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Geochemistry of the Martian Meteorite GRV 99027

Wang Henian(王鹤年), Xie Zhidong(谢志东) and Liang Ying(梁英)
State Key Laboratory for Research of Mineral Deposits, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210093, China

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Abstract GRV 90027 is a Martian lherzolitic shergottites (L-S) containing poikilitic, non-poikilitic, and melted pocket components. GRV 99027 is mainly composed of olive (55 vol%) and pyroxene (37.5 vol%), with minor maskelynite (6 vol%) and chromite (1.5 vol%), and trace whitelockite and troilite, ect. In this paper, the mineralogy and petrology of GRV 99027 are reported, in addition, the geochemical characteristics of the REEs and H isotopes in the GRV 99027 are also further investigated. The ΣREE in GRV 99027 is relatively low; HREEs are enriched in olivine and pyroxene grains; LREEs are enriched in plagioclase with a high positive Eu anomaly. High ΣREE value is found in rare mineral whitlockite (less than 0.2 vol%), LREE≈HREE, and whitlockite has a negative Eu anomaly. The REE distribution patterns of the whole-rock of GRV 99027 is similar to but different from that of other L-S Martian meteorites, indicating that they came from different location of Mars. GRV 99027 has a high δD value. Different water-bearing minerals give different contribution for δD value. The δD of phosphates generally does not correlate with water content, and δD has a weak negative correlation with water content. GRV 99027 can be classified as an L-S Martian meteorite based on mineralogical assemblage patterns, REE distribution patterns, and hydrogen isotope. The isotope data of Sr, Nd, Pb, Os and REE from other L-S Martian meteorites were collected to discuss the formation history of the GRV 99027. Similar to other L-S Martian meteorites, GRV 99027 originated from part of Mar' s mantle; during one strong impact event about 4M years ago, the meteorites were ejected from deep mantle into space, and traveled for a different duration in space (indicated by different cosmic exposure time), and captured by the Earth later in different time, ultimately falling on the Antarctica as L-S Martian meteorites.

Key words Martian meteorite, GRV 99027, lherzolitic, REE, Hydrogen isotope.

1 Introduction

More than 33 of those 30000 plus found meteorites were identified as Martian meteorites. These include twenty four pieces of the Shergottites, seven pieces of Nakhlites, one piece of Chassignite, and one piece of Orthopyroxenite. The majority of the Martian meteorites were found from arid regions, only few pieces come from Antarctica. Most representive Martian meteorites (SNC) were found early (Shergotty, was found in India, August 25th, 1865; Nakhla, in Egypt, June 28, 1911; Chassigny, in France, October 3rd, 1815; Orthopyroxenite, ALH 84001, in Allan Hills of Antarctica in 1984). Until 1983, Bogard and Johnson found the captured Ar in the impact melted glass of Shergottite EETA 79001[1]. Based on that the isotopic compound and the relative abundance of Ar, along with other noble gases, N_2, CO_2, match with these of Mars atmosphere very well, the origin of Mars for these meteorites were confirmed, and then, the research of the SNC meteorites set a foundation for the studies of Mars and planetary sciences.

Among the SNC Martian meteorites, Shergottites are divided in two groups: one is the Basaltic-Shergottites, Like Shergotty, Zagami, EETA 79001, and QUE 94201; another group is Lherzolitic-Shergottites, such as ALH A77005, LEW 88516, and Y793605. GRV 99027, the first Martian meteorite found by Chinese, is a new member of L-S[2-7]. This paper first describes this meteorite's petrology and its mineralogy and chemistry characteristic, and then represent the results of the rare-earth element and the hydrogen isotope geochemistry and its characteristics, and finally discusses the formation conditions and the evolution history of the GRV 90027.

2 Sample and analysis methods

The meteorite GRV 90027 was discovered and retrieved at Antarctica's blue ice regions in the Grove Mountains during China's 16th Antarctic expedition (1999/2000). The meteorite weighs 9.97 g, and it's shape is round and triangular. The majority of its surface is covered with thin black brown melt shell (1-2 mm). The petrography characteristics of GRV 90027 were investigated under Leitz Polarizing microscope and Nikon DXM 1200 digital microscope. The mineral chemistry ingredient analysis is performed by using Japan's JEOL JXA 8800M electron microprobe in National Mineral Deposits Research Key Laboratory, Nanjing University. The acceleration voltage are 15 kV, beam flux 10 nA, the measurement characteristics of the peak time was 10 seconds, background value's time was 5 s. The Standard Samples from the United States National Bureau of Standards are: Hornblende (Na, Al, K, Ca, Ti), forsterite (Mg), fayalite (Si, Fe, Mn), Cr (Cr_2O_3), phosphorite (P); the standard for Si in pyroxene is using the hornblende standard sample, and the standard for Al in maskelynite Al is using anorthite standard sample. Silicate mineral analysis results are got though the Bence-Albee computation, the ZAF adjustment method is used too. The methods of debunching, beam fluxes with diameter of 2 μm are used during the analysis of Maskelynite to reduce the loss of volatile elements as much as possible.

Phosphate hydrogen's isotope and its water content is measured using IM-2f iron probe in Arizona State University, U. S. Due to small cracks on the phosphate pellet, very tiny ion beam (approximately 2—5 μm) Cs+ are used to avoid oxygen resin pollution. In order to increase Secondary ion transmission rate, the secondary ion signal are gathered after pressurized by 9 keV and passing through the aperture with 75 μm grating. The accumulation of electric charge in sample's surface is neutralized by electron stream gun. Carries on the instrument quality fractionation and the hydrogen background adjustment with the Earth apatite standard sample and the GRV 99027 thin slice olivine, the sample surface electric charge accumulates by the electron stream gun comes neutral. Analyzing the D/H ratio water content, also is based on the Earth apatite standard sample, and choosing P as the reference element. In our measurement, the relative water content error is approximately 5% —

18% . The principle, method and application of the ion probe measurement of hydrogen isotope please refer the relevant paper of Xu *et al.* [6].

3 GRV 99027 Martian meteorite' s petrological and mineralogical characteristics

3.1 Lithofacies characteristics

The area of GRV 99027' s optical slice is 1.3 cm × 0.8 cm, its shape appears to be an irregular trapezoid (Figure 1). Endoscopic identification of the meteorite shows that it is free chondrules, referring to the whole granular crystalline structure, granularity medium. It is mainly composed of olivine and the pyroxene, containing small amounts of Maskelynite. The minor minerals are chromite, troilite, and phosphate. Apparently GRV 99027 is an lherzolitic shergotties, containing characteristics of igneous differential textures, including the basic three structures: Poikilitic, non-poikilitic, melt pocket. In the poikilitic section (Figure 1' s Poi), brown idiomorphic, , half euhedral olivine (0.05 – 0.10 mm) and black idiomorphic chromite (0.01—0.1 mm) were enveloped by more volatile pyroxene crystal (2.5—4 mm); small amount of interstitial melt feldspar-like distribution can be seen in poikilitic 3 area (Figure 1' s Poi3). In non-poikilitic area (Figure 1 Right side), larger olivine crystals (0.1—2.5 mm) were aggregate crystals (Figure 2b), or symbiosis with pyroxene (~ 0.05 mm). Maskelynite, whitelockite (0.05—0.15 mm) are often appearing in irregularly shaped interstitial (Figure 2c). Some glass were formed by shock in "shock-induced melt textures" structural zone (Figure 1 left). Some of them were self-shaped, or half idimorphic olivine crystalline with sub-band characteristics (Figure 2d). GRV 99027' s decency degree is very low (W1), with non-limonite veins development. Degree of shock metamorphism is around S4. GRV 99027' s mineral assemblage and the structure are similar to other L-S meteorites, such as ALHA 77005, LEW 88516, Y793605[8-11].

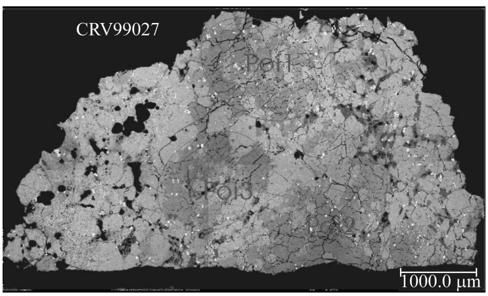

Fig 1 Back-Scattered Electron (BSE) image of GRV 99027 showing shock melt texture on the left light gray region, poikilitic texture (Poi), and non-poikilitic texture in rest of the region

3.2 GRV 99027 Martian Meteorite mineral composition model

GRV 99027 ' s minerals includes majorly olivine (55 vol%), pyroxene (37.5 vol%), maskelynite (6 vol%), chromite (1.5 vol%), and other minor minerals, such as whitlockite and troilite. As can be seen from Table 1, the model composition is extremely similar to L-S meteorite ALPHA 77005, LEW 88516 and Y793605. This type of Martian meteorite's olivine is about 40%-50%, pyroxene 35%-50%, plagioclase is scarce (< 10%), pyroxene which is with low calcium and high calcium pyroxene characterized is the L-S olivine of the Martian meteorite. Nevertheless, other Types of Martian meteorite's mineral composition models' combinations are different (Table 1), Nakhla (Nakhlite) is mainly composed of augite (78.6%); Chassigny (Chassignite) is mainly composed of olivine (88.5%); Shergotty (B-S) is mainly composed of molten feldspar (23.3%), pigeonite (36.3%), augite (33.5%) as the defining characteristics; ALH 84001 Orthopyroxenite) is mainly composed of orthopyroxene (> 90%).

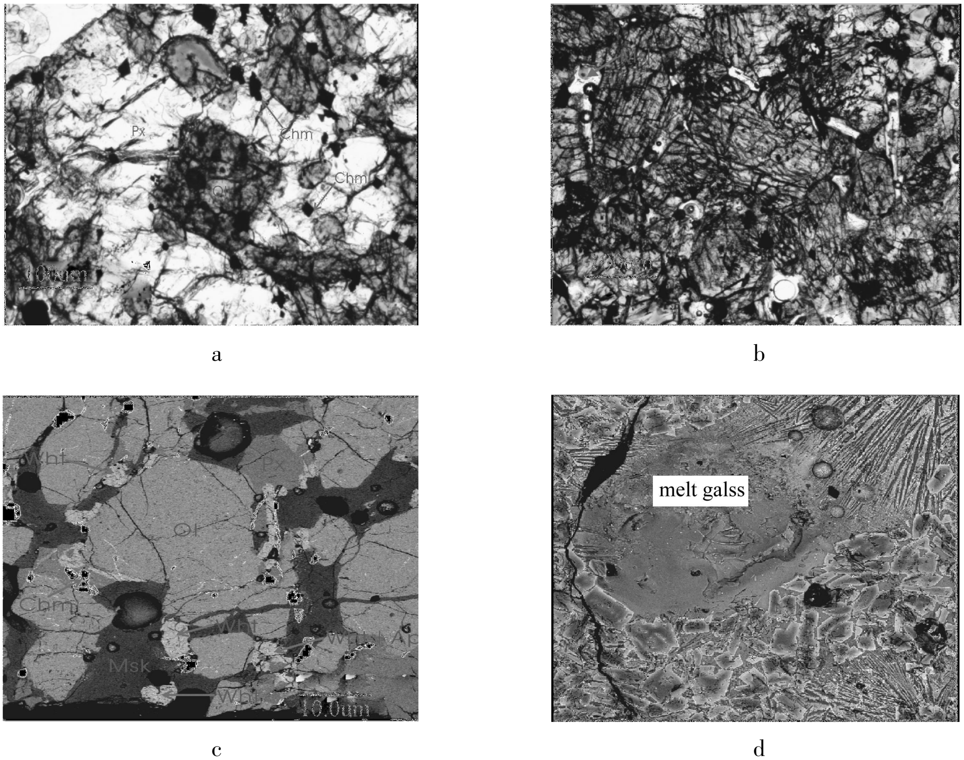

Fig 2 Petrology of Martian Meteorite, GRV 99027. a poikilitic texture: euhedral and subhedral olivine (Ol) and euhedral chromite (Chm) are poikitically enclosed by large pigeonite (Px), PPL; b cumulate texture: olivines cumulus, interstitial maskelynite (Msk), PPL; c interstitial texture: maskelynite, whitlockite and chromite fill in interstitials of olivine and pyroxene, BSE; d shock melt pocket texture: melt glass and olivine crystallites, BSE (the field of view of figure is about 500 μm).

3.3 Chemical composition of minerals

We systemically investigated the chemical composition of olivine, pyroxene, maskelynite in the different structure area of GRV 22097 meteorite. One of its characteristic is the homogeneity of the mineral chemical composition (Table 2), and does not show chemical differentaion and any chemical zonation. Poikilitic area is rich in Mg. Non-poikilitic area is richer in calcium. Mineral compositions are: olivine ($Fo_{69.1\text{-}76.6}$ $Fa_{23.4\text{-}30.9}$, average $Fo_{72.4}$

$Fa_{27.6}$), pigeonite ($En_{59.3-75.1}$ $Fs_{20.5-26.9}$ $Wo_{3.1-14.9}$, Average $En_{68.6}$ $Fs_{23.5}$ $Wo_{8.0}$), Augite ($En_{46.6-53}$ $Fs_{13.1-16.1}$ $Wo_{31.9-37.8}$, Average $En_{50.7}$ $Fs_{14.5}$ $Wo_{34.8}$), Maskelynite ($An_{43.6-59.3}$ $Ab_{40.2-54.6}$ $Or_{0.5-1.8}$, Average $An_{52.4}$ $Ab_{46.7}$ $Or_{0.8}$), Homogeneous composition of phosphate, chromite with rich Al, Mg, Fe; impact melted pockets contain basaltic glass which are rich in Ca, Fe, Mg, Fe; and Al. They contain olivine crystallite with strong zonation, too. GRV 99027' s mineral chemical composition is similar to L-S meteorites ALHA 77005 and GRV 020090, LEW 88516, Y 793605, YA 1075 and NWA 1950, but different from B-S, Nakhlite, Chassignite, Orthopyroxenite' s mineral chemical composition (Table 2, Figure 3 and 4). GRV 99027' s whole-rock chemical composition and diversity index Fe / (Fe + Mg) is also similar with Mars and other L-S Martian meteorites, however is different from B-S, Nakhlite, Chassignite, Orthopyroxenite. (Table 3, Figure 5).

4 The REE Geochemistry of GRV 99027 Martian meteorite

4.1 The REE abundance and distribution patterns of the GV 99027 minerals

GRV 99027' s single mineral' s REE abundance data is shown in Table 4 and Figure 6. Olivine, Pyroxene, plagioclase' s REE element abundance are very low (ΣREE 0.35—16.40 ppm), white phosphorus has highest REE element abundance (ΣREE 1410.50 ppm). LREE is rich in maskelynite (ΣLREE/ΣHREE 15.74), while HREE are rich in other minerals. Olivine, maskelynite, and melted glass have a positive Eu anomaly in addition to maskelynite' s abnormal sudden increase in Eu (δEu 64.70); fused glass does not have Ce abnormalities (δCe 1.0), other minerals also have a negative anomaly, pyroxene and olivine have a more pronounced negative Ce abnormity.

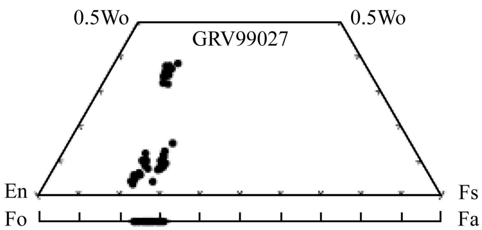

Fig 3 Fo-Fa of olivine and En-Fs-Wo of pyroxene in GRV 99027. Fo, Fa means forsterite and fayalite, En, Fs, Wo mean enstatite, ferropyroxene and wollastonite

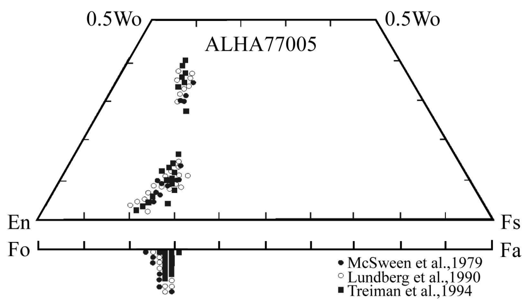

Fig 4 Fo-Fa of olivine and En-Fs-Wo of pyroxene in ALHA 77005 (L-S). Data are from[8][32, 33].

Table 1. Mineralogical modal composition (vol%) of GRV 99027 and SNC Martian meteorites

	GRV 99027	GRV 99027	ALHA 77005	LEW 88516	Y 793605	NWA 1950	Shergotty	Nakhla	Chassigny	ALH 84001
olivine	55	39.4	52	50 – 59	40.4	~55		15.5	88.5	
pigeonite			26				36.3			
augite	~37.5(px)	55.1(px)	11	35(px)	50.8(px)	~35(px)	33.5	78.6	3.8	
clino-px									4.0	>90
maskelynite	6	4.4	10	5 – 8	7.4	~8	23.3	3.7(plg) 1.1(kf)	2.6(plg) tra(kf)	1 – 2%
phosphate	tra(wht, ap)	tra(wht)	tra(wht)	1.7(wht)		tra(mel)	tra(wht, chp)	tra(chp)	tra(chp)	
oxide	1.5(tim, ilm)	1.1(chm) tra(ilm)	1(chm) tra(ilm)	0.7 – 2 (chm)	1.2(chm) 0.2(ilm)	tra(chm, spl)	2.3(tim, ilm)	1.9(tim)	1.2(chm, ilm)	~4%
sufide	tra(tro)	tra(tro)	tra(tro)		0.04	tra(po)	tra(po)	tra	tra(pt, mr)	
Cabonatite										~1%
Resources	This study	Lin *et al.*, 2002[4]	Ma *et al.*, 1981[12]	Wadhwa *et al.*, 1994[13]	Ikeda, 1997[14]	Russell *et al.*, 2004[15]	Stopler and McSween, 1979[16]	Bunch and Reid, 1975[17]	Nehru *et al.*, 1983[18]	Wadhwa and Crozaz, 1998[19]

Note: tra represents trace, px-pyroxene, plg-plagioclase, kf-feldspar, wht-whitlockite, mel-merrillite, chp-chlor-apatite, ap-apatite, chm-chromite, ilm-ilmenite, tim-titano-magnetite, tro-troilite, po-pyrrhotite, pt-nickel-pyrite, mr-marcasite, spl-spinel.

Table 2. Comparison of mineralogical chemistry of GRV99027 to other Lherzolitic Shergottites

	GRV 99027		GRV 020090		ALHA 77005		LEW 88516		Y 793605		YA 1075		NWA 1950	
Fo	69.1-76.6(72.4)		60-70		69-73(71)		64-70(67)		64-75		67.7-74.5(70.7)			
Fa	23.4-30.9(27.6)		30-40		24-30(29)		26-38(33)		25-36		25.5-32.3(29.3)			
	pigeonite	augite	pigeonite	augite	pigeonite	augite	pigeonite	augite	pigeonite	augite	pigeonite	augite	pigeonite	augite
En	59.3-75.1 (68.6)	46.6-53 (50.7)	60-72	47-52	61-77	48-55	54-77	47-55	60-76	49-52	65-70	47-52	60-78	45-53
Fs	20.5-26.9 (23.5)	13.1-16.1 (14.5)	24-29	16-19	19-27	12-15	20-28	14-17	21-28	14-16	22-26	14-16	19-26	14-16
Wo	3.1-14.9 (8.0)	31.9-37.8 (34.8)	3-14	31-36	4-16	30-40	3-18	29-38	3-13	32-37	7.5-9.5	32-38	2-14	31-41
An	43.6-59.3(52.4)		37-57		48-58(52.2)		48-58(52.4)		45-55		38.2-53.6(48.5)		40-57	
Ab	40.2-54.6(46.7)		41-58		41-49		41-49		44-52		45.3-59.8(50.1)		41-57	
Or	0.5-1.8(0.8)		1-6		1-3		1-3		1-3		0.9-2(1.3)		1-3	
Ref.	This study		Base on the report of Ling *et al.*, 2004		Treiman *et al.*, 1994[8]; Mikouchi and Miyamoto, 2000[11]		Treiman *et al.*, 1994[8]; Harvey *et al.*, 1993[9]; Mikouchi and Miyamoto, 2000[11]		Ikeda, 1994[20], 1997[14]; Kojima, Miyamoto and Warren, 1997[21] Mikouchi and Miyamoto, 1996[22], 2000[11]		Yanai, 2002[23]		Russell *et al.*, 2004[15]	

Table 3. Comparison of mineralogical chemistry (wt%) of GRV99027 to these of other Martian meteorites and Earth and Mars

	L-S						B-S				Nakhlite	Chassignite	Orthopyroxenite		
	GRV 99027	GRV 99027	L-S	ALHA 77005	LEW 88516	Y 793605	Shergotty	EETA 79001A	EETA 79001 B	QUE 94201	Nakhla	Chassigny	ALH 8400	Earth	Mars
SiO_2	49.84	44.59	45.27	43.08	46	45.35	50.4	50.49	49.93	47.92	49.33	37.1	52.84	46.49	43.46
Al_2O_3	3.3	2.57	3.39	2.59	3.31	2.32	6.89	5.86	13.4	9.82	1.64	0.36	1.21	4.03	3.64
TiO_2		0.23	0.24	0.44	0.39	0.35	0.81	0.7	1.25	1.98	0.35	0.07	0.2	0.19	0.18
Cr_2O_3		0.28	0.28	0.96										0.43	0.67
FeO	18.55	18.34	17.52	19.95	19	19.68	19.1	18.53	16.97	19.17	21.7	27.45	17.37	8.10	17.87
MnO	0.22	0.29	0.28	0.44	0.49	0.48	0.5	0.49	0.41	0.47	0.55	0.53	0.47	0.14	0.31
MgO	23.38	27.51	26.28	27.69	25	26.2	9.27	14.59	5.14	6.3	11.82	32.83	24.7	36.71	30.10
CaO	3.79	5.03	5.41	3.35	4.2	4.05	10.1	7.4	10.78	11.47	14.3	1.99	1.8	3.45	3.08
Na_2O		0.45	0.60	0.44	0.56	0.35	1.37	0.80	2.03	1.37	0.57	0.15	0.15	0.4	0.86
K_2O		0.03	0.04	0.027	0.029	0.03	0.16	0.04	0.08	0.04	0.17	0.03	0.01	0.03	0.08
P_2O_5		0.29	0.30	0.36							0.10	0.04		0.02	0.23
合计	99.08	99.64	99.62	99.33	98.98	98.81	98.6	98.9	99.99	98.54	100.5	100.55	98.75	100	100.01
Fe/(Fe+Mg)	0.31	0.27	0.27	0.29	0.30	0.29	0.53	0.41	0.65	0.63	0.50	0.32	0.28	0.25	0.25
Resources	Wang *et al.*, 2002[2]	This study	This study	Dreibus *et al.*, 1992[24]	Lodders, 1998[25]	Warren *et al.*, 1999[26]	Stolper and McSween, 1979[16]	Warren *et al.*, 1999[26]	Warren *et al.*, 1997[27]	Warren *et al.*, 1999[26]	Dreibus *et al.*, 1982[28]	McCarthy *et al.*, 1974[29]	Warren *et al.*, 1999[26]	Kargel and Lewis, 1993[30]	Lodders and Fegley, 1997[31]

Table 4. REE abundances (ppm) of the minerals in GRV 99027

	Olivine	Poikilitic area		Non-poikilitic area		Maskelynite	Molten glass	Whitlockite
		Pigeonite	Augite	Pigeonite	Augite			
La	0.086 ±0.008	0.037 ±0.003	0.213 ±0.020	0.028 ±0.003	0.289 ±0.036	0.179 ±0.008	1.73 ±0.07	54.2 ±0.6
Ce	0.080 ±0.008	0.023 ±0.002	0.238 ±0.023	0.021 ±0.003	0.697 ±0.072	0.228 ±0.010	4.17 ±0.12	140.8 ±1.1
Pr	0.020 ±0.004	0.008 ±0.001	0.053 ±0.010	0.006 ±0.001	0.194 ±0.032	0.028 ±0.003	0.58 ±0.04	26.8 ±0.5
Nd	0.052 ±0.006	0.028 ±0.003	0.297 ±0.023	0.041 ±0.004	1.236 ±0.086	0.129 ±0.007	3.33 ±0.11	159.3 ±1.2
Sm	0.004 ±0.004	0.010 ±0.003	0.145 ±0.024	0.022 ±0.004	1.033 ±0.102	0.033 ±0.007	1.71 ±0.11	105.4 ±1.4
Eu	0.004 ±0.002	0.005 ±0.001	0.060 ±0.013	0.010 ±0.002	0.373 ±0.043	0.851 ±0.018	0.97 ±0.06	22.9 ±0.3
Gd	0.010 ±0.006	0.036 ±0.005	0.360 ±0.046	0.078 ±0.009	2.754 ±0.266	0.049 ±0.007	3.29 ±0.16	202.4 ±2.8
Tb	0.003 ±0.001	0.006 ±0.001	0.093 ±0.014	0.021 ±0.003	0.547 ±0.059	0.007 ±0.002	0.57 ±0.05	–
Dy	0.018 ±0.004	0.075 ±0.004	0.585 ±0.033	0.184 ±0.008	3.932 ±0.163	0.036 ±0.005	4.36 ±0.12	289.5 ±2.0
Ho	0.007 ±0.002	0.023 ±0.002	0.128 ±0.015	0.051 ±0.004	0.790 ±0.074	–	0.96 ±0.05	54.6 ±0.8
Er	0.021 ±0.004	0.060 ±0.004	0.286 ±0.026	0.142 ±0.008	1.931 ±0.124	–	2.54 ±0.10	164.4 ±1.8
Tm	0.005 ±0.002	0.013 ±0.002	0.059 ±0.012	0.021 ±0.003	0.302 ±0.038	–	0.35 ±0.04	–
Yb	0.038 ±0.005	0.093 ±0.005	0.367 ±0.030	0.197 ±0.009	2.029 ±0.125	–	2.38 ±0.10	164.9 ±2.1
Lu	0.006 ±0.003	0.013 ±0.003	0.049 ±0.011	0.021 ±0.004	0.290 ±0.048	–	0.30 ±0.04	25.3 ±0.8
δCe	0.46	0.32	0.54	0.39	0.71	0.78	1.0	0.89
δEu	1.93	0.81	0.80	0.74	0.68	64.70	1.25	0.48
$(La/Yb)_N$	1.53	0.27	0.39	0.10	0.10	–	0.49	0.22
$(Sm/Nd)_N$	0.24	1.10	1.50	1.65	2.57	0.79	1.58	2.04
∑REE	0.35	0.43	2.93	0.84	16.40	1.54	27.24	1410.50
∑LREE/∑HREE	2.28	0.35	0.52	0.18	0.3	15.74	0.85	0.57

Note: The data are from Hsu W *et al.* (2004)[34]. – means the content below the limit of measurement, not aviliable, δ means anormal value.

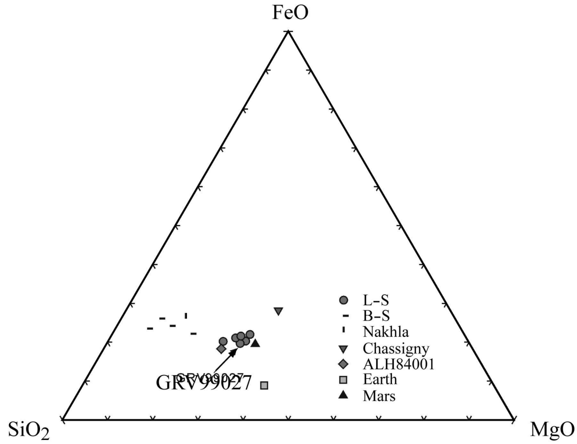

Fig 5 The SiO_2-MgO-FeO (wt%) compositions of GRV 99027, other Martian meteorites, Earth and Mars

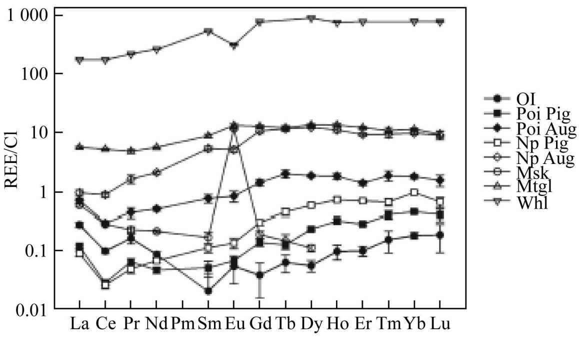

Fig 6 CI normalized REE patterns of minerals in GRV 99027. Symbols with vertical lines represent REE abundances and standard deviations (σ); Poi, poikilitic; Np, non-poikilitic; Ol, olivine; Pig, pigeonite; Aug, Augite; Msk, maskelynite; Mtgl, melt glass; Wht, whitelockite.

(1) Olivine The olivine of GRV 99027 has the same HREE abundance level as other L-S meteorite's olivine[9, 33, 36], such as ALHA 77005, LEW 88516, and Y 793605. However, GRV 99027's olivine LREE abundance level is much higher than ALHA 77005's. GRV 99027's olivine also shows it has positive Eu abnormity (δEu, ~ 1.93) and negative Ce abnormity (δCe, ~ 0.46), suggesting that GRV 99027 has suffered severe Terrestrial weathering. Because the REE abundance level in olivine in Martian meteorites is pretty low in general, within the error limits, it is difficult to explain why GRV 99027 has high LREE in olivine, . LEW 88516 and Y793605 olivine's LREE were not shown in Figure 7.

(2) Pyroxene The distribution REE pattern of the GRV 99027 pyroxene. The distribution primarily concentrates by the heavy rare-earth element. Within the individual pyroxene particle, the REE abundance levels are homogenous. High-calcium augite possesses higher abundance of the REE than low calcium pyroxene. For pigeonite and augite, their REE abundance levels in the non-poikilitic are higher than in poikilitic (Table 4, Figure 8). GRV 99027 pyroxene's REE abundance and distribution patterns are similar (Figure 9) to other L-S meteorite's[33, 9, 36]. However, the other L-S meteorite's negative δEu is

clearly abnormity (δEu, 0.39-0.91).

(3) Maskelynite LREE in maskelynite is characterized by its enrichment (ΣLREE/ΣHREE 15.74), it also contains high, positive Eu anomaly (δEu, 64.70) (Figure 10). It has basically the same abundance as ALHA 77005, LEW 88516, and Y 793605's maskyelynite REE.

(4) Whitelockite The mainly phosphate mineral is whitelockite with high REE abundance (ΣREE 1410.50 × 10^{-6}), and is rich in HREE in partition pattern (ΣLREE/ΣHREE 0.35), while the slope of the HREE line is extremely gentle (Table 4 Figure 11). It has a strong negative Eu abnormality (δEu, ~0.48). The REE distribution pattern is basically parallel with the whitelockite's distribution patterns of ALHA 77005 and LEW 88516, and HREE is more enriched, and negative Eu abnormality is clearer.

(5) Impact molten glass Impact molten glass's REE distribution pattern is parallel with ALHA 77005's whole-rock's distribution pattern (Figure 12). However, the abundance is significantly higher (3—5 x), indicating that the impact molten glass was formed by the partial melting of the whole rock. The REE distribution pattern of LEW 88516 and Y 793605's impact molten glass are also nearly parallel with GRV 99027's, however, their REE abundance level are slightly lower.

4.2 GRV 99027's whole-rock REE distribution pattern

According to GRV 99027's mineral composition (olivine 55 vol%, pyroxene 37.5 vol%, maskelynite 6 vol%) (Table 1) and its single mineral's REE abundance level (Table 4), whole-rock's REE abundance level can be calculated. Table 5 listed whitelockite's calculated value as ~0.2vol%. For comparison purposes, we used currently found L-S meteorite's average mineral composition (olivine 50 vol%, pyroxene 38 vol%, maskelynite 9 vol%, molten glass 11 vol%, [34]) to calculate REE abundance level of the whole-rock of L-S meteorite. Both patterns of the whole-rock's REE distribution give us the similar result. For comparison, the table also listed some other significant REE abundance level for the Martian meteorite's whole-rock.

The whole-rock's distribution pattern of GRV 99027's REE element are the same as L-S meteorite ALHA 77005 and LEW 88516's, however, it is slightly higher than Y 793605's. Comparing with whole-rock REE distribution patterns of the other types of Martian meteorite's shows that the GRV 99027's whole-rock REE distribution pattern is complete different from that of Shergotty (B-S), Nakhla (Nakhlite), Chassigny (Chassignite), and ALH 84001 (Orthopyroxenite). GRV 99027's whole-rock REE has a tendency of increasing from LREE to HREE; however, Shergotty has very gentle whole-rock's REE distribution pattern, with high REE abundance level. Nakhla and Chassigny have clearly a trend of decreasing from LREE to HREE, from Nd to Lu, Chassigny's whole-rock REE abundance level is much lower than that of GRV 99027. The REE distribution level's change of ALH 84001 is moderate. It gets higher on the right side of the HREE, its REE abundance level is clearly lower than that of GRV 99027's.

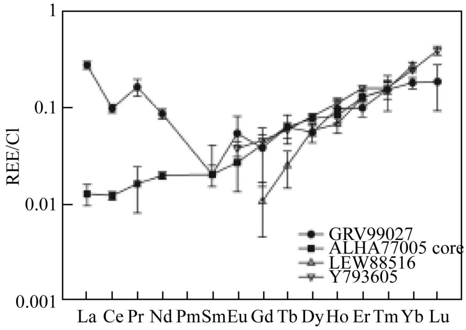

Fig 7 CI normalized REE patterns of olivines in GRV 99027 and other L-S Martian meteorites. Symbols with vertical lines represent REE abundances and standard deviations (σ); core represents core of olivine grain; the data of ALHA 77005 are from [33]; LEW 88516 from [9]; Y 793605 from [36].

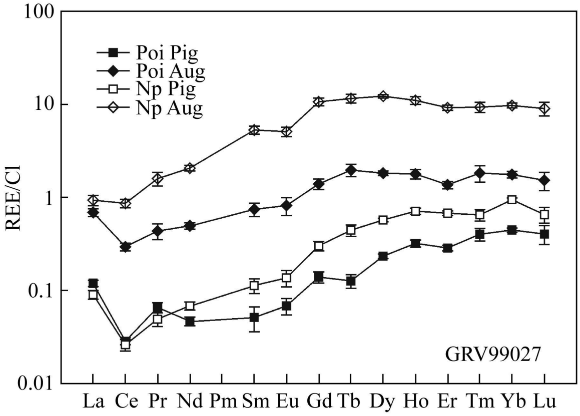

Fig 8 CI normalized REE patterns of pyroxenes in GRV 99027. Symbols with vertical lines represent REE abundances and standard deviations (σ); Poi, poikilitic; Np, non-poikilitic; Pig, pigeonite; Aug, Augite.

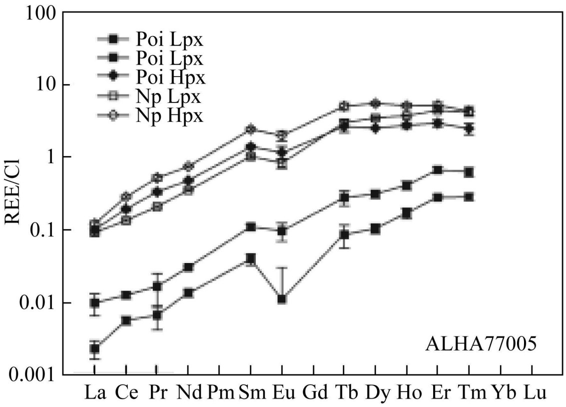

Fig 9 CI normalized REE patterns of pyroxenes in ALHA 77005. Lpx represents low-Ca-pyroxene; Hpx, high-Ca-pyroxene; data are from [33].

Table 5. REE abundances of whole rocks of SNCO Martian meteorites

Meteorite	L-S					B-S	Nakhlite	Chassignite	Orthopyroxenite
	GRV 99027	L-S	ALHA 77005	LEW 88516	Y 793605	Shergotty	Nakhla	Chassigny	ALH84001
La	0.36	0.36	0.34	0.33	0.0804	1.56	2.06	0.53	0.19
Ce	0.78	0.79	0.91	1.26	0.192	3.73	5.87	1.12	0.59
Pr	0.13	0.13	0.13	–	0.0362	0.568	0.67	0.13	0.06
Nd	0.74	0.76	0.95	0.82	0.226	2.97	3.23	0.62	0.265
Sm	0.43	0.44	0.49	0.44	0.156	1.18	0.77	0.14	0.12
Eu	0.21	0.24	0.22	0.22	0.0715	0.479	0.235	0.045	0.035
Gd	0.88	0.89	0.92	–	0.338	1.94	0.86	0.11	0.14
Tb	0.09	0.10	0.17	0.16	0.0659	0.381	0.12	0.03	0.038
Dy	1.24	1.26	1.08	1.08	0.489	2.53	0.77	0.2	0.28
Ho	0.25	0.26	0.25	0.23	0.103	0.548	0.155	0.044	0.076
Er	0.7	0.71	0.66	–	0.305	1.52	0.37	0.09	0.21
Tm	0.06	0.06	0.088	0.1	0.042	–	0.047	–	0.036
Yb	0.71	0.73	0.59	0.57	0.281	1.32	0.39	0.11	0.29
Lu	0.1	0.10	0.078	0.083	0.0418	0.202	0.055	0.015	0.049
δCe	0.86	0.86	1.04	–	0.86	0.95	1.2	1.03	1.33
δEu	1.05	1.16	1.0	–	0.95	0.97	0.88	1.11	0.83
$(La/Yb)_N$	0.34	0.34	0.39	0.39	0.19	0.80	3.56	3.25	0.44
$(Sm/Nd)_N$	1.78	1.79	1.59	1.65	2.12	1.22	0.73	0.69	1.39
$\sum$REE	6.70	6.83	6.88	5.29	2.43	18.93	15.60	3.14	2.38
$\sum$LREE/$\sum$HREE	0.66	0.66	0.79	1.38	0.46	1.24	4.64	4.32	1.13
Resources	This study	This study	Lodders, 1998[25]	Lodders, 1998[25]	Ebihara *et al.*, 1997[38]	Barrat *et al.*, 2001[39]	Lodders, 1998	Lodders, 1998[25]	Lodders, 1998[25]

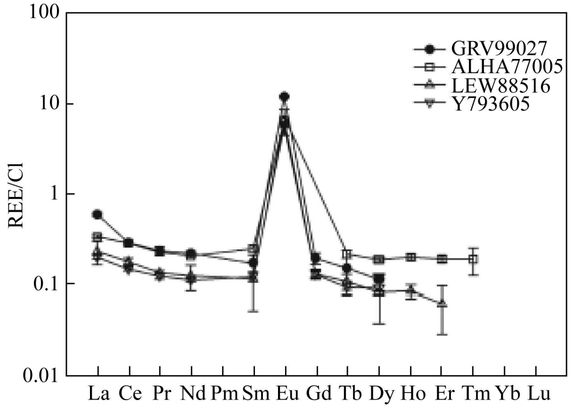

Fig 10 CI normalized REE patterns of molten plagioclases in GRV 99027 and other Martian meteorites Symbols with vertical lines represent REE abundances and standard deviations (σ); the data of ALHA 77005 are from [33]; LEW 88516 from [9]; Y 793605 from [36].

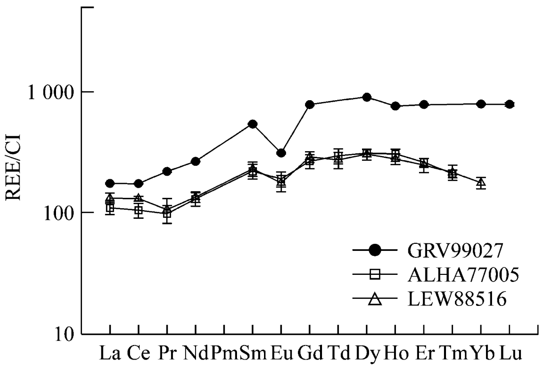

Fig 11 CI normalized REE patterns of phosphates in GRV 99027 and other Martian meteorites Symbols with vertical lines represent REE abundances and standard deviations (σ); the data of ALHA 77005 are from [33]; LEW 88516 from [9].

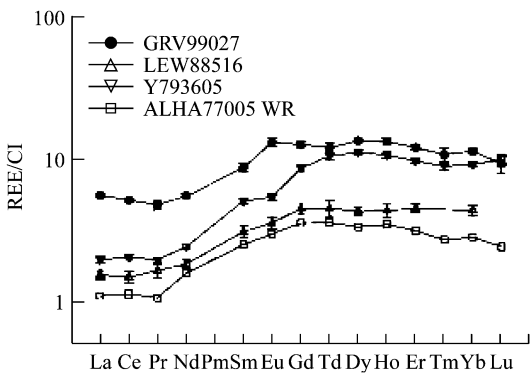

Fig 12 CI normalized REE patterns of molten glasses in GRV 99027 and other Martian meteorites Symbols with vertical lines represent REE abundances and standard deviations (σ); the data of LEW 88516 are from [9]; Y 793605 from [36]; ALHA 77005 whole-rock (WR) from [25].

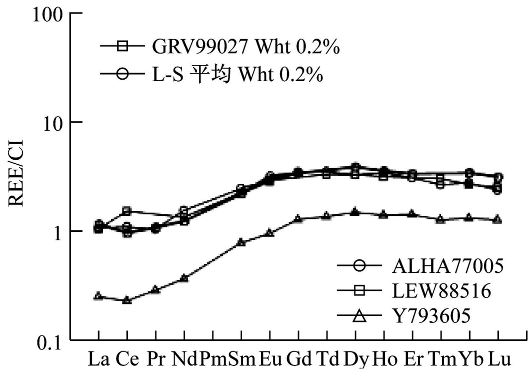

Fig 13 CI normalized REE patterns of whole rocks in GRV 99027 and other L-S Martian meteorites The data of ALHA 77005 and LEW 88516 are from [25]; Y 793605 from [37].

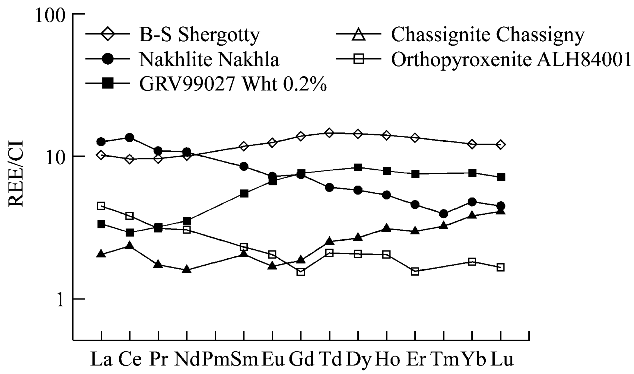

Fig 14 CI normalized REE patterns of whole rocks in GRV 99027 and other SNC Martian meteorites The data of Shergotty are from [38]; the data of Nakhla, Chassigny, and ALH 84001 are from [25].

5 GRV 99027 hydrogen isotope geochemistry

5.1 GRV 99027's H-isotope

The H isotope data fo GRV 99027 phosphate is obtained from six phosphate grains SEM identified the minerals as whitelockite ($Ca_9MgH(PO_4)_7$) and apatite ($Ca_5(PO_4)_3(F, OH, Cl)$), or their mixture (Fig 15). The ion probe results are shown in Table 6 and figure 16, δD values ranges from + 1300 to + 4700‰, and water contents ranges from 0.04—0.43wt%.

5.2 Martian meteorite H isotope's geochemistry

5.2.1 High values of δD in Martian meteorites

GRV 99027's δD value of phosphate is high It is similar to Martian meteorite whole-rock's δD characteristic (Nakhlites for ~ + 250‰ to + 900‰, Splendor Bolivia chondrites ~ + 1200‰ to + 2100‰, AlH 84001 for ~ + 800‰[39]). Compared to Martian meteorite phosphate's δD (Figure 16), GRV 99027 phosphate's δD is similar to the δD of apatite of QUE 94201 and Zagami EETA 790012B's δD is + 146 ± 25‰, ALHA77005's δD is + 22 ± 15‰, which is significantly lower. It can be inferred from Figure 16 that there are no correlation between Martian meteorite phosphate δD and its water content. Only in B-S meteorite QUE94201 that δD and water content contains valid correlation. In GRV 99027 there only exists weak and negative correlation.

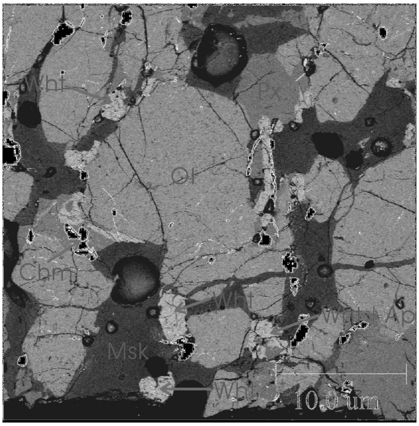

Fig. 15 Phosphate minerals in GRV 99027. Ol represents olivine; Px, pyroxene; Chm, chromite; Wht, whitlockite; Ap, phosphate.

Table 6. Ion Microprobe results of D/H and water contents of GRV 99027 phosphates

Sample	Analysis	δD (‰) ± 2σ	H_2O (wt%)
Particle1	Wht	4745 ± 309	0.04
Particle2, a	Wht	2179 ± 246	0.10
Particle2, b	Wht	2153 ± 251	0.07
Particle3	Wht	2387 ± 271	0.06
Particle4	Wht+Ap	1902 ± 167	0.24
Particle5	Wht+Ap	1326 ± 193	0.10
Particle6	Ap	4064 ± 283	0.43

Note: Wht, Ap, respectively, are whitelockite, apatite; σ is the standard deviation.

Martian meteorites have characteristics of a high value δD is due to water gas in the Martian atmosphere with a high value of δD (δD = + 4200 ± 200‰[44]). The continental water's δD is about 5.2 times of that of ocean water's δD vaule on the Earth (the δD is about − 440‰ — + 100‰[45,46]). An exchange between the D-rich water in Mars' atmosphere and the storage near the Martian surface, resulting of isotope fractionation in the storage spaces. H isotope of water-bearing minerals in the Martian meteorite exchanged with storage. It caused the formation of Martian meteorite with high D/H values. The impact event may also result in implantation of the Martian atmospheric materials into the melt. The volatilization of elements by the impact would significantly reduce the water content of the meteorite, resulting a melt rich with D. However, they cannot cause huge enrichment of D in phosphate minerals. Some Martian meteorites have a low δD value, generally be believed to be resulted by either contamination by the Earth materials or due to the Mars' magma component.

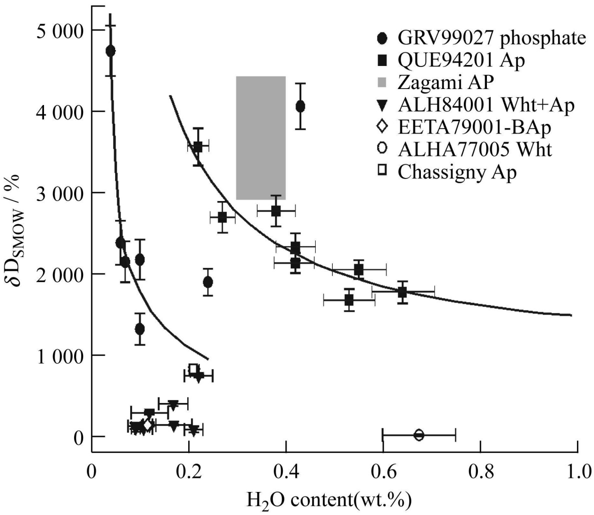

Fig 16 The relationship of δD (‰) and water content in GRV 99027 and Martian meteorites[41-43].

5.2.2 Contribution to the δD value by water-bearing minerals of the Martian meteorites

Figure 17 shows that Martian meteorites' water bearing minerals enrich in heavy D, its δD value is significantly higher than that of the Earth's water, tend to move to the Martian atmosphere's high δD value. Different water-bearing minerals (phosphate, biotite, kaersutite), their contribution to Martian meteorite's δD are different, however, δD is largely concentrated in two zones. Biotite and kaersutite are concentrated in the low-value area (+510‰—+1900‰); while, phosphate's δD value varies a lot (−20‰—+4700‰), mainly concentrated in the high values (> +2800‰). GRV 99027's phosphate δD is +1300‰—+4700‰, clearly higher than biotite, kaersutite's δD value, indicating that phosphate's D value is much higher than that of other water bearing minerals. This is characteristic of Martian meteorite phosphate mineral's[47, 40, 48].

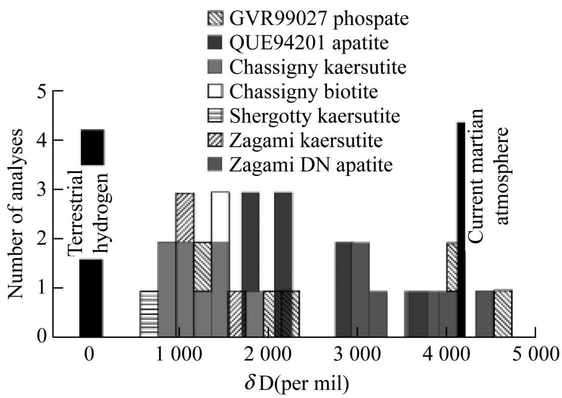

Fig 17 Histogram comparison of δD value of water-bearing minerals in GRV 99027, QUE 94201, Chassigny, Shergott, and Zagami. Based on[47].

GRV 99027's phosphate has a high δD value, which is similar to the other Martian meteorite's H isotope analysis, also confirms again GRV 99027 come from Mars and the H isotopic exchange had occurred between phosphate in GRV 99027 and Mars interchangeable shell storage, such as Mars atmosphere.

6 The formation and evolution history

6.1 GRV 99027 meteorite mineral crystallization sequence

According to the study of meteorite GRV 99027's petrography and mineral chemistry, REE abundance and distribution patterns, as well as H, O stable isotope vaules, all are similar to the characteristics of Martian meteorite L-S. Therefore, we think that GRV 99027 belongs to the L-S meteorite group, and shares the similar crystallization history. The continuous change of the primary and secondary elements of L-S meteorite's pyroxene[9, 11, 14, 36] are consistent with the progressive fractional crystallization model of the closure system of a single magma reservoir's. It can be separated into two stages (Figure 18), the first stage-the olivine and chromite in the poikilitic area begin to crystallize and accumulate. The second stage, calcium-low pyroxene (pigeonite) starts to crystallize, growing into main poikilitic, creating an inclusion of the newly formed olivine and chromite. This process is followed by augite and plagioclase's crystallization, mainly happened in non-poikilitic region, finally, chromite (Titanium-iron spar), ilmenite, whitelockite and etc., formed by melted residuals, as a interstitial materials.

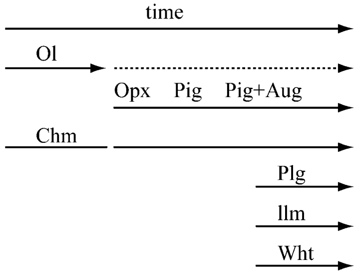

Fig 18 Crystallization sequence of the minerals in GRV 99027. Time represents crystallization time; Ol, olivine; Opx, orthopyroxene; Pig, pigeonite; Aug, Augite; Chm, chromite; Plg, plagioclase (molten plagioclase); Ilm, ilmenite; Wht, whitlockite.

The chemical compostion of the minerals of GRV 99027 is homogeneous compared with the other L-S meteorites. Silicate mineral basically does not have element zonation (Figure 2, 5, 6), and this shows that in its parent body, it has suffered strong thermal metamorphism, and experienced extensively sub-solid-phase re-equilibrium processes.

6.2 Physicochemical conditions of the formation of GRV 99027 meteorite

In GRV 99027, there exist two types of pyroxenes: pigeonite and augite. When the two compounds were projected onto the pyroxene thermometer[49], the result shows that the crystallization pressure was < 2 kbar at the equilibrium temperature of about 1000—1190℃.

(Figure 19); GRV 99027's equilibrium temperature during crystallization is consistent with that of ALHA 77005's 1160 °C, 1200 °C[9, 11, 20, 50, 51], Y 793605's 1220 °C[14].

GRV 99027 has experienced the strong shock effects, which include fractured olivine and pyroxene; wavy extinction of silicates under polarized light; parallel planar fractures in olivine grains; maskelynite transformation from plagioclase; and also the appearance of partial impact-induced melt pocket. The shock degree (S4) is smaller than L-S meteorite ALHA 77005, LEW 88516 (S6) and Y 793605 (S5)[8, 14]. The shock pressure of ALHA 77005, LEW 88516, Y 793605 was estimated as about 30—55 GPa, temperature after the impact ~ 600°C[14, 20, 52]. Greshake[53] believe that the when plagioclase were shocked into glass, the peak shock pressure might be in range of 28—45 GPa. Similarly, the shock pressure experience by GRV 99027 is around 30—45 GPa.

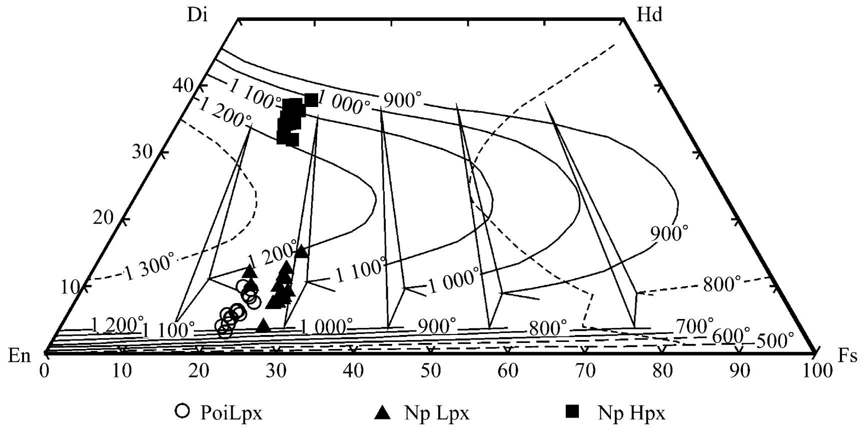

Fig. 19 The thermometry profiles based on three pyroxenes in GRV 99027. Pressure < 2 kbar; the data are from [49], Poi represents poikilitic; Np, non-poikilitic; Lpx, low-Ca-pyroxene; Hpx, high-Ca-pyroxene.

6.3 *GRV 99027's parent body*

The Sr, Nb, Pb and Os' isotope system and its REE distribution pattern of the Martian meteorites suggests that Martian meteorites come from different source regions. Martian meteorite's Rb-Sr, Pb isotope model ages are ~ 4.5 Ga years (figure 20), which suggests that an early magmatic differentiation (~ 4.5 Ga ago) occurred on Mar's parent body when nebular accelerated into planetesimal nuclear. Sr-Pb isotope map (Figure 20) specified Martian meteorite's different source storages. B-S meteorites (Shergotty, Zagami, Los Angeles) have higher Rb/Sr and U/Pb ratios, indicating they came from the planet shell; Nakhlite, Chassigny and some B-S meteorites (DaG, QUE 94201, SaU) have very low Rb/Sr and U/Pb ratios, representing the origin of the depleted mantle; other L-S meteorites, such as ALHA 77005, LEW 88516, and Y793605 have medium Rb/Sr and high U/Pb ratios, indicating they are from the original un-differentiated mantle reservoir, or from areas combined with components of crust and the loss mantle.

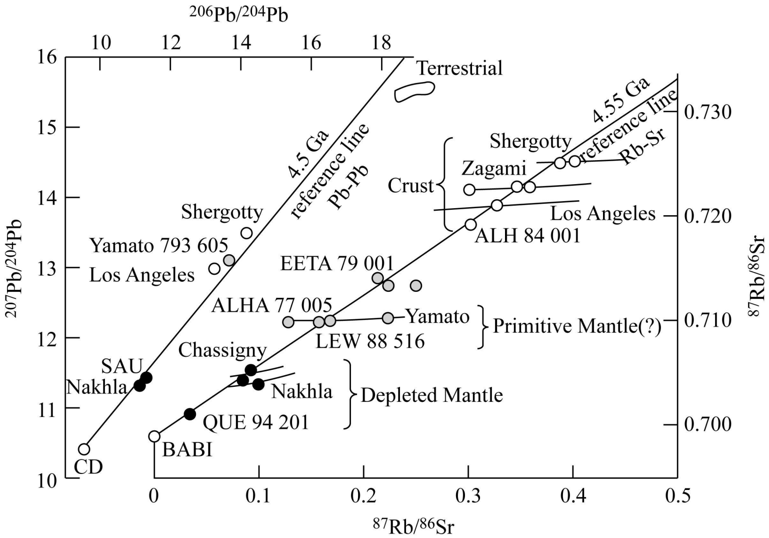

Fig 20 Rb-Sr-Pb isotope of Martian meteorites Data are from [54].

GRV 99027's single mineral REE abundance and distribution pattern (Figures 6–12) are basically the same as that of other L-S meteorite ALHA 77005, LEW 88516, and Y793605[9, 33, 36]. The REE distribution pattern of GRV 99027's whitelockite is also similar to the distribution pattern of L-S meteorite's molten glass and whole-rock's GRV 99027's mineral and whole-rock's REE abundance and distribution pattern are similar to other L-S meteorites, especially ALHA 77005, LEW 88516. Therefore, GRV 99027 is a L-S meteorite, it countains materials from the same source region, come from loss LREE of part of Mar's mantle, and experienced similar magmatism as other L-S meteorites. GRV 99027's olivine and pyroxene shows negative Ce anomaly (δCe 0.32— 0.71), indicating that after landing in Antarctica, it suffered a certain terrestrial weathering.

6.4 The history of formation and evolution of GRV 99027

GRV 99027 and L-S meteorites, such as ALHA 77005, LEW 88516, Y793605 are found on different ice sheet areas, where Yamato mountain area is 3000 km away from Allan hills and 2500 km away from Lewis Cliff. It's distance from Grove Mountains is 1000 km, therefore, it is probable that the debris did not land in one event (unpaired). Using activities of many different radioactive elements, such as ^{3}He, ^{10}Be, ^{21}Ne, ^{26}Al, ^{36}Cl, ^{38}Ar, ^{81}Kr, the calculable cosmic ray exposure age and residential age are slightly different of ALHA 77005, LEW 88516, Y 793605, however, their escape age from Mars is similar, about 4Ma (Table 7, Figure 21). Kong and others[55] calculated GRV 99027's cosmic ray exposure age as 4.4 ± 0.6 Ma according to 10Be's content. GRV 99027 and other L-S Martian meteorite contain significantly consistent escaped age, showing that they might have experienced the same impact event, ever since its escaped out of Mars, it has experienced different levels of exposure to cosmic rays in space, then, captured into the Earth's orbit, landing in Antarctica, its residence time in the ice sheet slightly differs.

Table 7. The ages of L-S Martian meteorites

Meteorites	ALHA 77005	LEW 88516	Y 793605
The crystallization age	Rb-Sr 187 ±12 Ma, 154 ±6 Ma, 185 ±11 Ma; Sm-Nd 173 ±6 Ma; U-Th-Pb ~170 Ma	Rb-Sr 183 ±10 Ma; Sm-Nd 166 ±16 Ma; U-Th-Pb ~170 Ma	Rb-Sr 173 ±14 Ma, 165 ±10 Ma; U-Th-Pb 4433 ±9 Ma, 212 ±62 Ma
Cosmic exposure time	2.5 ±0.3 Ma, 2.8 ±0.6 Ma, 2.9 ±0.17 Ma, ~2.6 Ma, 3.4 Ma, 2.87 ±0.2 Ma	3.0 Ma, 4.1 ±0.4 Ma, 3.6 Ma?	4.4 ±1.0 Ma, ~4 Ma, 5.4 ±0.3 Ma, 3.9 Ma, 3.9 ±0.5 Ma
Terrestrial age	190 ±70 ka, 210 ±80 ka	21 ±1 ka	35 ±35 ka
Ejection age	3.06 ±0.2 Ma, 3.8 ±0.7 Ma	3.94 ±0.4 Ma, 3.9 ±0.4 Ma	4.7 ±0.5 Ma
Reference	Ref [56—66]	Ref [8, 57, 59, 67—69]	Ref [70—76]

According to systematic characteristic of the L-S meteorite's major and trace elements and radioisotopes, and the comparative study of the similar Martian meteorite, we can generally infer GRV 99027's formation steps: (1) ~4.5 Ga ago, the consecutive gravitational accretion of the solar nebula caused the formation of the Mars planetesimal; (2) ~180 Ma, Mars had its initial global differentiation, the Martian magma crystallized quickly and formed the different material source area; (3) ~4 Ma, strong collision of asteroids occurred on Mars, the Martian mantle-derived material was ejected and escaped into space, and was subjected to different durations of exposure to cosmic rays; (4) later, captured by Earth's gravity and orbited the Earth, and finally landed in different ice sheets of Antarctica in different time, forming L-S Martian meteorites. GRV 99027 meteorite, landed in Antarctica's Grove mountains area, experienced a certain degree of weathering alteration.

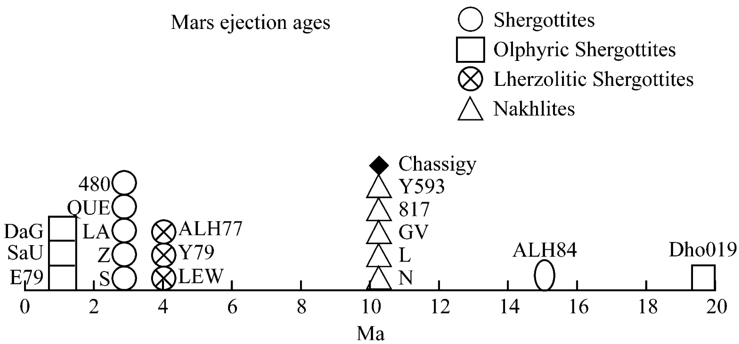

Fig. 21 The mean ejection ages of Martian meteorites[77—79].

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