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Progress in study of Chinese Antarctic Meteorites

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Abstract This paper reviews and summarizes the Chinese Antarctica meteorite search, classification and research. During the past four antarctic explorations, a total of 9834 meteorites were collected in the Grove Mountains region. Among them, 2431 meteorites were classified by the end of 2008. So far, 684 meteorites have been officially published in the Meteoritical Bulletin, Meteoritical Society, including 2 martian meteorites, 2 eucrites, 6 ureilites, 5 mesosiderites, 1 pallasite, 1 iron and 10 carbonaceous chondrites. Comprehensive studies were carried out on a number of these rare type meteorites. In addition, we propose to continue the meteorite searching project in Grove Mountains and other regions in Antarctica. We also suggest several key topics of the future researches on the Chinese Antarctic meteorites.

Key words Antarctic meteorites, the Grove Mountains, meteorite search, classification of meteorites, review.

1 Introduction

Besides lunar samples, meteorites are the only available extraterrestrial rocks from the Moon, the Mars, asteroids, and probably comets. They are the "fossils" of the solar system, but rather rare and precious. For a long time, the total of meteorites collected are less than 2000[1]. This situation began to change from 1969, when 9 meteorites of different chemical groups were found in Yamato area, Antarctica, by the Japanese Antarctic Expedition[2]. The discovery of many different meteorites within a limited area suggests that there were unique processes in Antarctica, which transfer meteorites and concentrate them in specific locations. This starts a new episode of meteorite search in Antarctica. Since 1969, Japanese Antarctic expedition have searched for meteorites mainly in Yamato, Asuka, Belgica, and Thiel regions, and they have collected a total of ~16000 meteorites. USA began antarctic search for meteorites by joining the Japanese team in 1976, and later organized their own team in 1979. They mainly searched meteorites along the Trans-Antarctic Mountains, and have collected about 14500 meteorites. Europeans searched Antarctic meteorites also along the Trans-Antarctic Mountains from 1984, and found about 400 samples (based on Meteoritical Bulletin Database).

In 1985, the first antarctic station of China, namely the great wall station, was built in King George Island, and China became an entente of the Antarctic Treaty. In 1989, the second Antarctic station of China, namely Zhongshan station, was established in Larsemann Hills, eastern Antarctica, the only base supporting Chinese antarctic exploration in the inland. During the 15th Chinese antarctic exploration between 1998—1999, a Chinese team did their first field survey of Grove Mountains, with the first discovery of 4 meteorites. Since then, 28, 4449 and 5353 meteorites have been collected in Grove Mountains during the following three times of exploration in 1999—2000, 2002—2003, and 2005—2006, respectively. In the paper, we make a review on the field search, classification and study of Grove Mountains meteorites, and give suggestions for the future exploration and study of antarctic meteorites.

2 Field search, spatial distribution and curation of Grove Mountains meteorites

Grove Mountains locate east to Lambert Glacier, eastern Antarctica, about 400 km from the Zhongshan station. There are more than 60 nunataks scattering in the area of 3600 km^2, including a total surface of 560 km^2 of blue ice and the altitude ranging from 1400 to 2600 m[3]. The prevailing flow direction of ice sheet is west by north, but changed locally due to block by mountains, which make blue ice emerging on the surface. Erosion by strong northeast wind sculpted scale-shaped concave on the surface of blue ice and various sand-blasted stone of base rocks.

2.1 Spatial distribution of Grove Mountains meteorites

Most of the Grove Mountains meteorites collected during the 4 times of field exploration distributed along the west side of Gale Escarpment. The concentration of meteorites significantly increased from south to north. About 60% of the meteorites were found in moraines. Except for Gale Escarpment, only two meteorites were found in Mt. Harding in the center of Grove Mountains areas[4], and 47 pieces in moraines between Mt. Harding and Zakharoff ridge. No meteorite was found either in moraine or on blue ice in Mason Peak, the west part of Grove Mountains region. After collection of 4448 meteorites during the 19th Chinese Antarctic Research Expedition (CHINANRE), more 5354 meteorites were found in the same area by the 22nd CHINANRE. The spatial distributions of the meteorites collected by these two expeditions completely overlap (Fig. 1).

2.2 Field search for meteorites

In the austral summer season of 1998—1999, the 15th CHINARE carried out their first geological survey of Grove Mountains area, with the first discovery of 4 meteorites, including an iron and 3 chondrites. In the next austral summer season, the 16th CHINARE continued their field exploration, and found 28 meteorites[5], including a martian meteorite and an eucrite that was considered to have an origin of asteroid-4 Vesta. Discovery of these meteorites demonstrates that Grove Mountains is a new meteorite concentrating area in Antarctica. According to proposal by experts of Antarctic meteorite research, Chinese Arctic and Antarctic Administration organized a meteorite-hunting team to search for meteorites in Grove Mountains in 2002–2003, which resulted in a very successful discovery of 4448 meteorites[4]. During the 4th field survey of Grove Mountains by the 22nd CHINARE in 2005—2006, a total of 5354 meteorites with mass of 62 kg were collected in the first 20 days[6]. Up to date, the total number of Antarctic meteorites collected by CHINARE is 9834, following only Japan and USA.

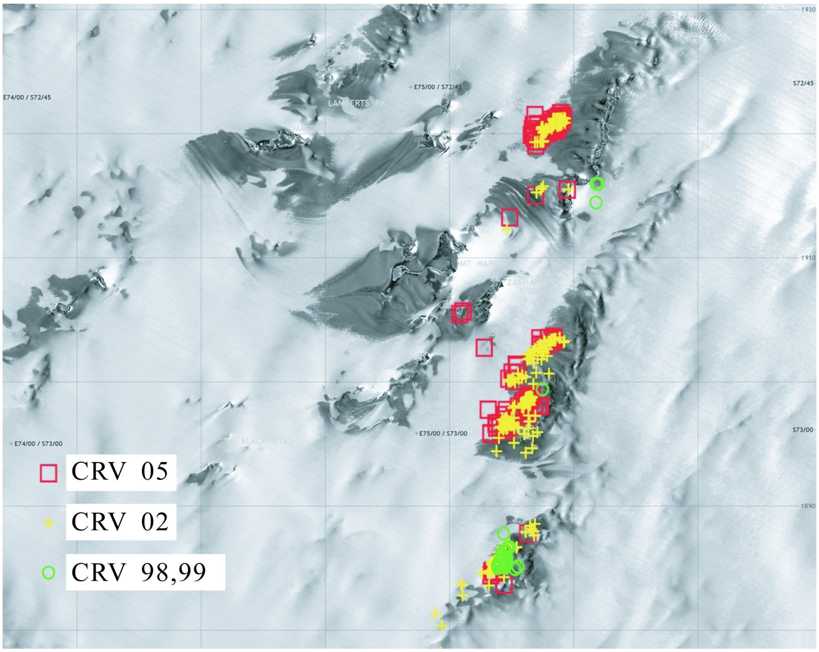

Fig. 1 Find sites of 684 Grove Mountains meteorites classified.

2.3 *Storage of meteorites in the field*

All samples were packed with clean polyethylene bags, and then stored in heat preservation boxes in order to keep them frozen. After returned to Zhongshan Station from the field, the samples were immediately transferred to the ice breaker, Snow Dragon, by helicopter, and kept in a refrigerator on board. Finally, all meteorites were curated in the freezer lab of ice cores in the Polar Research Institute of China, Shanghai, before classification and study. The samples were kept in frozen after collected in the field until transferred to the lab, in order to avoid any weathering effects by liquid water that may appear when the samples were thawed in atmosphere.

3 Classification of meteorites

3.1 *Progress of meteorite classification*

The first 4 Grove Mountains meteorites were classified into 3 chondrites[7, 8] and one ungrouped iron meteorite related to IAB complex (IAB-ung)[9], and their classifications were published in *the 84th Meteoritical Bulletin* in *Meteoritics and Planetary Sciences*. In December 2000, the Arctic and Antarctic Administration of China organized a cooperation of classifying all 28 meteorites collected during the 2nd field survey of Grove Mountains, with participation of the Guangzhou Institute of Geochemistry, Institute of Geology and Geophysics, and Institute of Geochemistry, Chinese Academy of Sciences, and Nanjing University. These meteorites were classified into 1 martian meteorite[10-12], 1 eucrite[13], 6 L3 chondrites[14], 1 LL4-6 brecciated chondrite, and 19 equilibrated ordinary chondrites[15-18]. Later, the Arctic and Antarctic Administration of China organized the above 4 groups to conduct another classification of 51 representative samples selected from 4448 meteorites found in the 19th CHINARE. Of these 51 meteorites, there are 1 new martian meteorite[19], 1 pallasite, 3 ureilites, 7 carbonaceous chondrites[20], and 39 ordinary chondrites (2 H3, 1 LL3, and 36 equilibrated)[21]. The classification of above 79 meteorites was published in the 86th and 89th *Meteoritical Bulletin*, respectively.

From 2006, classification of the Grove Mountains meteorites was finally supported by the National Development Research Programme of the Ministry of Science and Technology of China. It was planned to complete classification of a total of 2350 meteorites. Each 100 of the first 600 meteorites have been classified by Institute of Geology and Geophysics, Guangzhou Institute of Geochemistry, Institute of Geochemistry, and National Astronomical Observatories, Chinese Academy of Sciences, Guilin University of Technology, and Nanjing University, respectively. There are 1 eucrite (Liu *et al.*, this issue), 5 mesosiderites, 2 ureilites, 3 carbonaceous chondrites, 31 Type 3 ordinary chondrites, and 558 equilibrated ones.

3.2 Sample selection and preparation

All 32 meteorites collected during the first two explorations of Grove Mountains have been classified. Only 851 out of 4448 meteorites found by the 19th CHINARE and 600 out of 5354 meteorites by the 22nd CHINARE were selected and classified. One of considerations is representative of the samples, e.g. their spatial distribution from the southern, middle, and northern of the Gale Escarpment, and geographic occurrences (on blue ice or in moraine). Another consideration is apparent weathering degree of the hand samples. In addition, representative samples of carbonaceous chondrites, achondrites and metal nodules, which can be recognized in the field, were selected for classification.

All samples were thawed in vacuum, to prevent condensation of liquid water on their surfaces. Before further treatment, the samples were measured for magnetic susceptibility, in order to investigate its application in future classification. Small pieces of the meteorites were chipped off with tools of tungsten carbide to eliminate contamination. GRV 051523 is only 0.8 g, and it is a rare achondrite. This meteorite was cut into halves with diamond thread saw, and the smaller part was used for classification. Most of the chips were embedded in epoxy in vacuum, and then cut into < 1 mm thin slices with low speed diamond saw. They were prepared to standard polished thin sections. Instead o epoxy, crystal bond embedding material was used to prepare polished sections of samples with shock-induced melt veins, in order to reduce background of Raman spectrum.

3.3 Comparison between Grove Mountains meteorites and other antarctic meteorites

As described above, relative abundances of non-ordinary chondrites to ordinary chondrites are artificial of sample selection. However, the relative abundances of chemical groups of ordinary chondrites (H, L and LL), petrographic types (3-6), and shock metamorphic degrees (S1-S6) are intrinsic, but not results of sample selection.

Based on statistics of the classified 653 ordinary chondrites, the relative abundances of H, L, LL groups are 30.5%, 65.4%, 4.1%, respectively. The relative abundance of L chondrites is as high as by a factor of 2 of H group, while LL chondrites are rather few. In contrast, of other antarctic meteorites, H group is more than L group, and LL group is also common (Fig. 2). Because of low abundance of LL chondrites, we compare petrographic types of H and L groups. Their relative abundances are also distinct from those collected in other regions in Antarctica (Fig. 3), except for abundance ratios of H3 to H4—6 (4.0% in Grove Mountains versus 3.9% in other regions). Abundance ratios of L3 to L4—6 are not significantly different between Grove Mountains (6.1%) and other regions (5.4%). The difference in the relative abundances of H, L and LL of Grove Mountains meteorites in comparison with those of other antarctic meteorites may be related to small sizes of the former (peak at 1 g) than those collected along the Trans-Antarctic Mountains (peak at 24 g, after AnMet database). In Grove Mountains, the field team searched for meteorites by foot and as small as 0.1 g meteorites can be found, while blue ices along the Trans-Antarctic Mountains were swept with sikdoo, snow motors.

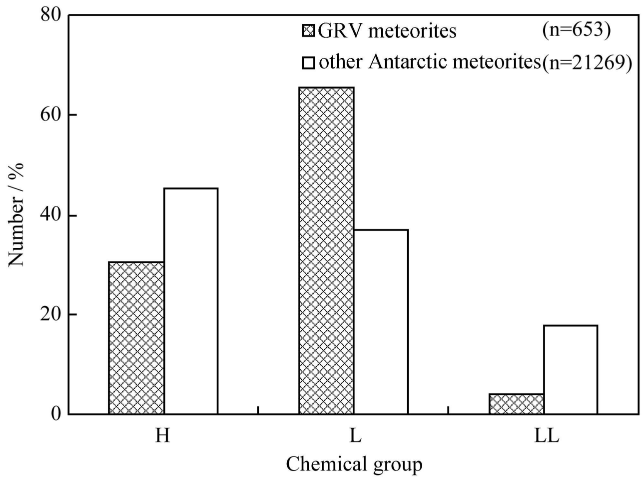

Fig. 2 Distribution pattern of ordinary chondrite groups of Grove Mountains meteorites, in comparison with other Antarctic meteorites. Data of Grove Mountains Meteorites are from[22-26], and others from the Meteoritical Bulletin Database (http://tin.er.usgs.gov/meteor/metbull.php).

Figure 4 shows statistic results of shock metamorphism degree of H and L groups of Grove Mountains meteorites. For the same reason of low abundance, LL group was not considered. The H and L groups display distinct abundance patterns. 26% of L chondrites were heavily shocked (S4—6) with occurrence of shock-induced melt veins and high-pressure polymorphs, while most of H chondrites experienced mild impact with only 8 meteorites classified as S4—5. This observation suggests different physical properties of their parent asteroidal surfaces. Compact and hard surfaces of asteroids favor for strong shock metamorphism, and thick regolith form elting by impact. As shown in the distribution of petrographic types of H and L groups (Fig. 3), most of L chondrites are Types 5 and 6 in comparison with H chondrites. Lu *et al.* (this issue) discuss shock metamorphism of Grove Mountains meteorites and its significances in detail.

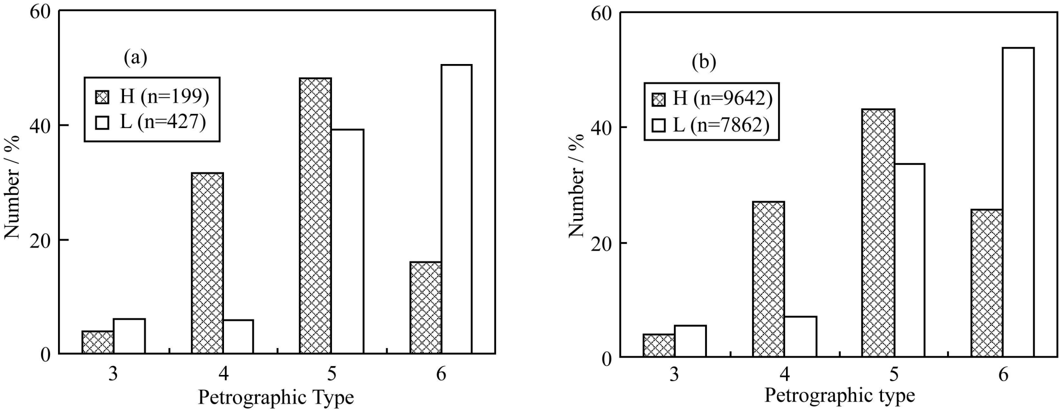

Fig. 3 Distribution patterns of petrographic types of ordinary chondrites. (a) Grove Mountains meteorites; (b) other Antarctic meteorites. Data of Grove Mountains Meteorites are from [22-26], and others from the Meteoritical Bulletin Database (http://tin.er.usgs.gov/meteor/metbull.php).

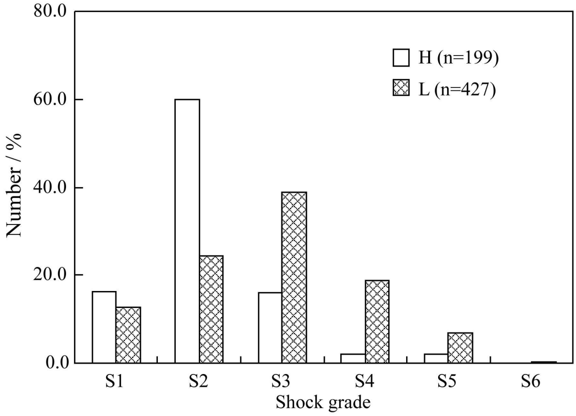

Fig. 4 Distribution patterns of shock grades of Grove Mountains meteorites. Data from [22-26].

4 Study of Grove Mountains meteorites

According to the classification of Grove Mountains meteorites, many non-ordinary chondrites were recognized and most of them were new types of meteorites in China, including martian meteorites, eucrites (probably originated from Vesta), ureilites, and carbonaceous chondrites (CK, CR, CO, CM). In addition, there are several stony irons. These non-chondrites were studied in various detail, and the results were summarized below.

4.1 Martian meteorites

The two martian meteorites, GRV 99027 (9.97 g) and GRV 020090 (7.54 g), are complete rocks, instead of fragments of a large sample broken due to transfer by glacier after fell on the surface of ice sheet of Antarctica. About half of the fusion crust of GRV 99027 has lost, but that of GRV 020090 preserves complete with glazy luster and flowing features (Fig. 5).

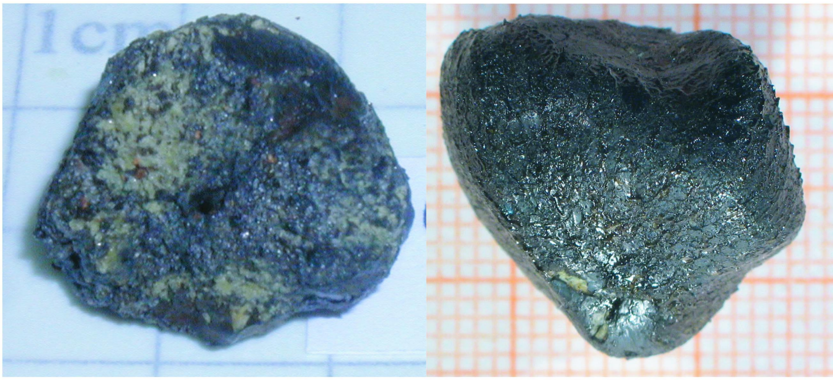

Fig. 5 Two lherzolitic shergottites found in Grove Mountains, Antarctica. (a) GRV 99027, (b) GRV 020090.

GRV 99027 is the 4th lherzolitic shergottite classified[10,12], its martian origin was confirmed by oxygen isotopic composition[11] and ^{2}H-enrichment[27]. Similar to other lherzolitic shergottites (ALH 77005, Y-793605, LEW 88516), GRV 99027 is composed of poikilitic and interstitial (or non-poikilitic) parts[28]. The poikilitic part consists mainly of coarse-grained orthopyroxene with inclusions of euhedral olivine and chromite. The orthopyroxene oikocrysts and olivine chadacrysts contain melt inclusions. The interstitial part consists mainly of granular subhedral orthopyroxene, augite and olivine with interstitial plagioclase and accessory phosphates, chromite and ilmenite. The orthopyroxene and olivine may contain chromite and melt inclusions. Crystals of olivine and chromite show orientations same in both textural parts, indicating cumulative crystallization in the parent magma in the Mars[28]. In situ SIMS analysis of REE and other trace elements of the component minerals[28,29] revealed fractional crystallization of a closed system. The temperature of crystallization of GRV 99027 was determined about 1100–1200℃ and the oxygen fugacity (relative to quartz-fayalite-magnetite) of $\lg fO_2$ (QFM) = -2.0 ± 0.4. After crystallization, the meteorite was heavily shocked, with silicates partially melted to produce the melt pockets and plagioclase transformed to diaplectic (maskelynite). Different from other lherzolitic shergottites, GRV 99027 experienced a slow cooling history buried in regolith in depth after the main impact event, which had maskelynite recrystallized[30,31]. At about 4.4 ± 0.6 Ma, another impact event excavated GRV 99027 from depth on the Mars, and ejected it to an Earth-crossed orbit. Finally, the meteorite fell on the ice sheet of Antarctica[32].

The bulk composition of GRV 99027 shows LREE-depletion, indicating of a depleted martian mantle and little contamination of the magma by the martian crust[33]. The Ni and Co concentrations of GRV 99027 are consistent with fractionation between metal and silicates in a deep magma ocean. Relative to compatible refractory elements, the absence of W- or Ga-depletion suggests a more oxidizing condition during metal-silicate fractionation of the Mars than the Earth. Platinum group elements (PGEs) have chondritic ratios, and their abundances (0.004~0.008 × CI) much higher than those of silicate mantle in equilibrium with the metal core, arguing for later accretion of chondritic materials after the core-mantle segmentation of the Mars[33].

GRV 020090 is the 6th lherzolitic shergottite. In comparison with GRV 99027, it contains more plagioclase but less olivine, and ferromagnesian silicates are FeO-enriched. GRV 020090 probably crystallized from a FeO-rich magma[19]. It was heavily shocked too, with all plagioclase transformed to maskelynite. GRV 020090 shows different petrographic and mineral chemical features from other lherzolitic shergottites, hence it may sample a new location on the Mars.

4.2 *Eucrites*

Two eucrites have been classified, namely GRV 99018 and GRV 051523. GRV 99018 is a tiny fragment, 0.23 g, consisting mainly of anorthite and pyroxenes with accessory silica and opaque minerals. GRV 99018 started to crystallize at 1 100 ± 50°C, following by slow cooling with a rate of 0.02°C/y probably buried in depth. A heavy impact event excavated the meteorite from depth and then reburied it with hot regolith. This explains partial melting and annealing of the melt in GRV 99027. The meteorite was ejected from asteroid-4 Vesta by another impact event, and captured finally by the Earth[13].

GRV 051523 is a small (0.8 g) but complete meteorite. It has an elongated and round shape, completely covered with fusion crust. White breccia of coarse-grained plagioclase can be seen under transparent part of the fusion crust. Liu *et al.* (this issue) report petrography and mineral chemistry of this meteorite in detail, and have a discuss on its formation and evolution. GRV 051523 has a similar modal composition of GRV 99018, consisting mainly of coarse-grained pyroxenes and plagioclase with minor fine-grained FeO-rich olivine, silica, chromite and troilite. Pyroxenes and olivine contain relatively high MnO contents, and their FeO/MnO ratios plot within the ranges of eucrites. There are augite and pigeonite, both show exsolution. The exsolved lamellae are 1–3 μm thin, with a few up to 10 μm, consistent with slow cooling after crystallization in depth. Recrystallization of shock-induced melts indicates a strong shock metamorphism followed by reburied in regolith. There are also thin melt veins with tiny opaque spherules embedded in glass of silicate, which was produced by another shock event on the surface of Vesta.

Petrography and mineral chemistry of GRV 99018 and GRV 051523 reveal complicated shock and thermal metamorphism of the surface of Vesta. It suggests that impact energy is one of major heat sources during the early histories of asteroids.

4.3 *Ureilites*

Six ureilites have been classified from Grove Mountains meteorites. Miao *et al.*[34] reported petrographic features of two of them (GRV 021512, 022931). Except for GRV 052382, other 3 ureilites share similar modal compositions and textures[34]. They consist mainly of coarse-grained olivine and pigeonite, fine-grained interstitial carbonaceous materials and alteration products with various abundances. The coarse-grained olivine and pyroxene show 120° triple junction and alteration with various width along their boundaries and fractures. In BSE images, the altered margins of olivine and pyroxene contains numerous tiny Ni-poor metal grains, and the host silicates are darker than the unaltered areas. Micro-sized diamond is common in the interstitial carbonaceous materials, and graphite was also found. The 120° conjunction of coarse-grained silicates and reduction features of olivine in the ureilites exhibit a strong thermal metamorphism accompanied by reduction (carbonaceous materials as reducing agent). The diamond could be transformed from graphite by a heavy shock event predating the thermal metamorphism that has erased other shock-induced features.

GRV 052382 is an unique ureilite[35]. Besides similar modal composition, diamond-bearing carbonaceous mesostasis and reduced margins of olivine, the large olivine grains have been transformed into assemblages of small crystals (10–20 μm), likely recrystallized by a strong impact event. coarse-grained pigeonite is heterogeneous, with various patches and many tiny voids that were probably due to decomposition or transformation under high pressure and temperature conditions. GRV 052382 probably preserves the most heavily shock-induced features of known ureilites, providing with an unique sample to clarify formation of ureilites.

4.4 Carbonaceous chondrites

Ca-, Al-rich inclusions (CAIs) are typical components of Carbonaceous chondrites, which consist of refractory oxides and silicates predicted by gas-solid condensation of the solar nebula. They are probably the first assemblages formed in the solar nebula. Furthermore, CAIs show ^{16}O-enriched isotopic anomaly and have isotopic excesses due to decay of short-lived nuclides. CAIs are the key components to clarify origins of the short-lived nuclides, and formation and evolution of the solar nebula. Based on textural features, CAIs are classified as coarse-grained and fine-grained, each divided into various petrographic types according to modal compositions. Coarse-grained CAIs are large and visible on the surface of hand samples, and were intensely studied. It appears that individual chemical group of carbonaceous chondrites has different types of CAIs. The carbonaceous chondrites and unequilibrated ordinary chondrites collected in Grove Mountains supply with samples for systematic comparison of CAIs among chemical groups of chondrites. Survey of the primitive meteorites found many CAIs[20]. Study of these CAIs, and previous analyses of CAIs from the ungrouped Ningqiang carbonaceous chondrite and other unequilibrated chondrites fell in China, reveal similar distribution patterns of petrographic types and sizes of CAIs from various groups of chondrites[36]. This discovery suggests that most of CAIs have similar origins and reservoirs. Various abundances and distinct alterations of CAIs among chemical groups of chondrites are consistent with their transfer from same reservoirs and being altered under different redox conditions in the chondrite-accreting regions.

4.5 Cosmogenic nuclides of GRV meteorites

After ejected from parent asteroids by impact events and before fell on the Earth, meteorites were irradiated by cosmogenic ray exposure (CRE), producing noble gases and short-lived radionuclides. Given compositions and flux of the cosmic ray, concentrations of cosmogenic noble gases of meteorites with know bulk compositions correlate with exposure time, so do short-lived radionuclides before saturation. After fell on the Earth, concentrations of the short-lived radionuclides decrease due to decay, hence determine how long the meteorites lying on the Earth (terrestrial ages). Cosmogenic noble gases of > 20 GRV meteorites were measured in an international cooperation. Most noble gases are cosmogenic with little contamination of the terrestrial atmosphere by weathering. This indicates good preservation of the meteorites under very cold and extremely dry conditions in Antarctica. GRV 98004 was found to have a very short CRE age (0.005 Ma)[37, 38] according to analysis of the noble gases, one of the 4 meteorites with CRE ages of < 0.1 Ma. The short-lived ^{10}Be and ^{26}Al of the above meteorites have also been analyzed, in order to determine their CRE ages, parameters of their orbits and terrestrial ages. Measurements of standards show good quality of the data[39], and those of GRV meteorites are in progress.

4.6 Shock metamorphism of GRV meteorites

Classification of GRV meteorites shows that a large fraction of equilibrated L chondrites are heavily shocked, with occurrences of shock-induced melt veins and pockets. Feng *et al.*[40] found predominant majorite-pyrope (up to 3 μm in size) in the melt veins in a L5 chondrite (GRV 052049). Silicate fragments entrained in melt veins are round or embayed in shape, and most grains of olivine contain ringwoodite along the boundaries and fractures. Crystals of ringwoodite were also found in the centers of large olivine grains. The ringwoodite is very heterogeneous, with the Fa content varying from 36 mol% to 75 mol%. FeO contents of olivine coexisting ringwoodite show significant decrease (Fa_{8-14}). The chemical variation of ringwoodite and olivine indicates equilibrium diffusion of Fe and Mg between both phases under high pressure and temperature. The diffusive process should have last for enough time. Concentric zoning texture was found in several large grains of olivine in the melt veins, with low-FeO dark bands (Fa_{13-17}) alternating with high-FeO bright ones (Fa_{26-28}). Both dark and bright bands are olivine according to Raman spectra. A possibility is that the grains of olivine were transformed to FeO-rich ringwoodite and FeO-poor wadsleyite lamellae by a strong shock event, and later retrograded back to olivine. In addition, thin layers (< 10 μm) of ringwoodite were found in the host rock in contact with the melt veins, indicative of importance of high temperature during formation of high pressure polymorphs.

Feng *et al.*[41] found systematic shift of Raman spectra of ringwoodite with different FeO contents. Based on a large number of analyses, they established a function between the peak shift and the FeO contents of ringwoodite. It means that it is possible to obtain both crystographic and chemical information of ringwoodite simultaneously by Raman spectra. This discovery may have important applications in future deep space exploration, e.g. in situ measurement of chemical composition of ringwoodite in the south pole Aitken crater on the Moon and other large craters on planets. Another potential application is on-line measurement of chemical compositions of ringwoodite in equilibrium with other phases under high pressure and temperatures in the diamond anvil.

5 Prospects

Discovery of the large number of GRV meteorites has great contribution to the progress of cosmochemistry and planetary sciences in China. The Moon exploration mission of China is going on well, and the deep space exploration has been one of the National Guidelines on Medium- and Long-Term Program for Science and Technology Development, with demands of cosmochemistry and comparative planetology development in China. We should continue to search meteorites in Antarctica, in order to collect more extraterrestrial materials. In addition, we need to classify the meteorites collected in Antarctica, a basic but important routine work. Also important are comprehensive studies of these meteorites, in order to clarify key processes and events during formation and evolution of the solar system.

5.1 Collection of antarctic meteorites and interplanetary dusts

Grove Mountains is one of the most meteorite-enriched region on the Earth, 9834 meteorites found in 4 times of exploration. It is noted that the 22nd CHINARE collected most of the 5354 meteorites in the same areas, where had been searched by the field team of 19th CHINARE with discovery of 4448 meteorites. This indicates that a large number of meteorites have emerged on blue ice for an interval of 3 years only. The strong wind not only evaporated blue ice, but change spatial distribution of firn on blue ice. After removed the thin layer of firn, meteorites will appear on the surface. It's important to search for meteorites in this region every few years, in order to increase the antarctic meteorite collection of China.

Besides Grove Mountains, meteorite search in other regions may be considered in future, according to improvement of capability of antarctic exploration. For instance, the south Prince Charles Hills locate east to Lambert Glacier and are only 440 km from Grove Mountains. The altitude, occurrence of blue ice and landscape of the south Prince Charles Hills appear similar with Grove Mountains, probably with meteorites concentrated too. Many meteorites may be collected in Trans-Antarctic-Mountains regardless where have been searched many times by USA field teams.

Besides meteorites, antarctica is good site for collecting interplanetary dust particles (IDPs). Large mass of IDPs are depositing on the Earth every year besides micrometeorites. IDPs could be more primitive than meteorites. Most of antarctica is covered by snow and ice and locates far from rocky lands, less diluted by terrestrial dust particles. Hence, relative abundance of IDPs in antarcitic snow and ice is much higher than those in other regions on the Earth. Collection of IDPs should be considered in future antarctic exploration, and study of antarctic IDPs will be a new field in China.

5.2 Routine classification of antarctic meteorites

Supported by the Experimental Standardization and Sharing of the Polar Region Biological and Geological Samples Project, 2433 GRV meteorites have been classified. However, there are another 7400 meteorites to classify, and the total number could be increased by future meteorite search. Classification of antarctic meteorites will be a long-term routine work.

5.3 Frontiers and hot spots of antarctic meteorite research

As mentioned above, 10% of 684 meteorites classified are special samples, including 2 martian meteorites, 2 eucrites, 6 ureilites, 5 mesosiderites, 1 pallasite, 1 iron, 10 carbonaceous chondrites, and 40 Type 3 ordinary chondrites. In addition, 20% ordinary chondrites were heavily shocked with occurrence of many high pressure polymorphs and their assemblages, opening a window to the deep mantle of the Earth. Based on the large GRV meteorite collection, below topics of research are proposed.

Study of martian meteorites Besides the Moon, the Mars will be a major target of deep space exploration for a long period. In addition, martian meteorites are the only available samples of the red planet for analysis in laboratories before the samples returned. Of the GRV meteorites, there are two martian meteorites and both are classified as lherzolitic shergottites, a rare type of martian meteorites. Comprehensive studies have been conducted on GRV 99027, but there are many issues unsolved, especially dating of crystallization, shock events, cosmic ray exposure history and terrestrial age. Preliminary analysis of GRV 020090 reveals significant differences from other 5 lherzolitic shergottites reported earlier, probably sampling a new location on the Mars. In addition, most of GRV meteorites have not been classified, and more martian meteorites or even lunar meteorites are expected.

Presolar grains in meteorites Chondrites contain various components of the solar nebula. The most primitive chondrites were suffered little thermal metamorphism in their parent bodies and well preserved presolar grains that are products of earlier generation of various stars. They are the only available materials from other stars, which can be analyzed in laboratory. Isotopic compositions of many elements of the presolar grains have crucial constraints on astrophysical models of different types of stars. Meanwhile, mineralogical features and chemical compositions of the presolar grains reveal physicochemical conditions of ejecta of stars at their last stage of evolution. In addition, comparative study of presolar grains among different chemical groups of chondrites reveal their spatial distribution in the solar nebula, which is related with origin of the latter.

Short-lived nuclides in meteorites Meteorites are the oldest "fossils" of the solar system and contain information of its early evolution, including presence of isotopic excesses (or anomalies) formed by decay of short-lived radionuclides. Half-life of the short-lived nuclides ranges from 0.1 to 100 Ma, much shorter than the age of the Earth, and hence all of them are extinct. The half-life of the short-lived nuclides is compatible with intervals between various events in the early solar system, they are commonly used for isotopic dating of these events, including condensation of the solar nebula, flash heating, low-temperature alteration, and segmentation of the core-mantle-crust of planets. Furthermore, origins of the short-lived nuclides are related with formation of the solar nebula. They may be produced by strong irradiation of the solar energetic particles, or injected from a neighboring supernova that probably triggered collapse of the nebula to form the solar system. In addition, decay of the short-lived radionuclides had the most important contribution to heat sources of the early evolution of asteroids and planets. A key issue of short-lived nuclides is their spatial distribution in the solar nebula, which has crucial constraints on origins of the short-lived nuclides and in turn their applications for isotopic dating.

Condensation and Accretion of the solar nebula As mentioned above, unequilibrated chondrites are deposits of various components of the solar nebula, including CAIs, chondrules, opaque mineral assemblages, mineral fragments and fine-grained matrix. These components were formed by condensation of the nebula, flash heating and other events. On the other hand, various groups of chondrites accreted in different locations of the solar nebula, representative of the chemical gradient of the solar nebula. Comparative study of various groups of chondrites will clarify condensation and accretion of the whole solar nebula. The key issues are origin of oxygen isotope anomalies, genetic linkage between CAIs and chondrules, accreting regions of individual groups of chondrites and chemical fractionation of the solar nebula.

Melting fractionation in early solar system and formation of the core-mantle-crust of planets Formation of the core-mantle-crust of the Earth and other terrestrial planets, and compositions of the metallic cores are fundamental issues of Earth Sciences and comparative planetology. Achondrites, stony irons and iron meteorites are available samples of the early melting fractionation of solar system. Trace element partitioning between metal and silicates of differentiated meteorites have constraints on the fractionation between metal and silicates of planets and their initial bulk compositions (or redox conditions); existence of magma oceans in the early histories of asteroids and terrestrial planets; dating of melting fractionation of asteroids and planets; fractional crystallization of iron meteorites and heterogeneous chemical compositions of the metallic cores of the Earth and other terrestrial planets.

Shock metamorphism of meteorites and mineral composition of the deep mantle of the Earth Most natural high-pressure polymorphs were found in meteorites, and coesite and stishovite in craters formed by impact of meteorites. Meteorites were excavated from asteroids and planets by impact events, hence commonly experienced strong shock metamorphism and formed various high-pressure polymorphs. As mentioned above, about 20% of ordinary chondrites collected in Grove Mountains were classified as ≥S4 of shock degree, and they are excellent samples for study of the Earth's deep interior. Of the numerous heavily shocked meteorites, there may be new high-pressure polymorphs, including metastable intermediate phases. In addition, partially due to high heterogeneity of shock metamorphism, it is possible to preserve products of various shock stages and P-T-t track in retrogradation. With combined focused ion beam (FIB) cutting technique and nanoSIMS, it is possible to map trace elements of high-pressure polymorphs, which will clarify mechanism and dynamic procedures of phase transformation under high pressure and temperature conditions.

6 Conclusions

All four field surveys of Grove Mountains found meteorites, and the total number of GRV meteorites has been updated to 9834. Grove Mountains has been known as a most meteorite-enriched area in the world. The spatial distribution of GRV meteorites suggest more samples there to be found, and meteorite searching project should be continued. Furthermore, meteorite searching in other regions, e.g. south Prince Charles Hills and Trans-Antarctic Mountains, should be considered in future antarctic research exploration. In addition, establish of the new station in Dome A will provide a chance to collect IDP from snow and ice.

A total of 2431 meteorites have been classified up to date, and there are 7400 GRV meteorites remained in the refrigerator. The number of unclassified meteorites will be increased in future antarctic research exploration. Classification of antarctic meteorites is an important and long-term routine work.

Many meteorites of rare types, including martian meteorites and eucrites, have been studied in detail. The study of the two lherzolitic shergottites revealed their crystallization of magma, shock and thermal metamorphism, CRE histories and constraints on the core-mantle fractionation of the Mars. Besides collecting and classifying of antarctic meteorites, more comprehensive studies of these samples should be conducted. Based on the GRV meteorite collection, the future researches may be focused on presolar grains and the short-lived nuclides in primitive meteorites, chondrites and condensation of the solar nebula, differentiated meteorites and melting fractionation of planets, and shock metamorphism and compositions of the Earth's deep interior.

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