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Grove Mountains (GRV) 99027: A new Martian meteorite

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Abstract **We report the petrography, mineral chemistry and oxygen isotopic composition of GRV 99027, a new Martian meteorite recently collected during the 16th Chinese Antarctic Research Expedition. This meteorite consists of two textural regions. The interstitial region is characterized by the presence of plagioclase and phosphate, and higher FeO contents of olivine and orthopyroxene, in comparison with the poikilitic region. All of the observations are similar to the three known Martian lherzolites. We classify GRV 99027 as the fourth sample of Martian lherzolite.**

Keywords: meteorite, planet, Mars, lherzolite, igneous texture.

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Meteorites are extra-terrestrial rocks that have preserved records of formation and evolution of the solar system. Most meteorites came from the asteroid belt, but a few from the Moon[1] and Mars[2]. Of more than 28000 meteorites, most were collected on blue ices in Antarctica. They were buried by snow after falling on the ice surfaces, then transported together with glacier, and finally concentrated at sites where the glacier erodes fast. Following the discoveries by Japan, USA and European Union, the Chinese in their 15th Antarctic Research Expedition (CHINARE) in 1998/1999 found 4 meteorites in the Grove Mountains region, eastern Antarctica[3,4]. This is the first discovery of meteorites in this location. Additional 28 meteorites were found in the same location during the 16th CHINARE[4]. We classified all the newly discovered meteorites, and found GRV 99027 to be a new Martian meteorite. Preliminary result was reported by Lin et al.[5].

1 Sample and experiments

GRV 99027 weighs 9.97 g, with a size of 2.2 cm×2.5 cm×2.8 cm. Much of its surface is covered with a thin black fusion crust. Where the fusion crust is removed, it shows a grey color (Fig. 1). A polished thin section was made from a slice, labeled as GRV 99027-3 with a surface of 0.9 cm×1.3 cm. Petrographical study was conducted using an optical microscope and a JEOL JXA-8800R electron probe microanalyzer (EPMA) in the mode of back-scattered electron image (BSE), at Zhongshan University, Guangzhou. Quantitative analyses of individual minerals were conducted using the same EPMA and another type JEOL 733 at Ibaraki University, Japan. The operating conditions are 15 kV of accelerating voltage and 20 nA (10 nA for feldspar) of beam current. Silicates and oxides were used as standards. Oxygen isotopes were analyzed using the BrF_5 method[6] by R. N. Clayton and T. Mayeda in the Enrico Fermi Institute, the University of Chicago. The analyses were done on fresh grains without fusion crust.

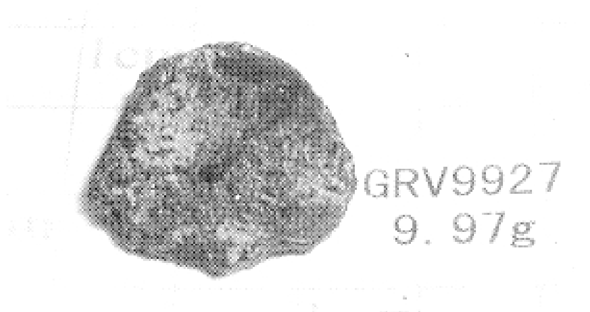

Fig. 1. Photo of the GRV 99027 Martian meteorite. Grid is 1 cm.

2 Results

The meteorite shows typical igneous textures, and consists of two textural regions. The larger region shows a poikilitic texture, with abundant euhedral grains of olivine enclosed in a megacryst of orthopyroxene. Most olivine crystals are 100—500 μm in size, and show rounded feature and orientation. The smaller region consists of subhedral to euhedral grains of olivine, orthopyroxene and clinopyroxene, with anhedral plagioclase filling the interstices. This region is hereafter referred to as interstitial. Crystals of olivine in the interstitial region show similar orientation as those poikilitically enclosed in the orthopyroxene megacryst. Minor chromite was found in both textures, as euhedral grains in silicates. However, other minor minerals, including ilmenite, sulfides and phosphate (probably merrillite), were confined to the interstitial part. These accessories usually coexist with plagioclase. A few of ilmenite occur as lamellae in chromite. Variation between the two textures is continuous, and there is no sharp boundary between them. Modal composition of the poikilitic region is (in volume): 66.4% orthopyroxene, 1.4% clinopyroxene, 30.9% olivine and 1.2% chromite; that of the interstitial part is: 39.0% orthopyroxene, 10.6% clinopyroxene, 34.6% olivine, 14.9% plagioclase and 0.9% chromite.

Only two melt pockets have been found in the polished thin section. The larger one (1 mm in diameter) is recrystallized, mainly consisting of bars of olivine and orthopyroxene with minor clinopyroxene. Another pocket (600 μm in diameter) is also recrystallized, and has the similar texture and mineral assemblage. No shock-induced veins were found. Fracturing of silicates is highly developed. Undulose and mosaic extinctions of olivine and pyroxenes are common. Most plagioclase crystals show the planar fracture, probably due to the shock metamorphism too. Only a few grains are isotropic, and probably have been transformed into maskelynite.

EPMA data show a correlation between the composition and occurrence of the minerals (Table 1). Generally, olivine and orthopyroxene in the interstitial region contain higher FeO than those in the poikilitic region. Fa (atomic ratio of Fe/(Fe+Mg)×100) value of olivine is higher for the interstitial region (29.7±0.7) than the poikilitic (26.7 ±1.4). Olivine in the melt pockets is heterogeneous in and among grains, with a range of Fa 20—35. However, there is no systematic variation with distance to the host wall. Similarly, the orthopyroxene megacryst (En_{66-77}- $Fs_{20-23}Wo_{3-14}$) contains lower FeO than the crystals in the interstitial region ($En_{61-70}Fs_{24-27}Wo_{7-16}$, except for 6 of 62 analyses overlapping with the megacryst). In addition, the megacryst contains on average lower abundances of TiO_2 (<0.20%, weight percent) and Al_2O_3 (0.32%—0.82%, weight percent) than the grains in the interstitial region (TiO_2 0.08%—0.87%, weight percent, Al_2O_3 0.52%—1.44%, weight percent). Chromite is TiO_2-poor in poikilitic region ($Chm_{68-82}Sp_{13-22}Mt_{2-6}Usp_{2-4}$, 0.87% — 1.61% TiO_2, weight percent), in comparison with that in the interstitial region ($Chm_{42-71}Sp_{11-22}Mt_{3-11}Usp_{5-36}$). Especially, those grains in contact with or enclosed in plagioclase are highly TiO_2-enriched (7.21%—13.9%, weight percent). Composition of clinopyroxene ($En_{48-54}Fs_{13-19}$- Wo_{29-38}) shows no textural preference. Plagioclase ($An_{42-55}Ab_{45-57}Qr_{<2}$) is K_2O-poor.

Bulk oxygen isotopic composition of GRV 99027 is: $\delta^{18}O$ (mean±1σ) 3.97 ‰±0.07 ‰, $\delta^{17}O$ 2.34 ‰± 0.07 ‰, which is ^{17}O-rich, with $\Delta^{17}O$ of 0.28 ‰ ($\Delta^{17}O = \delta^{17}O - 0.52\delta^{18}O$) relative to terrestrial materials.

3 Evidence for a Martian origin

First, GRV 99027 has a fusion crust that was produced by high temperature ablation when it fell through the Earth's atmosphere, hence the stone is a meteorite of extra-terrestrial origin. The typical igneous textures indicate an achondrite. There are only a few types of meteorites resembling GRV 99027 in terms of textures, modal

Table 1 Summary of electron probe analyses of minerals in GRV 99027 (%, weight percent)

	Olivine		Orthopyroxene		Clinopyroxene		Plagioclase	Chromite	
	1*	2	3*	4	5*	6	7*	8*	9
SiO_2	37.8 ± 0.4	38.2 ± 0.6	53.9 ± 0.7	55.1 ± 0.6	52.9 ± 0.6	53.0 ± 0.5	55.4 ± 1.1	0.01	0.02
	37.1—38.7	*36.6—39.1*	*52.1—55.5*	*53.2—56.4*	*51.6—54.3*	*52.1—53.9*	*53.5—59.2*	*<0.18*	*<0.17*
TiO_2	0.01	0.01	0.49 ± 0.22	0.10 ± 0.04	0.36 ± 0.09	0.33 ± 0.14	0.04 ± 0.03	7.12 ± 4.44	1.81 ± 1.88
	<0.10	*<0.08*	*0.08—1.07*	*0.00—0.19*	*0.21—0.55*	*0.19—0.88*	*<0.14*	*0.88—13.9*	*0.76—8.07*
Al_2O_3	0.01	0.02	0.82 ± 0.25	0.58 ± 0.12	1.65 ± 0.39	1.44 ± 0.35	27.6 ± 0.6	6.57 ± 0.97	7.65 ± 1.55
	0.36	*<0.18*	*0.44—1.44*	*0.32—0.83*	*1.02—2.44*	*1.02—2.27*	*25.3—28.9*	*4.66—9.48*	*5.44—11.7*
Cr_2O_3	0.03 ± 0.03	0.03	0.36 ± 0.15	0.47 ± 0.11	0.87 ± 0.09	0.84 ± 0.06	0.01	45.0 ± 10.0	55.8 ± 4.8
	<0.16	*<0.29*	*0.18—0.91*	*0.33—1.09*	*0.69—1.05*	*0.70—0.98*	*<0.16*	*31.8—60.3*	*42.9—61.5*
V_2O_3			0.03	0.01	0.08 ± 0.03	0.06 ± 0.04		0.49 ± 0.11	0.54 ± 0.14
			<0.11	*<0.10*	*<0.15*	*<0.13*		*0.29—0.88*	*0.33—0.93*
FeO	26.1 ± 1.0	24.4 ± 1.2	15.5 ± 0.8	13.6 ± 0.7	9.02 ± 0.54	8.73 ± 0.45	0.47 ± 0.16	34.5 ± 5.2	27.8 ± 2.1
	24.4—28.0	*20.9—27.3*	*13.2—17.0*	*11.6—14.9*	*7.81—10.2*	*7.90—9.67*	*0.19—0.93*	*27.2—44.8*	*24.5—33.0*
NiO	0.05 ± 0.03	0.03 ± 0.02						0.05 ± 0.04	0.03 ± 0.03
	<0.11	*<0.06*						*<0.21*	*<0.09*
MnO	0.53 ± 0.06	0.50 ± 0.06	0.56 ± 0.04	0.48 ± 0.05	0.37 ± 0.05	0.37 ± 0.05	0.00	0.45 ± 0.08	0.35 ± 0.16
	0.38—0.68	*0.34—0.65*	*0.48—0.64*	*0.31—0.58*	*0.29—0.45*	*0.27—0.44*	*0.06*	*0.21—0.62*	*<0.55*
MgO	35.4 ± 0.7	37.3 ± 1.1	23.2 ± 1.1	25.2 ± 1.4	17.7 ± 0.5	18.0 ± 0.7	0.24 ± 0.17	4.93 ± 0.56	5.70 ± 0.72
	34.2—37.8	*34.4—40.2*	*20.5—25.8*	*22.4—28.5*	*16.7—19.1*	*16.7—19.5*	*0.07—0.86*	*4.02—6.84*	*4.34—7.21*
CaO	0.19 ± 0.10	0.17 ± 0.09	5.00 ± 1.09	4.38 ± 1.62	17.1 ± 0.9	17.3 ± 1.0	10.9 ± 0.6	0.02	0.01
	0.08—0.69	*0.06—0.57*	*3.14—7.69*	*1.36—8.46*	*15.1—18.9*	*14.8—18.9*	*8.91—12.4*	*<0.24*	*<0.10*
Na_2O			0.07 ± 0.04	0.05 ± 0.03	0.02	0.28 ± 0.07	5.63 ± 0.44		
			<0.18	*<0.16*	*<0.22*	*0.23—0.33*	*4.25—6.93*		
K_2O							0.12 ± 0.05		
							0.03—0.34		

Average ±σ. Italic: ranges; blank: not analyzed. * Interstitial texture, others are poikilitic.

compositions and mineral chemistry. These meteorites are howardite (H)-eucrite (E)-diogenite (D) clan (HED), basaltic lunar meteorites, and shergottites. All of plagioclase in HED ($An_{80\text{-}100}$)[7], and in lunar meteorites and rocks ($An_{90\text{-}100}$)[1] are typically anorthitic. In contrast, plagioclase in GRV 99027 is Na-rich ($An_{42\text{-}55}$). Hence, GRV 99027 cannot be a lunar meteorite or HED meteorite.

Extensive studies suggest Martian origins of shergottites, chassignite, nakhlite and orthopyroxenite[2]. The primary lines of evidence are: (1) Except for the oldest ALH 84001 (4.5 Ga), the others have young crystallization ages (⩽1.3 Ga,)[8], suggestive of a planetary parent body; (2) chemical and isotopic compositions of the captured gases in these meteorites plot on a mixing line between the terrestrial and Martian atmospheres, the latter being analyzed by the Viking spacecraft[9,10]; and (3) the bulk compositions of these meteorites are consistent with the analyses of Martian soils done by the Viking and the Mars Pathfinder missions[11].

Based on textures and modal compositions, shergottites are divided into three types, i.e. basaltic, olivine-phyric and lherzolitic. Table 2 shows a comparison of GRV 99027 with the Martian lherzolites. It is obvious that GRV 99027 is very similar to the known lherzolites in terms of textures, modal compositions, Fa content of olivine and its distribution, An content of plagioclase, and compositions of orthopyroxene, clinopyroxene and chromite. Furthermore, the minor elements of silicates are also within the ranges of the lherzolites. Hence, we classify GRV 99027 as a new Martian lherzolite. In addition, GRV 99027 is a magmatic cumulate according to the orientation of olivine crystals.

Oxygen isotopic composition is one of the critical parameters used to determine the origin of meteorites. Fig. 2 is a three oxygen isotope plot of GRV 99027. The analysis of GRV 99027 is within the range of Martian meteorites, distinct from terrestrial and lunar materials, HED and other meteorites. All analyses of Martian meteorites plot on a line with a slope of 0.52, parallel to the Terrestrial Fractional (TF) line. The variation indicates mass-depended fractionation during physical-chemical processes on the surface of Mars. Different $\Delta^{17}O$ values between groups of meteorites reflect their individual oxygen reservoirs. Hence, the Martian origin of GRV 99027 is confirmed by the oxygen isotopic composition.

4 Significance of GRV 99027

Martian meteorites are, so far, the only samples available from Mars. They are probes into the formation, compositions, and magmatism of the red planet as well as origin and evolution of its atmosphere. The report of possible old bacterial fossil in ALH 84001[19], evidence for activities of water flows on the surface of Mars[20], and existence of water ice buried close to its surface[21,22] suggest probable existence of extra-terrestrial life forms on Mars, which, if proven correctly, will be of far-reaching scientific significance. Martian meteorites are very precious samples, because there are only 27 of the meteorites reported up to date, including GRV 99027. Furthermore, Martian lherzolites, that are similar to GRV 99027, are even rarer, and only three of them (Y 793605, ALH 77005 and LEW 88516) have been reported. Extensive studies of these three lherzolites show very similar petrography and mineral chemistry[12—15], and ejection and crystallization ages[8,23]. They probably came from the same rock on Mars. If GRV 99027 formed during another ejection event, it would more likely sample a different site on Mars. However, more comparative studies with the other lherzolites, and determination of cosmic-ray exposure age and terrestrial age of GRV 99027 are required in order to clarify this issue.

Also important is that GRV 99027 is fresh. Of 27 reported Martian meteorites, 4 are falls, 8 were collected on blue ices of Antarctica, and the others were found on deserts. Except for Antarctica, meteorites collected at other places after a long time of the falls experienced various degrees of terrestrial weathering, and contaminated by terrestrial organic materials. GRV 99027 is very fresh, hence important for studying weathering on the surface of Mars, and traces of Martian life.

Table 2 Comparison of GRV 99027 with Martian lherzolites

	GRV 99027	Martian lherzolites*
Texture	poikilitic and interstitial	poikilitic and interstitial
Modal composition (%, volume percent)	orthopyroxene 55.7, clinopyroxene 5.1, olivine 32.3, plagioclase 5.9, chromite 1.1, and minor ilmenite, sulfides and phosphate	orthopyroxene 10—60, clinopyroxene <28, olivine 35—60, plagioclase 5—15, chromite 0.7—2.1, and minor ilmenite, sulfides and phosphate
Fa (%, molar percent)	poikilitic: 26.7 ± 1.4; interstitial: 29.7 ± 0.7	bi-peak, higher in interstitial part: 22—40
Orthopyroxene	$En_{61\text{-}78}Fs_{20\text{-}27}Wo_{2\text{-}16}$	$En_{57\text{-}78}Fs_{22\text{-}43}Wo_{2\text{-}18}$
Clinopyroxene	$En_{48\text{-}55}Fs_{13\text{-}19}Wo_{29\text{-}39}$	$En_{46\text{-}55}Fs_{12\text{-}18}Wo_{27\text{-}41}$
An (%, molar percent)	42—55	30—65
Chromite	poikilitic: $Chm_{68\text{-}82}Sp_{13\text{-}22}Mt_{2\text{-}6}Usp_{2\text{-}4}$ interstitial: $Chm_{42\text{-}71}Sp_{11\text{-}22}Mt_{3\text{-}11}Usp_{5\text{-}36}$	higher TiO_2 in interstitial part than in poikilitic region

*Based on refs. [12—15].

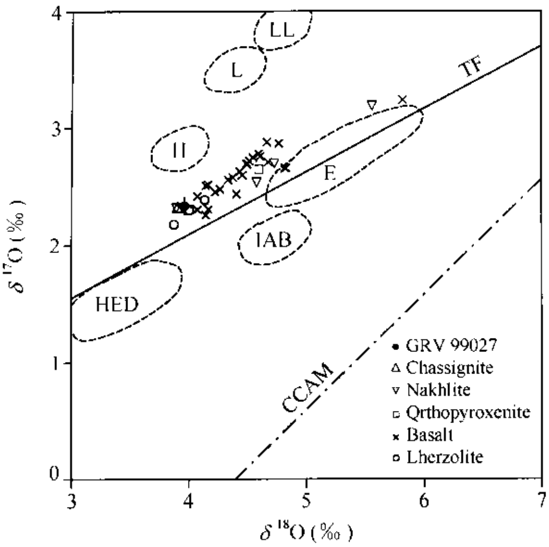

Fig. 2. Oxygen isotopic composition of GRV 99027, in comparison with ordinary chondrites (H, L, LL), enstatite chondrites and achondrites (E), silicate inclusions in IAB iron (IAB), and HED meteorites[16]. Analyses of other Martian meteorites are from refs. [6, 17, 18]. TF, Terrestrial fractionation; CCAM, carbonaceous chondrite anhydrous minerals.

Because of the very important scientific values of GRV 99027, a comprehensive study of this meteorite has been proposed, and the project is supported by the National Natural Science Foundation of China (NSFC). The main subjects are: (1) determining terrestrial and exposure ages of GRV 99027 using cosmogenic nuclides; (2) determining crystallization and main impact event ages using radioactive nuclides; (3) characterizing textural details, mineral chemistry, trace elements and stable isotopes, to clarify processes and conditions of crystallization of magma, and compositions of the magma source; (4) studying secondary minerals, to clarify processes on the surface of Mars, and to find hints for or against existence of Martian life; and (5) studying shock metamorphism and searching for high-pressure polymorphs.

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