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A Study on the Recovery and Classification of Meteorites from the Mt. Grove Region of Antarctica *

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Abstract The Antarctic Continent has become the largest natural preservatory of meteorites in the world because of its unique geographical position and climatic conditions. Mt. Grove is located in the inland area of the Antarctic Continent where the conditions are favorable for the preservation of meteorites. During China's 15th, 16th and 19th Antarctic Scientific Explorations a large number of meteorites were recovered in the Mt. Grove region. Especially during the 19th Exploration in 2002/03 a total of 4448 meteorites were recovered, which at one stroke put China among countries that have recovered most numbers of meteorites. Here, we report mainly the results of microscope and electron microprobe studies of 28 meteorites recovered during the 16th Exploration. The meteorites are chemically classified based on their mean Fa contents of olivine, mean Fs contents of low-Ca pyroxene and abundances of Fe-Ni metal. We also give a brief account of the meteorite recovery during the three Explorations and of some preliminary classification results of the Antarctic meteorites.

Key words: Earth — meteorites

1 INTRODUCTION

Besides the Apollo-samples and Luna-samples of lunar rocks and soils, totalling 382 kg, meteorites are the only specimens of extraterrestrial material acquired by mankind that can shed light on the formation and evolution of the solar system. Owing to its unique geographical position and climatic conditions, the Antarctic Continent is the largest natural preservatory of meteorites and has provided most numbers of meteorite recoveries. Compared with the other continents, Antarctica possesses a unique blue ice cover which accumulates and preserves meteorites, to be subsequently moved by slowly migrating ice and exposed to the air under special geomorphological conditions; these circumstances make the meteorites easy to recognize.

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Antarctica is a also natural ice storehouse, where meteorites are subject to little weathering and hence are easily preserved. In contrast, on the other continents with great humidity, meteorites, especially stony meteorites, are easily weathered chemically and physically. Moreover, the Antarctic ice cover has a long history of meteorite preservation (about 10 Ma), hence the great number of meteorites accumulated and preserved there.

2 A BRIEF ACCOUNT OF THE RECOVERY OF ANTARCTIC METEORITES

Nearly 100 years have passed since the first recovery of meteorites from the Antarctic Continent. The first recovery from the continent was accomplished by the West Sled Team of the Australia South Pole Exploration Party on 1912 Dec. 5, and the result is the well-known Adelie Land meteorite. The Lazarev meteorite was discovered at the Humboldt Mountains by the former Soviet Union Exploration Party in 1961; similar meteorites were also found in the regions of the Thiel Mountains and Neptune Mountains by the American Field Parties in 1962 and 1964. In the region of the Yamato Mountains, 9, 12 and 663 pieces of meteorite were recovered by Japanese meteorite workers in 1969, 1973 and 1974, respectively. A total of 518 pieces of meteorite were recovered in Victoria Land and Allan Hills by the 1975 Japan-American Joint Exploration Party. In the years 1975–1978 the Japan-American Joint Exploration Party continued the meteorite recovery in the region of the Hengduanshan Ranges. In 1987–1989 Japanese meteorite workers recovered more than 2000 pieces of meteorite in the region of the Sor Rondane Mountains. Since 1979 American meteorite workers have continued their recovery work. Up to the present, the number of meteorites recovered has exceeded 32000 (including 4480 recovered by the three Chinese Explorations, see Table 1). Many special types of meteorites, for example, Mars meteorites, lunar meteorites and the eucrite have been found among those recovered so far.

According to incomplete statistics, there had been more than 170 references pertaining to Antarctic meteorite study before 1970. Since the large-scale recovery of Antarctic meteorites in 1970, the relevant references have increased to 18600, of which 412 and 2824 are published research papers. The recovery of Antarctic meteorites has become one of the important research programs involved on an international scale.

On account of the importance of Antarctic meteorite recovery and the progress and the present status in Antarctic research, China conducted its 15th Antarctic Scientific Exploration in 1998 and decided to carry out on-the-spot geological field investigations, surveying and meteorite recovery in the Mt. Grove region. There are two reasons for the location: (1) Not much geological work had been done in the Mt. Grove region and it is one of the few regions where almost no scientific exploration has been carried out by any country. (2) The Grove Mountain region contains five extensive NNE–SSW groups of peaks composed of 64 individual ice islands, and presents a geomorphology characterized by high mountain ranges and lateral valleys (Liu et al. 2002). It should be a favored locus for the accumulation of meteorites. During the 15th Antarctic Scientific Exploration of China, 1999 January 3 witnessed the recovery of the first piece of Antarctic meteorite on the blue ice slope of the Escarpment by Liu Xiaochun, so heralding the work by Chinese scientists in this area. The same Exploration eventually recovered four meteorites. In the 16th Antarctic Scientific Exploration of China of 1999/2000, 28 pieces were recovered. In the 19th Antarctic Scientific Exploration of China of 2002/03, a team of meteorite hunters was organized, and this team recovered 4448 pieces of meteorite and provided valuable data for cosmochemical research.

Table 1 A Brief Account of the Recovery of Antarctic Meteorites

Date of recovery	Explanation
1912 Dec. 5	The first piece of meteorite was recovered from the Antarctic Continent by the Australia South Pole Exploration Party.
1961	The former Soviet Union Exploration Party.
1962, 1964	Meteorites were found in the regions of the Thiel Mountains and Neptune Mountains by the American Field Parties.
1969	Nine pieces of meteorite were recovered in the region of the Yamato Mountains by Japanese workers.
1973	12 pieces of meteorite were recovered in the region of the Yamato Mountains by Japanese workers.
1974	663 pieces of meteorite were recovered in the region of the Yamato Mountains by Japanese workers.
1975	A total of 518 pieces of meteorite were recovered in Victoria Land and Allan Hills.
1976–1978	The Japan-American Joint Exploration Party continued the meteorite recovery in the region of the Hengduanshan Ranges.
After 1979	American meteorite workers have continued their recovery work.
1987–1989	Japanese meteorite workers recovered more than 2000 pieces of meteorite in the region of Sor Rondane Mountains.
1999	Four pieces meteorite were recovered in Grove Mountain by Chinese geological workers.
2000	28 pieces meteorite were recovered in Grove Mountain by Chinese geological workers.
2002 Dec. – 2003 Feb.	4448 pieces meteorite were recovered in Grove Mountain by Chinese meteorite workers.
Up to now	32000 pieces meteorite were recovered from the Antarctic Continent.

3 GEOLOGY OF THE Mt. GROVE REGION AND CONDITIONS FOR THE ACCUMULATION OF METEORITES

The Mt. Grove region is located on the right bank of the Lambert Rift, in Eastern Antarctica. Its geographical position lies between $72°20' - 73°10'$S and $73°50'$–$75°40'$E, 450 km from China's Zhongshan Antarctic Station. It belongs to the ice island peak group of the Inland Antarctic Ice Cover and covers an area of about 3200 km^2. Blue ice covers an area of 560 km^2, in which are exposed 64 independent ice island peaks which are roughly arranged into five groups, extending along the NNE-SSW direction and distributed in the form of island chains, presenting a geomorphological pattern characterized by high mountain ranges and lateral valleys. The heights of the island peaks relative to the surface blue ice are in the range of 100–800 m (see Fig. 1). Because of the climbing-up and scrapping of the ice cover during its movement from southeast to northwest, the snow-ice line is generally high on the southeastern side of the ice island peak while on the northwestern side are usually developed erect fault-collapse cliffs (Liu et al. 2002).

Because of its unique geomorphological features and climatic conditions, as well as a relatively large exposed area of blue ice, the Mt. Grove region is a favored locus for the accumulation of meteorites, especially in its escarpment region. The latter extends almost 50 km from south to north and consists of three segments (their direction is almost perpendicular to the direction of motion of the icebergs) with the cliffs forming three terraces (Sun et al. 2001). There, the wind speed is high, leading to the blue ice melting at a greater speed. All these factors provide an excellent condition for large-scale accumulation of meteorites.

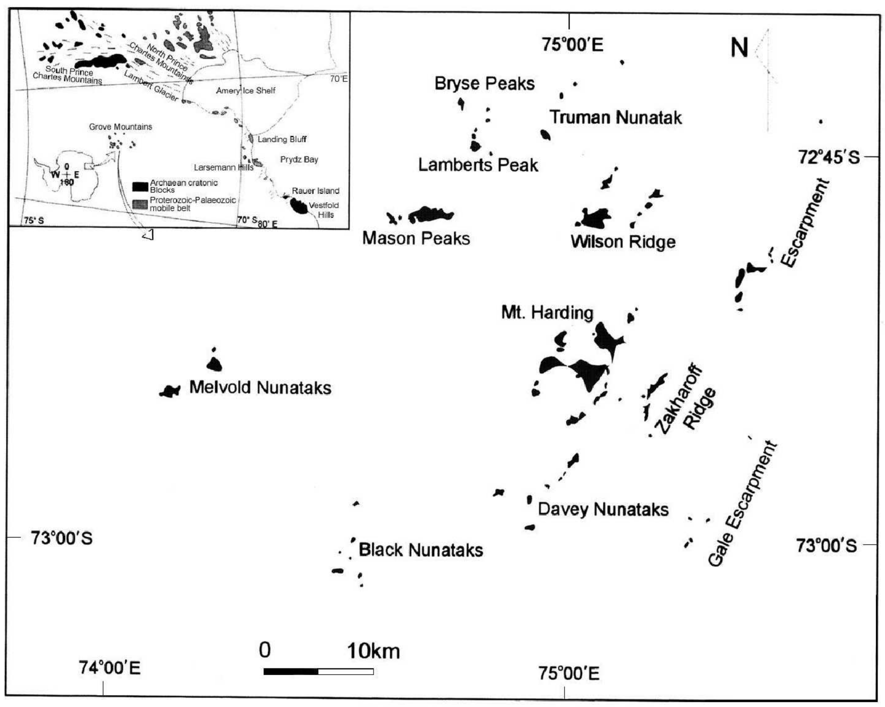

Fig. 1 Map showing the locations of meteorites recovered in the Mt. Grove region.

The Mt.Grove region is located in between the Archean craton block at South Charls Prince Mountain and the Proterozoic-Archean mobile zone at Prydz Bay. The strata exposed in this region are composed mainly of high-grade metamorphic rocks (80%) and granodiorite (20%), the former being composed predominantly of grayish-white and dark-colored gneisses intercalated with minor magnesoferrous granulite and metasedimentary rocks (Liu 2003). According to the SHRIMP zircon U-Pb age data, the protolith of the rocks in this region was dated at 870–953 Ma. During the pan-African orogeny at 530 Ma this region had experienced reworking by high-temperature metamorphism (Zhao et al. 2000).

4 CLASSIFICATION OF THE ANTARCTIC METEORITES RECOVERED BY CHINA

4.1 Classification of the Antarctic Meteorites Recovered during the 15th Antarctic Scientific Exploration of China

The 15th Antarctic Scientific Exploration was carried out from 1999 January 3 to 13 and four samples of Antarctic meteorite were recovered from the northern and middle segments of the Escarpment of the Grove Mountains. According to the nomenclature principle of the Meteorite Nomenclature Committee of the International Meteorite Society, these four samples were named GRV98001, GRV98002, GRV98003 and GRV98004, respectively.

No sections were prepared for GRV98001, because of its small size, but polished and thin sections were prepared for the other three samples for petrology, mineralogy and metamorphism studies (Chen 2001; Lin et al. 2002). Through high-resolution field emission scanning electron microscopic observation and ultra-thin window energy spectrometric analysis of its fusion crust, GRV98001 was preliminarily confirmed as a stony chondrite (Chen et al. 2001). Evidence from the petrological, mineralogical and metamorphic studies of the other meteorites have shown that GRV98002 is an L5 chondrite, GRV98003 is an H5 chondrite, and GRV98004 is an extremely fine-grained octohedrite (Chen et al. 2001; Lin et al. 2002).

4.2 Classification of the Antarctic Meteorites Recovered during the 16th Antarctic Scientific Exploration of China

On 2000 Feb. 2–5 the Mt. Grove Exploration Team under the 16th Antarctic Scientific Exploration Party recovered 28 pieces of meteorite in the southern segment of the Escarpment of the Grove Mountains in an encircling search. These meteorite samples were numbered GRV990001–GRV99028 (Ju et al. 2000). What is worthy of special mention is that among the 28 meteorites there are two achondrites (GRV99027 and GRV99018). Moreover, of the two, GRV99018 has been confirmed to be a Mars meteorite (Lin et al. 2002; Russell et al. 2000).

After the samples were photographed, fragments were cut into small discs 1 mm in thickness. The discs were boiled in epoxide resin. Thin sections prepared under water-free conditions for all the 28 meteorite samples were examined by microscopy for the following properties: composition of the silicate minerals, distribution and contents of the opaque minerals, structural and textural characteristics, developing characteristics of the chondrules, content and crystallinity of the groundmass, the crystal form and texture of the minerals, and so on. A quantitative analysis of the chemical composition of the minerals was conducted on the JEOL JXA-8800R Model electron microprobe of the Analysis and Test Center of Zhongshan University. Under a 15 kV accelerating voltage and 20 nA beam current, silicate mineral and oxide were used as standards and the analytical results were correlated by the ZAF method. Around 20 olivine and pyroxene grains were analysed for each meteorite, except for some individual meteorites with homogenous composition, where only a few points were selected for the analysis.

4.2.1 Characteristics and Classification of the Chondrites

The petrological characteristics and mineral compositional characteristics of the 26 chondrite samples are listed in Tables 2 and 3.

The classification of chemical groups and metamorphic degrees of the above 26 chrondrites is based only on the observation and analysis of the polished and thin sections, and we did not obtain their bulk chemical compositions. The classification of the non-equilibrium chondrites is not straightforward, because the mineral composition is heterogeneous.

In this joint research program divergent views emerged on the classification of the non-equilibrium meteorites, particularly with regard to GRV99001, GRV99019, GRV99020, GRV 99022, and GRV99026. In our studies these meteorites are significantly heterogeneous in their olivine composition (the average value (Fa) of 20 olivine grains is less than 20 mol%). According to the classification criteria (Ouyang, 1988), the above meteorites should belong to the H group, but Miao et al. (2002) gave an average Fa value (mol%) of olivine greater than 20, with a range of 21.9–24.9, which would assign them to the L group. Wang et al. (2002) conducted semi-quantitative chemical analysis of the above meteorites using energy-dispersive X-ray spectrometry and the results showed that the GRV99001 should belong to the H group, and GRV99026 to the L group. When the silicate composition is heterogenous, metal content becomes important in meteorite classification. The amounts of Fe-Ni metals in GRV99001, GRV99019, GRV99020, GRV99022 and GRV99026 are 6.9wt%, 3.9wt%, 7.8wt%, 8.6wt%, 5.2wt% and 8.7wt%, respectively. So, the above meteorites are tentatively designated as belonging to the L group. Further studies are necessary for a definitive determination.

Table 2 Characteristics of Groundmass and Chondrules in the Chondrites

Sample No.		99001, 99026, 99021, 99019, 99022, 99020	99003, 99008, 99006, 99011, 99028, 99015, 99012	99024, 99025, 99004, 99005, 99013	99009, 99010, 99016, 99023, 99007, 99014, 99017, 99002
Extent of development of chondrules		Extremely obvious	Obvious	General	Indistinct
Groundmass characteristics	Crystallinity		Semi-transparent, recrystallized to some extent	The extent of recrystallization of groundmass is relatively high, semi-transparent to transparent, crystalline grains 20–40 μm in size; regrown feldspar commonly observed crystals measured at 20–40 μm in grain size	The chondrule textures of these meteorites are hard to distinguish, intense recrystallization of glasses in the groundmass and chondrules; the recrystallized grains of the groundmass up to 50–200 μm in size, even up to 200–400 μm in size locally, regrown feldspar commonly observed
	Content of metals and their distribution state	Metals appearing as tiny grains on the margins of chondrules	Fe-Ni metal and troilite accounting for about 3–4 wt% of the samples, rounded grains dominant, mainly 30–50μm in grain size, some individual grains up to 500μm in size, distributed around chondrules or in the groundmass	Fe-Ni metal and troilite irregular in form, generally 100–200 μm in grain size, not too evenly distributed in the samples	Fe-Ni metal and troilite generally polygonal in form, generally larger than 200μm in grain size, largely filling in among silicate mineral grains

Table 4 lists the classifications based on various criteria, of the 26 chondrites recovered during the 16th Antarctic Scientific Exploration.

Table 3 Composition of Olivine and Pyroxene in the Chondrites

Meteorite	Olivine (Fa)	Pyroxene (Fs)	Feldspar	Chemical group
GRV99001	17.48, (8), 8.17∼29.53	14.0, (10), 6.96∼30.3	Seldom seen	H3
GRV99002	26.17, (11), 24.7 ∼ 26.9	17.78, (10), 14.0∼22.4	Commonly seen	LL6
GRV99003	23.6, (13), 22.29∼24.67	19.5, (9), 16.42∼19.99	Commonly seen	L4
GRV99004	25.88, (10), 25.37∼26.12	22.45, (11), 17.56∼22.89	Commonly seen	LL5
GRV99005	25.72, (11), 20.72∼26.73	22.0, (6), 15.32∼22.60	Commonly seen	LL5
GRV99006	17.25, (12), 16.28∼17.87	15.80, (10), 14.50∼18.08	Commonly seen	H6
GRV99007	23.00, (9), 22.70∼23.30	19.09, (11), 11.88∼20.015	Commonly seen	L6
GRV99008	21.27, (11), 17.93∼21.98	18.20, (10), 12.31∼18.57	Occasionally seen	L4
GRV99009	17.00, (10), 16.50∼17.38	15.55, (10), 14.63∼18.33	Commonly seen	H6
GRV99010	18.68, (10), 17.91∼20.16	15.18, (11), 15.77∼18.73	Ditto	H6
GRV99011	16.69, (13), 14.65∼17.72	14.96, (5), 14.04∼16.37	Occasionally seen	H4
GRV99012	25.82, (11), 21.95∼28.18	21.62, (8), 18.68∼26.66	Occasionally seen	L4
GRV99013	26.25, (12), 25.22∼26.53	22.33, (6), 17.83∼26.37	Commonly seen	LL5
GRV99014	23.06, (10), 22.71∼23.71	20.3, (10), 19.18∼24.93	Commonly seen	L6
GRV99015	27.42, (7), 26.51∼28.46	23.13, (3), 22.37∼23.91	Occasionally seen	LL4
GRV99016	25.25, (5), 24.74∼25.79	19.23, (6), 15.22∼21.23	Commonly seen	L6
GRV99017	22.42, (12), 21.94∼22.86	19.33, (9), 18.91∼19.49	Ditto	L6
GRV99019	13.5, (8), 3.57∼22.49	11.8, (10), 2.76∼22.3	Seldom seen	H3
GRV99020	13.33, (8), 5.28∼28.26	17.33, (11), 3.67∼37.53	Ditto	H3
GRV99021	22.18, (11), 11.36∼34.01	22.71, (14), 9.27∼35.48	Ditto	L3
GRV99022	15.33, (11), 8.98∼20.94	9.07, (10), 5.01∼17.04	Ditto	H3
GRV99023	25.1, (3), 25.09∼25.17	22.2, (4), 21.19∼22.91	Commonly seen	L6
GRV99024	25.02, (10), 20.12∼25.74	21.54, (11), 15.32∼26.67	Ditto	L5
GRV99025	16.17, (12), 15.74∼16.43	14.44, (9), 14.16∼14.96	Ditto	H5
GRV99026	12.4, (21), 4.66∼33.58	14.5, (10), 2.23∼35.48	Seldom seen	H3
GRV99028	17.75, (4), 17.65∼17.80	16.08, (7), 12.63∼19.57	Occasionally seen	H4

Notes: first item is the mean composition, the number in brackets is the quantity of minerals analysed; data interzone is the composition of the mineral.

Table 4 Classification of the 26 Ordinary Chondrites Recovered from the Mt. Grove Region of Antarctica

	3	4	5	6
H		GRV99011, GRV99028	GRV99025	GRV99006, GRV99009, GRV99010
L	GRV99001, RV99019, GRV99020, GRV99022, GRV99026, GRV99021	GRV99008, GRV99012	GRV99003, GRV99024	GRV99007, GRV99014, GRV99016, GRV99017, GRV99023
LL		GRV99015	GRV99004, GRV9900, GRV99013	GRV99002

4.2.2 Characteristics and the Origin of the Achondrites

The major minerals in the achondrite GRV99027 are coarse-grained enstenite, olivine, clino-augite and plagioclase, with chromite and sulfide present in minor amounts. The silicate minerals in GRV99027 are strongly fragmented and display obvious wavy extinction; the plagioclase commonly displays impact-induced micro-foliation with melted feldsparization or glasses. With results obtained from electron microprobe analysis, the mineral compositions all fall within the field of lherzolitic Mars meteorites: (a) the Fe/Fe+Mg ratios (Fa) of the olivine are in the range of 24.8∼27.9, falling within the field of lherzolitic Mars meteorites (Fa=22∼35); and (b) the chemical composition of enstenite (En81 Fs17 Wo2–En66 Fs24 Wo6) falls within the field of lherzolitic Mars meteorites(En78 Fs20Wo2–En58Fs25Wo17); (c) the enstenite (An49-55Ab44–500 $r < 1$) is rich in albite and its chemical composition falls within the field of Mars meteorites (Ab35–70). On the other hand, the feldspar contained in all HED group meteorites with similar mineral composition is anorthite (An80–100). The petrological and mineralogical characteristics of GRV99027 are similar to those of the lherzolitic Mars meteorites (Bridges & Grady 1999).

The major minerals in meteorite GRV 99018 are pigeonite (50.5 vol%) and feldspar (37.2 vol%), the minor minerals are silica (7.0 vol%) and opaque minerals dominated by chromite (5.2 vol%). Its mineral model composition is similar to that of anorthite-gabbro achondrite (anorthite 40–63 vol%, feldspar 30–56 vol%, silica < 4 vol%, opaque mineral < 4 vol%), except that its silica content is slightly higher. Pigeonite is present as coarse-grained euhedral crystals and is all formed through exsolution, composed of augite (En29-32 Fs 25-31Wo37-45) and orthohypersthene (En36-38Fs55-62Wo1-3). The mineral composition all fall within the field of anorthite-gabbro achondrite (augite En28-47Fs15-34Wo19-46, Ca-poor pyroxene En34-52Fs44-63Wo1-4). In addition, the Ca-low pyroxene is rich in MnO with a FeO/MnO ratio of 28, falling within the field of HED group meteorites (30). The fact that the pyroxenes in GRV99018 are Ca-poorer than those in Mars meteorites, lunar meteorites and terrestrial basalts (An88) is also consistent with the characteristics of anorthite-gabbro achondrite (An88-100). As judged by its mineral model composition, exsolution texture and chemical composition of pyroxenes, FeO/MnO ratios of silicates and Ca-enrichment feature of feldspar, GRV99018 is a typical anorthite-gabbro achondrite (Ruzicka & Snyder 1997).

4.3 Description of the Meteorites Recovered during the 19th Antarctic Scientific Exploration

During the 19th Antarctic Scientific Exploration of China a “Meteorite Hunting Team” was organized for the purposed of recovering meteorites in the Mt. Grove region. Between 2002 September 23 and 2003 Feb. 2, the team recovered a total of 4448 pieces of meteorite indicating that the Mt. Grove region is one of the regions in Antarctica where meteorites are most abundant.

The meteorite recovering work conducted this time has revealed the following properties:

(1) Among the recovered meteorites, the moraine-type meteorites account for 86% and the blue ice-type ones account for 14%. This shows that Mt. Grove meteorites are dominated by the moraine type, with the blue ice type coming next.

(2) The blue ice region below the Escarpment is an area where meteorites are accumulated. Meteorites were found from the southernmost part of the southern segment to the northernmost part of the northern segment, with varying densities influenced by ice flow and wind direction.

(3) Above the Escarpment, at its different terraces and in other blue ice regions meteorites

were also found (For instance, near the Hading Mountain), indicating that the other blue ice regions of the Grove Mountains would also be the regions where meteorites are accumulated.

A preliminary examination revealed that of the 4448 pieces of meteorite there is only one stony-iron and the rest meteorites are all stones. Of the 4447 stony meteorites, 22 are carbonaceous chondrites and six are achondrites from direct observation (Miao 2003, private letter).

5 CONCLUSIONS

From the analysis and summary of the Antarctic meteorite recovery during the three times of Antarctic Scientific Explorations, the following conclusions can be drawn:

1) The meteorites recovered from Antarctica by Chinese scientists are dominated by stony meteorites. Among the 4480 pieces recovered during the three Antarctic Scientific Explorations there is only one iron meteorite and one stony-iron meteorite, and the rest are all stony meteorites.

2) Observations under microscope and results of electron probe analysis of the 28 new meteorites collected from the Grove Mountains ice field, Antarctica, by the 16th Chinese Antarctic Research Expedition, show that two of these are achondrites (one is shergottites), and the other 26 are ordinary chondrites, including 11 with high iron content (H group), 10 with low iron content (L group) and five with low iron and other metal phase contents (LL group). In the H group, there are five primitive type-three meteorites and six evolutional meteorites, the latter are further classified into two type-four meteorites, one type-five meteorite and three type-six meteorites. The L group is further classified into one type-three, two type-four, two type-five and five type-six, and the five meteorites of the LL group, into one type-four, three type-five, and one type-six. The two achondrites, GRV99027 and GRV99018, belong to rare types, and a preliminary examination indicates that GRV99027 may be a martian lherzolite, and GRV99018 may be an eucrite.

3) Among the Antarctic meteorites recovered, there is a larger proportion of rare and valuable specimens. A detailed examination of the meteorite samples recovered during the 15th and 16th Antarctic Scientific Explorations revealed one Mars meteorite and one asteroid meteorite; among those recovered during the 19th Antarctic Scientific Exploration there are six pieces of achondrite.

4) Among the Antarctic meteorites recovered by Chinese scientists, the meteorite recovered from moraines account for 86% or more, those from blue ices account for 14% only, indicating that in the Mt. Grove region the meteorites are present largely in the moraines, thus moraine-distributed areas are the most important areas for meteorite recovery.

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