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Classification of Grove Mountains meteorites and its significance

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Abstract Meteorites are the extraterrestrial rocks, which provide insights into the origin and evolution of the solar system. During the past half century, a great number of meteorites has been discovered on the Antarctic Ice Sheet, confirming that the Antarctica is the most important meteorite concentration area on the earth. Since the first four Antarctic meteorites were found in Grove Mountains in 1998, a total of 9834 meteorites have been collected by four subsequent expeditions. It opens a new field of meteorite study in China, and also accumulates a great deal of scientific samples for China. Recently, classification of Grove Mountains meteorites has been carried out for 6 years, and made following progresses: (1) 2433 meteorites, which include many special meteorites, e. g. Martian meteorites, ureilites and carbonaceous chondrites, have been classified. (2) the Antarctic meteorite curation and the sample sharing system are set up preliminarily. (3) the classification procedure, the management of meteorite samples, and the application procedure for the Antarctic meteorites are completed after the systematic classification during these years. (4) young generation researchers on meteorite are trained through the cooperation of many universities and institutes on meteorite classification.

Key words Antarctica, Grove Mountains, classification of meteorites, chondrites, achondrites.

1 Introduction

Since 9 meteorites were discovered in Yamato Mountains by Japanese Antarctic Research Expedition (JAPANARE) in 1969, a series of meteorite surveys have been performed along the boundary of the huge ice sheet on Antarctica by many international Antarctic expeditions, e. g. JAPANARE and ANSMET, and also got a great achievement on meteorites[1-5]. On the one hand, the number of more than 40 000 meteorite samples found in Antarctica is much larger than that of the historical collection from the other continents. On the other hand, more than fifty meteorite concentrations are found along the boundary of the ice sheet where provide large information on field distribution of meteorites and also give insight into antarctic meteorite concentration mechanics. In addition, some other important discoveries, e. g. the relict fossil of life on the martian meteorite and some new type of meteorites, have been gotten on the research of these meteorites[6]. A large number of typical and precious meteorites were kept in the ice of the continent is due to its special environment and weather conditions. Therefore, the meteorite survey has been one of the most important and shining projects on Antarctic research expeditions.

Since the first 4 meteorites was found in Grove Mountains in 1998[7], the subsequent meteorite surveys in this region were performed so successfully that the big collection of 9834 meteorites have been made and then China has been one of the rich countries with antarctic meteorites[8-11]. Therefore the classification is one of the key tasks for Grove Mountains meteorites. Since 2000, a series of classifications of Grove Mountains meteorites have been performed and 2433 GRV meteorites are classified. In this paper, the history, results, standards, the processes of GRV meteorite classification in China are introduced, and the problems encountered on the classification of GRV meteorites are also discussed.

2 The Classification history of Grove Mountains Meteorites

Since 2000, six times of classifications on GRV meteorites are finished, now all classification results are submitted to the Nomenclature committee and issued in the Meteoritical Bulletins. Based on the organization ways of meteorite classification, the classification on Grove Mountains meteorites is arbitrarily divided into three stages as bellows:

2.1 The early initiation stage (before 2000)

During this period, the first 4 meteorites found in Grove Mountains were classified by the cooperation of IGGCAS and Peking University[12]. Except GRV 98001, the three meteorites of GRV 98002, 98003 and 98004 were studied and analysed on their petrology and mineralogical compositions in detail. In order to commemorate the finding of Antarctic meteorites and keep its integrality, GRV 98001 wasn' t cut to make thin section and didn' t be analysed on its petrology and mineralgoy. Then it' s roughly classified as stony meteorite only based on its structure and composition of fusion crust. Though during this classification only a few meteorites are worked and the classificaiton procedure is not perfect, it has the great significance of indicating the beginning of Antarctic meteorite research in China.

2.2 The criterion-forming stage (2001 – 2004)

This stage is about from 2001 to 2004. In the 1999/2000 austral field season, 28 meteorites were collected by the 16th CHINARE, indicative of a new meteorite-enriched region found in Antarctica[8]. The workshop of classification was organized by Chinese Arctic and Antarctic Administration and supervised by Chinese Committee of Antarctic Meteorites. During this period, we finished two taskes. One task is to classify 28 meteorites. The other task is to set up the procedure and criteria of classificaiton of meteorites. Since there lacks an experience of classification for a batch of meteorites in China, four working groups of Guangzhou Institute of Geochemistry, CAS, Institute of Geology and Geophysics, CAS, Institute of Geochemistry, CAS, and Nanjing University cooperated to finish the classification of all 28 meteorites. First these meteorites were cut into four sets and worked separately by the four groups, then the results of classification were compared and the types of the meteorites were identified after the discussion at last[13]. Then they are submitted to the Nomenclature Committee of the Meteoritical Society and accepted in Meteoritical Bulletin[14]. After this classification, the procedure of classification and criteria of different meteorite types have been set up primarily. In 2003/2004, under the supervision of Chinese Committee of Antarctic Meteorites, the second systematic classification has been performed. The sample for this classification are 51 meteorites chosen from the 4448 meteorites that were collected by the 19th CHINARE[15]. Though this time the classification task are finished by the same four work group, the 51 meteorites are divided into four group and the different work group has separate samples. During this two times of systematic classification of GRV meteorites, the work procedure of classification and the criteria of meteorite types have primarily built up for Antarctic meteorites.

2.3 The stage of of the share platform construction of Antarctic meteorites

During 2006– 2008, under the support of the project on the construction of Scientic nature resources platform, we began the systematic classification with batches of GRV meteorite specimen and constructed the library of meteorites and share platform at the same time. Under the organization of Polar Research Institute of China (PRIC), the classification has been finished by the eight working groups, including Guangzhou Institute of Geochemistry, CAS, Institute of Geology and Geophysics, CAS, Institute of Geochemistry, CAS, Guilin University of Technology, and Nanjing University. The annual tasks of meteorite classification are 600, 800 and 950 respectively in 2006, 2007 and 2008. Now, all the classified meteorites have been declared to the International Meteorite Nomenclature Committee and issued in the Meteoritical Bulletins[14-19].

3 The classification result of Grove Mountains Meteorites

The classification results are summaried in Table 1. Except one meteorite (GRV 98001) was only classified roughly, all other meteorites are classified into various chemical groups accurately. Besides the majority of ordinary chondrites, the classified GRV meteorites include 29 achondrites, 20 carbonaceous chondrites, and 1 enstatite chondrite.

3.1 Special or rare types of meteorites

Martian meteorites. There are two martian meteorites, GRV 99027 and GRV 020090, found in GRV meteorites. Both of them are the lherzolite[28, 29].

HED meteorites. Two HED meteorites are GRV 99018 and GRV 051523. Both of them belongs to eucrite achondrites[30, 31].

Iron meteorites. Only one iron meteorite GRV 9803 was found in the GRV region. It's found by the 1st expedition in 1998. It's a very fine-grained octahedron iorn and weighs 282.2 g[12].

Table 1. The Result of Classification of GRV meteorites

	Class	Clan	Group	Results						
				2000	2002	2004	2006	2007	2008	others
Chondrites	CC	CI	CI							
		CM-CO	CM			3	2	1	1	
			CO			1				
		CV-CK	CV			1		5	1	
			CK			1				
		CR	C			1		1	2	
			CH							
			CB							
	OC	H-L-LL	H3			2	14	7	9	1
			H4		3	2	58	91	100	
			H5	1	1	9	86	118	147	
			H6		2	1	28	43	39	
			H7					1		
			Introgroup						1	
			L3		6		12	9	2	
			L4		3	3	19	22	21	
			L5	1	1	12	152	162	275	
			L6		5	6	199	323	342	
			L7						1	
			L(impact-melt)					1		
			LL3			1	5			
			LL4		2	1	7	2		
			LL5		3	1	4	2	1	
			LL6			1	2	7	1	
			Metal				3		1	
	EC							1		
	R group									
	K grouplet									
Primary achondrite	Ureilite					3	2	3	1	1
	Brachinite									
	ACA-LOD		Acapulcoite					1		
			Lodranite							
	WIN-IAB-IIICD		Winonaite						1	
			IAB							
			IIICD							
	Iron		IC、IIAB、IIC、IID、IIE、IIIAB、IIIE、IVA、IVB	1						

Table 1. The Result of Classification of GRV meteorites

Class	Clan	Group	Results 2000	2002	2004	2006	2007	2008	others
Achondrites	Martian meteorites	Shergotite		1	1				
		Nakhlite							
		Chassignite							
		Orthopyroxenites							
	Lunar meteorites								
	HED	Eucrite		1		1			
		Diogenite							
		Howardite							
	Aubrite								
	Angrite								
	Mesosiderite					4	2	4	1
	Pallasite				1				
Stony meteorite			1						
Total			4	28	51	598	802	950	3

Data are cited from literatures[12, 14, 15, 20-26] [27].

Stony Iron: Five stony irons of these classified meteorites were found. They are GRV 055364 (396.4 g), 050212 (0.96 g), 020175 (1.54 g), 020214 (1.47 g) and 021525 (3.87 g). All of them are mesosiderites. Except GRV 055364 has a relative big mass which is 396.4 g, the others are very small (less than 1 g).

Ureilites: There are 9 ureilites found in our classification. They are all tyical ureilites or monomict ureilites. Among them, GRV 024516 and GRV 022382 belong to the type II with medium Fa (Fa15—18), while GRV 021512, 021729, 021788 and 02293 are the type I with FeO-rich type (type I, Fa> 18)[32].

Carbonaceous chondrites: 10 carbonaceous chondrites found in the classified meteorites include 5 CMs, 2 COs, 1 CVs, 1 CK, and 1 CR. Except the CR meteorite (GRV 021710) is more than 400 g in mass, others carbonaceous chondrits are very small with masses less than 10 g.

3.2 *Ordinary chondrites*

Of the classified GRV meteorites, 96% are ordinary chondrites, and some metals are also classified into ordinary chondrites by the compositions of silicates. Fig. 1 shows the distribution pattern of chemical groups and rock types of ordinary chondrites. And Fig. 2 and Fig. 3 display the shock stages and weathering degrees of these ordinary chondrites. Based on statistics and the above histograms, the main characteristics of GRV ordinary chondrites can be drawn as follows:

(1) The L chemical group is the biggest one among the three groups of ordinary chondrites, acounting for more than a half (64%); H group is smaller, with a proportion of 32%; the LL group is the smallest, the proportion is only 4%.

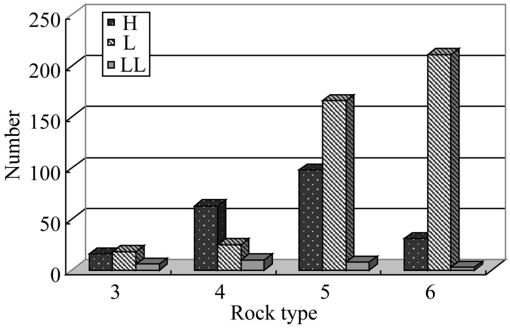

Fig 1 Histogram of chemical groups and rock types of ordinary chondrites from Grove Mountains, Antarctica

(2) The rock types of 5 and 6 are dominating with the proportions of 41% and 37% respectively, while the types 3 and 4 account for small ratios with the proportians of 15% and 6%.

(3) The GRV ordinary chondrites have different shock stages of S1 to S5. They have the distribution with a peak of S2 and more than half of the ordinary chondrites have the higher shock stages S3 to S5 which usually have shock melt veins.

(4) Weather degrees: GRV meteorite samples are much fresh relatively and the low weathering degrees of W2 and W3 account for almost all the samples, indicating that the concentration history of GRV meteorites are young.

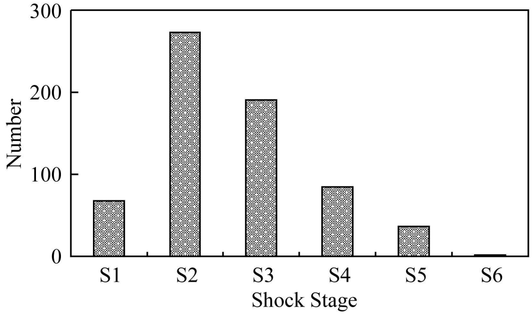

Fig 2 Distribution of shock stages of Grove Mountains ordinary chondrites

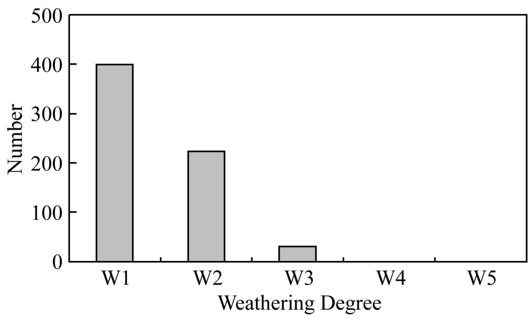

Fig. 3 Histogram of weathering degrees of Grove Mountains ordinary chondrites

4 The significance of GRV meteorite classification

Based on the features of the petrological texture, mineral assemblage, chemical composition etc, the chemical groups or rock types are classified and then their relationship can be identified. The main significanc of the meteorite classification includes two aspects: one is to provide fundamental data for the further research of meteorites and the better comparison between the groups, the other is to get insights into the origin and evolution from the meteorite information. Classification is in favor of getting new information of meteorites and finding new types of meteorites. Furthermore, the big collection of Antarctic meteorites has provided abundant samples from the asteroids or the planets for the scientific research, from which we can get more information of both the solar system and other planets, especially the types and amount of the asteroids. Therefore, the meteorite classification is an important fundament work for meteorite research and cosmochemistry. During these years, nearly ten thousands meteorite samples have collected in the Grove Mountains regions by CHINARE, then a great deal of efforts have been invested into the classification of GRV meteorites. Hence, the collecting and classification of GRV meteorites will be an important contribution to the meteorite study and antarctic sciences in China. Besides the above, there are some other important achievements on GRV meteorites as bellow:

(1) Through the systematic classification, a large deal of fundamental information of GRV meteorites have been achieved and the database of Antarctic meteorites also have been built up. It has made an important contribution to the Construction of Chinese Natural Science Resources Platform. Additionally, there are a few tens thousands of meteorite samples discovered in Antarctic ice sheet and the deserts, but they are very limited relative to the constituents of the solar system, therefore, the discovery of GRV meteorites is still an important supplement to the meteorite resources.

(2) A lot of rare and special types of meteorites of which are devoid in China before are discovered, e.g. martian meteorites, HED clans, ureilites and some groups of carbonaceous chondrites. They are filling the gaps of meteorite types in Chinese meteorite curation. Obviously, the big collection of GRV meteorites not only is one of the important achievements in CHINARE but also will make prefound influence on cosmochemistry and planetary sciences in China.

(3) By the system classification, we have got the distribution information of GRV meteorite types and then we can analyse the similarities and differences which benefit for the mechanics of meteorite concentration in Grove Mountains.

(4) The classification study will provide the fundamental data and basic information for the further researches on Grove Mountains meteorites.

5 Criteria of meteorite classes and regulations on GRV meteorites classification

5.1 The criteria on meteorite classification

5.1.1 Types and groups of meteorites

7 In order to get insights into the origin of meteorites and better understand the relation-

ship among them, it' s significant to classify the meteorites which have just found The modern system of meteorite classification generally includes division, class, clan, group, and subgroup The group or chemical group, which represents the members of meteorites coming from the same parent body or same source region If some different chemical groups share the similarity on chemical composition and mineral chemistry, they will be gathered into a clan And if a group has fractionation in composition during the planetary processes of its parent body, its members can be subclassified into subgroups The scheme of class, clan, and group is widely accepted, the detailed classification scheme is listed in Table 1, but there are some subtle difference on the division, e g chondrites and differentiated meteorites[33]; chondrites and nonchondrites[34]; undifferentiated meteorites (chondrites), primitive achondrites and differentiated meteorites (irons, stony irons and achondrites)[26]. The key point of meteorite classification is to identify the chemical group, but the rock types need to be done to chondrites

The parameters or bases to classify meteorite types include petrological features, mineral chemistry, bulk composition and oxygen isotopes etc[35]. Besides the above parameters, the Mn/Mg ratio is also a very important parameter to classify the achondrite groups[36].

5.1.2 Shock stages and its metamorphic effects

Generally, the meteorite formation processes include nebular condensation, aseroid formation, asteroid collision, escaping from its parent body, passing through the earth atmosphere and landing on the earth surface From the evolution processes of meteorites, it' s easy to find that nearly all the meteorites have been experienced the shock events in various degrees Therefore, the shock metamorphic effects are the basic features for a meteorite and are one of the content of meteorite classification According to the Stöffler' s criteria, the shock stage can be judged by its metamorphic effects on olivine and plagioclase[37]. The shock stages and their classifying criteria are listed in Table 2.

Table 2 The shock stages and it shock effects of silicates

<table>
<tr><th>Shock stage</th><th>S1</th><th>S2</th><th>S3</th><th>S4</th><th>S5</th><th>S6</th></tr>
<tr><td>Normal extinction</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Mineral fracture</td><td colspan="6"></td></tr>
<tr><td>Undulatory extinction</td><td></td><td colspan="5"></td></tr>
<tr><td>Planar fracture</td><td></td><td></td><td colspan="4"></td></tr>
<tr><td>Shock melt vein</td><td></td><td></td><td colspan="4"></td></tr>
<tr><td>Mosaic extinction</td><td></td><td></td><td></td><td colspan="3"></td></tr>
<tr><td>Maskelynite</td><td></td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Solid phase-transformation</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>High pressure mineral (e g ringwoodite)</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

5.1.3 Terrestrial Weathering Degrees

The terrestrial weather degree is a sign to indicate the freshness of a meteorite In order to know the alteration or oxidation degree which a meteorite sample has undergone, some qualitative parameters or indexes are used for desert and antarctic meteorite samples. The weathering degree is generally how much the sample is oxidized after it fell on the earth. Because metal and troilite are easy to oxidize into limonite, so the amount of limonite is the key parameter to classify its weathering degree. After the metal and troilite are oxidized out, the alteration of silicates is another parameter for the weatering degree. There are different criteria for hand specimen and thin section, e. g. the meteorite work group of NASA Johnson Space Center in Houston uses the A、B、C to designate the light, medium, heavy rustiness and degree of fracture respectively for hand specimen. While the Wlotzka's criteria are used for the weathering degree of the thin sections, i. e. W0 represents new falling meteorite without any oxidation, W1 has less amount of limonite around the metal and troilite grains, the volume is less than 20%; the degree of W2 has the amount of limonite of 20-60%; W3 is a much higher degree with the limonite amount of 65-95%; In the degree of W4, there is almost no metal or troilite left and silicates begin to alterate[38]. Moreover, Bland proposed a new scheme for the weatering degrees in terms of the Fe^{3+} content detected by the Moessbauer spectrum[39], but it's not widely used in the meteorite classification.

5.2 The construction of classification procedure for GRV meteorites

5.2.1 Sample processing

Due to the rareness of meteorites, we should make full use of the samples during the processing and avoid the wasting of them. So, the thin section is used for the analyses only. The complexity of mineral assemblage of meteorites, especially the mix of metal and silicates, makes it hard to grind the thin section, since the metal grains are easy to lose from the glass floor. Generally, the small sample need to be mounted in epoxy resin first. The cut process should be carried out with ultrathin diamond blades. The processing procedure to make the thin section is as follows:

The splitting or cutting of original samples– epoxy resin mounting– slicing– adhering to glass– grinding (to normal thickness) – polishing

5.2.2 Petrological observation and their rock types

The petrological texture of meteorites is observed by using the optical microscopy and/or electric scanning microscopy, then the rock types are estimated with the petrological features. The various groups of meteorites have different petrology which is the key factor to judge the rock types. Therefore, the observation of petrology is the first and key step for the meteorite classification.

For the chondrites, the petrological observation includes chondrule texture (chondrule type, size, boundary definition etc.), metal and troilite (volume, grain size and their proportion), refractory inclusions (CAI) (amount, type and size etc.), matrix (volume, transparency, recrystallization and hydrous alteration. While for achondrites, the petrological observation includes texture (the grain size of mineral, the relationship among them), mineral assemblage and mineral alteration etc.

5.2.3 The mineral composition and chemical groups

On the basis of the above petrological observations, the divisions of chondrites, achondrites and primitive achondrites can further to be classified into chemical groups respectively by their compositions. In the early days of classification, the chemical composition can be made by the bulk analyses, then the chemical groups can be identified with the abundances of major elements of Si, Fe and Mg. But now, in order to make full use of or to protect samples, the classification of most meteorites is performed on the thin sections, the chemical groups are classified by the amount of metal and silicate compositions measured on the thin sections. The main method for mineral composition is the electron probe of microanalyses (EPMA). Now more methods have been tried for the mineral composition, e.g. the electron scanning microscopy and X-ray diffraction.

Based on the above petrological features including the metal content, chondrule volume, size of chondrule, volumes of CAI and amoiboid olivine agregation and the mineral composition, chondrites can be classified into various groups[26]. In addition, on the basis of mineral assemblage, petrologic texture and chemical composition, even the oxygen isotope composition, the achondrites can be distinguished into different groups, e.g. iron meteorites, stony iron meteorites, primitive achondrites, martian meteorites, HED meteorites, lunar meteorites[33, 40]. But the groups of irons are classified by their trace element abundances which generally were measured by the instrument nuclear action analyses (INAA) but now are tried by the ICP-MS with a good results.

5.2.4 Estimation of metal content

The contents of Fe-Ni alloy and troilite are also the important parameter to class chondrite groups. There are two methods to estimate the contents of metal and troilites. Generally, the contents of metal and troilite are measured under the reflective mode of optical microscopy. The optical method has some merits. First, it is more intuitionistic and easier to measure the proportions of Fe-Ni alloy and troilite; Second, it's also convenient to observe their shape, size, distribution and occurrence etc. But it's disadvantage is that the uneven distribution of metal and troilite distribution causes the accurate measurement sometimes. Another way for the contents of metal and troilite is the measurement of the susceptibility of the meteorite samples which is effective way to judge the relative amount of meteorites. In the classification of GRV meteorites, we have tried to judge the group of meteorits with the susceptibility and found it's useful for the majority of meteorits.

5.2.5 The shock stages

The shock stage is one of the important tasks of meteorite classification. It usually finished on the standard thin section. First, under the optical microscopy, the shock effects of silicates are observed, then, by the electron scanning microscopy and the Raman spectroscopy, the phenomena of opaque mineral distribution and high pressure minerals are observed and identified. Based on the above shock effects, the shock stages can be judeged which are listed detailed in Table 2[37].

5.2.6 The weathering degree

Antarctic meteorites have relative light weathering degrees in which only metal and troilite are oxidized and few of silicate grains are weathered. So the estimation of the weathering degrees mainly is to measure the oxidation extent of metal and troilite under the reflective light of the optical microscopy, including the ratio of limonite to the orginal metal and troilite volumes, the width of limonite veins and the dyed color of silicates etc. but sometimes it's needed to judge the alteration of silicates if the meteorite is weathered heavily.

5.3 The share platform of meteorites and the application procedure of meteorites

According to international conventions, all meteorites found in Grove Mountains are dinominated with its place name, different meteorites are plused with year and sequence number, e.g. GRV 050001. All found meteorites in Antarctica must be classified first, then they are declared to International Meteorite Nomenclature Committee and have their respective names. Until now 2433 GRV meteorites have been declared and got their own names which are issued in Meteoritical Bulletins[14-19]. In the Bulletins, the information of name, type, found address, mass, shock stage, and weathering degree, are included. In order to make full use of the samples and to protect the precious Antarctic resources, under the support of the national natural resources platform construction project, the sharing platform for the Antarctic meteorites has been established since 2006 (http://birds.chinare.org.cn/). Through the platform, we can not only retrieve the classified GRV meteorites, but also achieve the information of their types and other features. Now on the platform 2433 GRV meteorites are issued with their basic information and samples photos.

The workers of meteorites and the units for public propaganda are welcome to apply the samples to the Antarctic Meteorite Committee of China on the the Resource-sharing Platform of Polar Samples (http://birds.chinare.org.cn/) on which there are the application procedures, the regulations and the contacts.

5.4 The scientific values and social significance

Under the support of the national project of the natural resources shareing platform, not only the classification of GRV meteorites have been made much progress, but also the application of GRV meteorites has gone along well. On the one hand, itself has an importan significance of a new field of meteoritics in China and provides a great deal of samples for the meteoritists. On the other hand, the GRV meteorite samples have also been shown on the natural or scientific exhibitions. In conclusion, Grove Mountains meteorites have an important value but also expand the public effects or inflence of the expedition achievements of CHINAREs.

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