acapulco in comparison with other achondrite and chondrite groups. (b) Magnification of the achondrite and lordinary chondrite region outlined in panel a. Literature data for $\Delta^{17}O$ are from Clayton and Mayeda (1988, 1996, 1999), Clayton et al. (1984, 1991), Rubin et al. (2002), Scott et al. (2009), Jenniskens et al. (2012), Popova et al. (2013), Jenniskens et al. (2014), and Irving et al. (2014) and literature data for $\varepsilon\ ^{54}Cr$ are from Ueda et al. (2006), Shukolyukov and Lugmair (2006), Trinquier et al. (2007), Jenniskens et al. (2012), Popova et al. (2013), Jenniskens et al. (2014), Sanborn et al. (2013, 2014a, 2014b), and Schmitz et al. (2016).

A subgroup of low-FeO ordinary chondrites has been proposed previously for ordinary chondrites with lower FeO content in olivine and pyroxene (McCoy et al., 1994). This subgroup has several properties: (1) Fa values ranging from 12.8 to 15.3 mol.%; (2) modal abundance of Fe-Ni metal ranging from 11.2 to 19.4 wt.%; (3) Co content in kamacite varying between 3.0 and 4.5 mg/g; (4) average chondrule radius of ~0.4–0.6 mm; and (5) whole rock $\Delta^{17}O$ ranging from 0.32 to 0.87‰. McCoy et al. (1994) argued that low-FeO ordinary chondrites might originate from a separate parent body. The properties of low-FeO ordinary chondrites described above are very similar to GRV 020043, except for the bulk oxygen isotopic composition. The oxygen isotopic composition of GRV 020043 plots below the terrestrial fractionation line (TFL) on three-isotope space with a negative $\Delta^{17}O$ (Fig. 9a), whereas

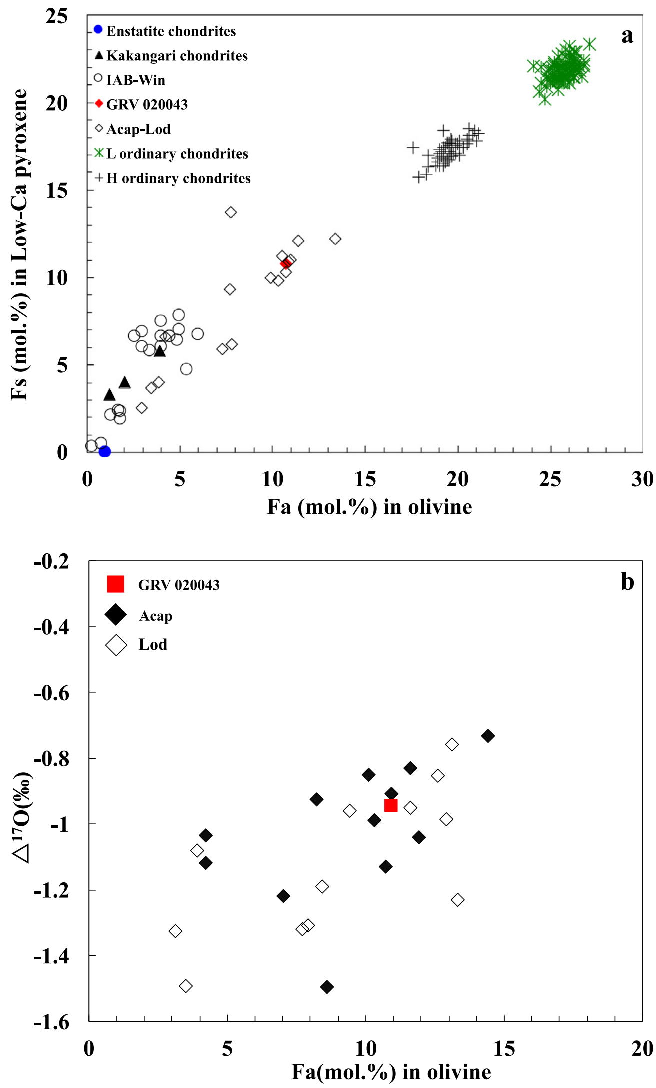

Fig. 11. (a) Olivine composition (Fa mol.%) versus low-Ca pyroxene composition (Fs mol.%) in GRV 020043 compared with the same items in enstatites (E), K chondrite grouplet, H chondrites, L chondrites, and the acapulcoite-lodranite clan (Acap-Lod). Data from Prinz et al. (1980), King et al. (1981), Yanai and Kojima (1995), Benedix et al. (1998, 2000), Yanai (2001), Patzer et al. (2004), Connolly et al. (2007), Weisberg et al. (1996), Li et al. (2008, 2011b, 2013). (b) Plot of $\Delta^{17}O$ vs. Fa for GRV 020043 and comparison with acapulcoites and lodranites. Other data is from Irving et al. (2007) and Clayton and Mayeda (1996).

all ordinary chondrites, including low-FeO ordinary chondrites plot above the TFL.

Markedly higher FeO contents of olivine and pyroxene in GRV 020043 compared to enstatite chondrites (Lin and Kimura, 1998; Floss et al., 2003) argues against any possibility of a similar origin for the two. The whole rock oxygen and chromium isotopic compositions (Fig. 10) also unambiguously indicate GRV 020043 originated from a distinct isotopic reservoir than the enstatite chondrites.

GRV 020043 shares many features with the K chondrite grouplet, as described by Weisberg et al. (1996), including: (1) high matrix abundance (33–77 vol.%); (2) high Fe-Ni metal abundance (~10 vol%); (3) lower FeO content in olivine and pyroxene than H chondrites; (4) the modal abundance of low-Ca pyroxene is higher than olivine; (5) similar whole rock chemical composition; and (6) the bulk oxygen isotopic composition plots in a similar region (Fig. 9a) as K chondrite grouplet, as well as the CR- and CH-type chondrites (Clayton and Mayeda, 1999). However, the average Fa value of olivine and Fs value of low-Ca pyroxene in the K chondrite grouplet are 2.2 mol.% and 4.4 mol.%, respectively, much lower than that in GRV 020043 (Fa and Fs are 10.7 mol.% and 10.8 mol.%, respectively) shown in Figs. 6 and 11a. As such, it appears GRV 020043 formed in more oxidizing conditions in a region of the solar nebular with an oxidation state intermediate between the K chondrite grouplet and H chondrites.

There are some similarities between GRV 020043 and CR-type chondrites, such as bulk oxygen isotopic composition (Fig. 9a) (Clayton and Mayeda, 1999), average radius of chondrules, occurrence of troilite and Fe-Ne metal in almost all chondrules, and the matrix modal abundance (Krot et al., 2003). However, absence of calcium–aluminum-rich inclusion (CAI), amoeboid olivine aggregates (AOA) and hydrous minerals in GRV 020043 indicates it is not related to CR or any other carbonaceous chondrite group. Furthermore, on a $\Delta^{17}O$-$\varepsilon^{54}Cr$ plot, GRV 020043 plots close to acapulcoite-lodranite clan, well resolved from all known carbonaceous chondrite groups (Fig. 10).

To date, 61 ungrouped chondrites have been recorded in Meteoritical Bulletin Database. Among these chondrites, 42 of them are carbonaceous chondrites (http://www.lpi.usra.edu/meteor/metbull.php). Among the 19 ungrouped non-carbonaceous chondrites, available data (e.g., mineral chemical compositions and bulk oxygen isotopic compositions) do not support any of them having a similar origin with GRV 020043. Kallemeyn and Wasson (1982) suggested 2–4 similar meteorites could establish a grouplet; hence GRV 020043 is an ungrouped chondrite.

4.2. Origin of GRV 020043 and relationship with acapulcoite-lodranite achondrites

We now consider the potential association of GRV 020043 with the acapulcoite-lodranite clan. There are multiple lines of geochemical and isotopic evidence that suggests that GRV 020043 (type 4 chondrite) might be a sample of the chondritic precursor material of the acapulcoite-lodranite clan. Although the acapulcoite-lodranite clan is generally considered to be composed of achondrites, some members (e.g., Y-74063, ALHA-77081, Monument Draw, Dhofar 1222, GRA 98028, and NWA 1058) have been observed to contain relic chondrules (Yanai and Kojima, 1991; Schultz et al., 1982; McCoy et al., 1996; Patzer et al., 2004; Benedix and Lauretta, 2006; Rubin, 2007). In retrospect, these meteorites should have been classified as "Acapulco" chondrites.

(1) GRV 020043 is composed of olivine, low-Ca pyroxene, diopside, plagioclase, kamacite, taenite, troilite, and some minor mineral phases, such as chromite and apatite. This mineral assemblage is similar to that of acapulcoite-lodranite clan. Low-Ca pyroxene (40 vol.%) is the most abundant mineral phase followed by olivine (24 vol.%) in GRV 020043. This is also the case for most of acapulcoite-lodranite members (Kimura et al., 1992; Grossman, 1994; McCoy et al., 1996, 1997a; Yugami et al., 1998; Patzer et al., 2004; Folco et al., 2006).

(2) In terms of mineral chemistry, GRV 020043 is consistent with acapulcoite-lodranite clan. For example, GRV 020043 has olivine and low-Ca pyroxene with average Fa and Fs values of 10.7 and 10.8 mol.%, respectively. In the acapulcoite-lodranite clan, these values range from 2.9 mol.% to 13.4 mol.% for olivine and from 2.5 mol.% to 13.7 mol.% for low-Ca pyroxene, respectively (Yanai and Kojima, 1991; Mittlefehldt et al., 1996; McCoy et al., 1996; Yugami et al., 1998; Yanai, 2001; Patzer et al., 2004). The values of Fa and Fs for GRV 020043 are in the range observed for the acapulcoite-lodranite clan (Fig. 11a), which means GRV 020043 and the acapulcoite-lodranite clan formed under similar redox conditions. FeO/MnO ratios in olivine and low-Ca pyroxene are 18.7 ± 1.3 and 11.8 ± 0.75, respectively; these ratios are also within the ranges of the acapulcoite-lodranite clan (7.9–26.6 for olivine and 5.6–16.4 for low-Ca pyroxene; Mittlefehldt et al., 1996; McCoy et al., 1996). The chromite composition, which can be used to distinguish different meteorites, plots in the acapulcoite-lodranite field on a Cr/(Cr + Al) versus Fe/(Fe + Mg) diagram (Fig. 7). MnO content in chromite of GRV 020043 is also higher when compared with that of ordinary chondrites; however, it is similar with that of acapulcoites ranging from 0.93 to 3.05 wt.% (Bunch et al., 1967; Mittlefehldt et al., 1996; Nehru et al., 1997). Potassium tends to be lower in plagioclase within the acapulcoite-lodranite clan than that in ordinary chondrites. The Or value of plagioclase in GRV 020043 is 3.4 ± 0.3 mol.% which is similar to the Or values of Dho 029 (2.8 ± 0.2 mol.%), GRA 98,028 (3.8 ± 0.6 mol.%), and ALHA 81261 (4.3 mol.%) (Mittlefehldt et al., 1996; Patzer et al., 2004). Cobalt concentration in kamacite within GRV 020043 is 5.7 wt.‰ which is in the range observed in the acapulcoite-lodranite clan (Yugami et al., 1998; Patzer et al., 2004). Diopside is an exception in GRV 020043 with its Cr_2O_3 content of 0.60 ± 0.04 wt.%, which is significantly lower than that of acapulcoite-lodranite clan ranging from 0.9 to 1.9 wt.% (Mittlefehldt, 2005). However, low Cr_2O_3 content in diopside alone does not rule out the link between GRV 020043 and acapulcoite-lodranite clan. For example, most members of the winonaite group have low Cr_2O_3 content in diopside, e.g., Y-74025, Y-75300 and Y-75305 with Cr_2O_3 content of 0.15, 0.24, and 0.14 wt.%, respectively (Kimura et al., 1992). Yet diopside in some winonaites are chromian diopside, for example GRV 021663 (with 1.5 wt.% Cr_2O_3 in diopside) and NWA 4937 (1.2 wt.% Cr_2O_3) (Weisberg et al., 2008; Li et al., 2011b).

(3) The chemical composition of the GRV 020043 whole rock is within the range of acapulcoites, though deviations for some elements do exist (Mittlefehldt et al., 1996; Patzer et al., 2004). Previous studies indicate that some elements including the REEs, B, Ba, Ce, Co, Cr, Cs, Cu, Nd, Ni, Rb, Sm, Sr, Zn, and Cs can be leached away, while U, Se, Hg and some other elements could be transported into meteorites from surrounding terrestrial sources during Antarctic weathering processes (Harvey, 2003 and references therein). Therefore, the influence of weathering on the abundances of certain elements in GRV 020043 is unavoidable.

(4) Similar to ureilites, Fa values in olivine and the whole rock $\Delta^{17}O$ values have a positive correlation trend among the members of the acapulcoite-lodranite group (Irving et al., 2007; Mittlefehldt et al., 2008). Our data shows that GRV 020043 plots along the acapulcoite-lodranite Fa versus $\Delta^{17}O$ trend as well (Fig. 11b) (Clayton and Mayeda, 1996; Irving et al., 2007).

(5) Heterogeneous distribution of ^{54}Cr has been documented for all meteorites groups (e.g. Trinquier et al., 2007; Yin et al., 2009; Qin et al., 2010; Warren, 2011a,b; Jenniskens et al., 2012, 2014; Popova et al., 2013). This extra dimension (in conjunction with Δ^{17}O) has been used to classify meteorites that are otherwise difficult to classify based mainly on mineral chemistry and oxygen isotopic composition alone and has been proven effective in providing a new perspective on a meteorite's origin (e.g. Sanborn et al., 2013; Sanborn et al., 2014a, 2014b; Sanborn and Yin, 2014; Schmitz et al., 2016; Goodrich et al., 2017; Benedix et al., 2017).

The Cr isotopic composition indicates that GRV 020043, GRV 021663, NWA 468, NWA 8054, NWA 8118, NWA 8287, and NWA 8422 likely originated from a similar isotopic reservoir, along with other acapulcoites (Goodrich et al., 2017) and winonaites (Schmitz et al., 2016). In contrast, despite similarities to acapulcoites-lodranites in terms of oxygen and a mineralogy unlike that seen typical ureilites, it appears NWA 11187 originated from a more ureilite-like source. Our data suggest that acapulcoites-lodranites and winonaites originated from a common Cr isotopic reservoir with variable oxygen isotopic composition indicative of variable water/ice interactions with rock and dust (Fig. 10).

Based on the information discussed in the previous sections, we suggest that GRV 020043 may represent a subsurface sample of the acapulcoite-lodranite parent body and is a precursor of the acapulcoite-lodranite clan that did not undergo the extensive thermal metamorphism or partial melting that generated the acapulcoites and lodranites (Palme et al., 1981; Nagahara, 1992; Zipfel et al., 1995; McCoy et al., 1996, 1997a, 1997b; Mittlefehldt et al., 1996; Floss, 2000; Patzer et al., 2004; Krot et al., 2005; Rubin, 2007). This proposed relationship is also supported by the cosmic-ray exposure (CRE) age of GRV 020043 of 6.7 ± 1.7 Ma (Li et al., 2016), which is in the middle of the range of acapulcoite-lodranite CRE ages (Eugster and Lorenzetti, 2005). Based on observations thus far, this study rules out the possibility that a CR-like carbonaceous chondrite material was the precursor of acapulcoite-lodranite clan as previously proposed (Rubin, 2007).

Certain achondrites, related to acapulcoite-lodranite clan, need to be discussed in the context of GRV 020043 representing the precursor material for the acapulcoite-lodranite parent body. The meteorite NWA 468, although classified as an IAB iron (Grossman and Zipfel, 2001), has affinities to lodranites (Rubin et al., 2002). The silicate portion of NWA 468 is a coarse-grained assemblage and mainly composed of olivine, low-Ca pyroxene, high-Ca pyroxene, troilite, and minor plagioclase, chromite, Fe-Ni metal, and schreibersite (Rubin et al., 2002). The Fa and Fs values of olivine and low-Ca pyroxene are 5.3 ± 1.2 mol% and 8.9 ± 0.3 mol%, respectively (Rubin et al., 2002). Oxygen and chromium isotopic composition of NWA 468 require a reclassification to an anomalous metal-rich lodranite (Sanborn et al., 2014b). NWA 468 is known to be similar to GRA 95209 petrographically and in terms of oxygen isotopic composition. GRA 95209 is a metal-rich lodranite considered to record information of the earliest stages of core formation in asteroids (McCoy et al., 2006).

NWA 8054 is composed predominantly of magnesian orthopyroxene, olivine, clinopyroxene, and minor intermediate-composition plagioclase and troilite (Irving et al., 2014). Some small blebs of kamacite exist on grain boundaries and within mafic silicate minerals. Olivine and orthopyroxene in this meteorite are compositionally zoned with cores richer in FeO content than that in rims. Fa values of olivine are 4.0–4.2 mol% in the cores while 2.2–2.9 mol% in the rims (Irving et al., 2014). The meteorite was classified originally as an ungrouped achondrite, but the overall mineralogy and bulk chemical composition is most similar to lodranites. However, NWA 8054 differs from typical lodranites in its low metal content, modal abundances of pyroxene (rich) and olivine (poor), and the occurrence of more calcic plagioclase. Kamacite occurs along grain boundaries and fractures.

NWA 8422 was termed an anomalous lodranite by Kuehner et al. (2015) due to the presence of marginal and interior reduction zones on olivine grains, which they proposed to be possible evidence of fluids or changing redox conditions during crystallization, and like NWA 8054 has magnesian zones within olivine. For NWA 11187, oxygen isotopes plot near the ureilite oxygen compositional trend, but also near the trend for the acapulcoites and lodranites. However, mineralogical characteristics (non-Cr-rich olivine and occurrence of olivine as chadacrysts) are not typical for ureilites (Meteoritical Bulletin No. 106).

Interestingly, our study also indicates GRV 020043 and the ungrouped achondrite NWA 7325 (Irving et al., 2013; Barrat et al., 2015; Weber et al., 2016; Goodrich et al., 2017) might originate from similar oxygen and chromium reservoirs (Fig. 10a and b). However, the plagioclase in NWA 7325 is much rich in Ca content (An_{79}-An_{94}; Barrat et al., 2015; Weber et al., 2016) than the plagioclase in GRV 020043 and acapulcoite-lodranite meteorites (An values are smaller than 30 in acapulcoite-lodranite meteorites; Mittlefehldt et al., 1996; Patzer et al., 2004).

Based on the above data, we suggest that GRV 020043, NWA 468/GRA 95209, NWA 8118, NWA 8287, and NWA 8422 all derive from the parent body of acapulcoite-lodranite clan, and GRV 020043 is the chondritic precursor of acapulcoites-lodranites. The CRE age (17.5–19 Ma) of NWA 7325 (Weber et al., 2016; Hopp et al., 2018) differs from the peak value of the acapulcoite-lodranite clan (Eugster and Lorenzetti, 2005). It may also indicate multiple break-ups of the parent asteroid, as NWA 7325 is likely not from the location of lodranites or acapulcoites. It does not necessarily rule out NWA 7325 is not coming from the acapulcoite-lodranite parent body. NWA 468, similar to GRA 95209, might be a lodranite admixed by the intrusion of metal melt.

4.3. Structure of the acapulcoite-lodranite parent asteroid

The acapulcoite-lodranite parent body may have accreted ~1.5–2 Ma after the formation of CAIs

(Touboul et al., 2008, 2009; Keil et al., 2018), subsequently experiencing complicated heating and cooling processes, before finally cooling to the Ar closure temperature at ~4.51 Ga and ~4.48 Ga for acapulcoites and lodranites, respectively (Bogard et al., 1993; McCoy et al., 1996, 1997a, 2006; Bogard and Garrison, 1999; Trieloff et al., 2001; Bogard, 2011). Under the heating by non-impact related processes, acapulcoites, transitional acapulcoite/lodranites, and lodranites experienced different degrees of partial melting and small-scale migration of melts (Mittlefehldt et al., 1996; McCoy et al., 1996, 1997a, 2006; Patzer et al., 2004). For most acapulcoites, only Fe, Ni-FeS cotectic melting occurred, while for most of lodranites, a higher degree of partial melting was experienced with Fe,Ni-FeS and basaltic partial melts generated (Mittlefehldt et al., 1996; McCoy et al., 1997b; Patzer et al., 2004). So, it is reasonable that the metal-rich lodranites (e.g. NWA 468 and GRA 95209) are the sink products of a metal-rich melt. Systemic differences in trace elements between acapulcoites and lodranites also indicate the formation of the latter is the result of removal of 15% or more silicate partial melt from the former (Floss, 2000). Transitional acapulcoite/lodranites are between acapulcoites and lodranites in terms of grain sizes and incompatible trace elements abundances (Floss, 2000; Patzer et al., 2004), which implies the thermal metamorphism of the transitional acapulcoite/lodranites is between that of acapulcoites and lodranites.

Increasing numbers of researchers agree that the heating sources of the acapulcoite-lodranite parent body and other differentiated small asteroids are short-lived ^{26}Al and/or ^{60}Fe (Miyamoto and Takeda, 1992; Bogard et al., 1993; Takeda et al., 1994; Zipfel et al.,1995; McCoy et al., 1996, 2006; Mittlefehldt et al., 1996; Zema et al., 1996; Pellas et al., 1997; Huss and Tashibana, 2004; El Goresy et al., 2005; Hevey and Sanders, 2006; Wadhwa et al., 2006; Sahijpal et al., 2007; Touboul et al., 2008, 2009; Lee, 2008; Schiller et al., 2010; Schulz et al., 2010; Greenwood et al., 2012, 2017; Wilson and Keil, 2012, 2017; Kita et al., 2013; Golabek et al., 2014; Neumann et al., 2018), although a few scientists suggest that the impact was the heating source (e.g. Rubin, 2007). From the observational facts mentioned in the above paragraphs, the increasing degrees of thermal metamorphism observed across the petrographic range of acapulcoites, transitional acapulcoite/lodranites, and lodranites are quite apparent. Furthermore, it is a common view that acapulcoite-lodranite members originated from a common parent asteroid (Keil and McCoy, 2018; and the references therein). Usually, the degree of thermal metamorphism of asteroidal material gradually decreases from the core to the outer layers of an asteroid. This scenario was previously proposed as the onion shell structure of the H ordinary chondrite parent body (e.g. Trieloff et al., 2003; Kleine et al., 2008). Therefore, such a scenario can also be the case for the acapulcoite-lodranite parent body.

The possibility of GRV 020043, NWA 468/GRA 95209, NWA 8054, NWA 8287, NWA 8422 all originating from the acapulcoite-lodranite clan parent body implies this asteroid should possess a layered structure. The highly siderophile elements abundance in acapulcoite-lodranite meteorites (Dhaliwal et al., 2017) supports the metal-silicate differentiation and layered internal structure of the parent asteroid. Such a body would contain chondritic (GRV 020043-like), achondritic (acapulcoite and lodranite-like), and metal-rich (NWA 468-like) materials. The degree of differentiation increases in the order as GRV 020043, acapulcoites, acapulcoite/lodranites transition type, lodranites, and NWA 468/GRV 95209-like if the heating sources are short-lived radionuclides (e.g., ^{26}Al and ^{60}Fe). To hold so many types of meteorites in one parent body, the two-layer shell structure of acapulcoite-lodranite parent body proposed by Eugster and Lorenzetti (2005) is somewhat simplistic. Our study suggests a multi-layer structure (Fig. 12). The proposed structure is analogous to structures proposed for the CV chondrite parent body by Elkins-Tanton et al. (2011) and CR chondrite parent body (Sanborn et al., 2014a). Recently, Neumann et al. (2018) proposed a multi-layered internal structure (an iron core, a silicate mantle, a partially differentiated layer, and an undifferentiated outer crust) of the acapulcoite-lodranite parent body with a radius of ~260 km based on their modeling calculation. Based on this study, there is not sufficient direct evidence of an iron core or silicate mantle on the acapulcoite-lodranite parent body. In the context of our proposed acapulcoite-lodranite parent body structure, the different meteorite types discussed are representative of the peak temperatures they experienced at different depths, but it does not rule out that positions were disturbed at some point by impact events. According to our model, the extent of thermal metamorphism increases with depth with the outermost layer being chondritic material (GRV 020043-like) and the deeper layers transitioning from acapulcoite-like, acapulcoite/lodranite-like, lodranite-like, to NWA 468-like (also GRA 95209) materials.

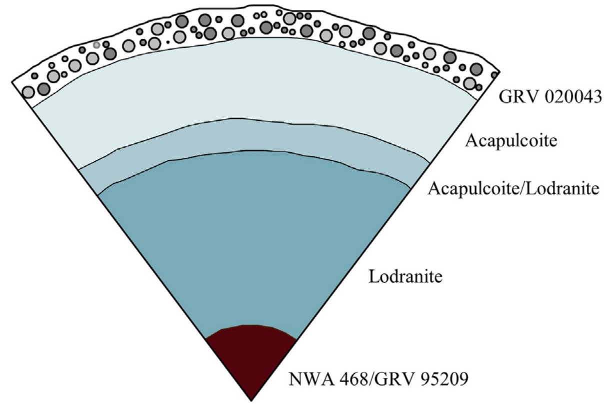

Fig. 12. Schematic diagram of proposed structure for the acapulcoite-lodranite clan parent asteroid, including an iron-rich core (NWA 468 and GRA 95209 like), toward the outside the sequences is lodranite-like, acapulcoite/lodranite-like, acapulcoite-like, and GRV 020043-like materials.

5. CONCLUSIONS

GRV 020043 is a type 4 chondrite composed of ~62 vol.% chondrules and ~38 vol.% matrix. Homogeneous compositions of olivine and low-Ca pyroxene, and the well-defined chondrules indicate a petrologic grade of 4. Petrographic observation, mineralogical study, and oxygen and chromium isotopic compositions reveal that this meteorite does not belong to any established chondrite group nor is related to any ungrouped chondrites. GRV 020043 formed under redox conditions that were intermediate between the K chondrite grouplet and H chondrites and was modified by moderate thermal metamorphism and shock after its formation. GRV 020043 shares the similar mineral assemblage, bulk chemical composition, mineral compositions, oxygen isotopic composition, and Cr isotopic composition with the acapulcoite-lodranite clan. This indicates that GRV 020043 represents the chondritic parental (precursor) composition for the acapulcoite-lodranite parent body.

Our study suggests that NWA 468 is associated with the acapulcoite-lodranite clan (e.g. NWA 8118, NWA 8287, NWA 8422). These samples document a complete suite of differentiation, metal melting and segregation processes in a multilayered interior structure of the acapulcoite-lodranite parent body, with GRA 020043 representing the unmelted chondritic parent composition on its subsurface.

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APPENDIX A. SUPPLEMENTARY MATERIAL

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