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Progress of Antarctic meteorite survey and research in China

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Abstract More than 50000 meteorite samples have been collected in Antarctica since 1969, making meteorite surveys a very important aspect of Antarctic expeditions. The Chinese National Antarctic Research Expedition has collected more than 12000 meteorites in the Grove Mountains region, where has been confirmed as one of the richest meteorite concentration sites in Antarctica. China, therefore, possesses one of the world's largest Antarctic meteorite collections and has made substantial contributions to this field of research. We summarize here the Chinese meteorite survey efforts in the Grove Mountains, as well as discuss progress of the classification and investigation of Grove Mountains meteorites. Outlooks are also proposed for the future of Antarctic meteorite work.

Keywords **meteorites, Antarctica, Grove Mountains, meteorite collection**

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1 Introduction

Antarctica is a vast continent that is nearly completely covered by an immense ice sheet. Antarctica's stable geological history, dry environment, and internal glacial movement make it the richest area on Earth for the accumulation and storage of huge quantities of meteorites (Miao, 2015; Harvey, 2003). The meteorite concentration mechanism in the Antarctic ice sheet was discovered in 1969 when nine different meteorites were found within narrow bare ice in the Yamato Mountains (Yoshida et al., 1971). Afterwards, Japan, the United States, a joint initiative of European institutions (EUROMET) and others have carried out a series of meteorite search missions (Miao, 2015; Folco et al., 2002; Wang, 1990). As the result, about 50000 meteorites have been collected in the Antarctic continent with the discovery of more than 50 different meteorite concentration sites (Miao, 2015; Harvey, 2003), strongly confirming that Antarctica is the continent enriched with meteorites. Since the 1990s, Chinese geologic and planetary scientists have also been interested in Antarctic meteorites, initiated investigations into Antarctic meteorite surveys, and prepared and deployed a Chinese-led Antarctic meteorite surveys (Wang et al., 2002a, 1996, 1990; Wang, 1999, 1990; Wang and Mao, 1998; Wang and Chen, 1995; Lin and Wang, 1995; Chen et al., 1994; Wang and Lin, 1993, 1992). Prior to the discovery of the Grove Mountain (GRV) meteorites, planetary scientists in China conducted multidisciplinary research with Antarctic meteorites including sample application, sample exchange, and international cooperation, and acquired some important results (Wang and Lin, 2002). For example, Lin and Kimura (1998b, 1997a) studied the petrology of enstatite chondrites

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and found the first unequilibrated EL3 chondrite from Antarctica. Additional surveys of Ca-Al-rich inclusions (CAIs) within carbonaceous chondrites and some Antarctic ordinary chondrites were reported with the discovery of a new type of CAIs (Lin et al., 2004a, 2003a; Lin and Kimura, 2003; Lin and Kimura, 1998a, 1998c, 1997b). Chen et al. (Chen and El Goresy, 2000; Chen, et al., 1996a, 1996b, 1995a, 1995b, 1995c) also found out seven high-pressure polymorphs in Martian meteorites and ordinary chondrites.

The Chinese National Antarctic Research Expedition (CHINARE) began its first inland field survey in 1998 and found its first four meteorites in the Grove Mountains, East Antarctica (Chen et al., 2001; Ju and Liu, 2000). At present, seven field expeditions in the Grove Mountains have been carried out with a remarkable collection of more than 12000 meteorite samples (Miao, 2015; Miao, et al., 2012, 2008c, 2004a). Hence, China possesses one of the world's largest Antarctic meteorite collections. Since classification is an important and fundamental aspect of meteorite curation, the substantial increase in the number of Antarctic meteorites led to improve the efficiency of classification for GRV meteorites (Miao and Wang, 2008). The GRV meteorites also rapidly promoted advances in Chinese meteoritical science and lunar exploration (Lin et al., 2013b). In this paper, the survey, collection, and research achievements of Antarctic meteorite in China are summarized based on cosmochemistry and Antarctic meteorite overviews (Miao, 2015; Lin et al., 2013b; Miao et al., 2012, 2008c, 2004a).

2 Survey and classification of Antarctic meteorites

2.1 Grove Mountains

The Grove Mountains are a group of nunataks distributed on a large bare ice field in Princess Elizabeth Land on the east bank of Lambert Rift in Prydz Bay, locating about 450 km north to Zhongshan Station and extending between 72°20′–73°10′S and 73°50′–75°40′E. The GRV region covers an area of about 3000 km^2, including 500 km^2 of blue ice field (Figure 1). The Grove Mountains terrain trends from southeast to northwest with a height difference of about 1200 m and average altitude of 2000 m. Steep slopes and cliffs (i.e., Gale Escarpment) separate the Grove Mountains region to the east from an ice plateau. The relative altitude difference between these features is moderate (~100–300 m), such that the glacier flows over the Gale Escarpment.

The Gale Escarpment can be divided into three segments from south to north, based on the outcropping of some bedrocks and ice flows. The nunataks have a relative height of 300–600 m, but outcrops of other bedrocks occur only as cliffs or steep slopes. In addition, the blue ice field distribution shows an NNE or NE trend (Figure 2). Most blue ice fields are located near the nunataks and their distribution constitutes 12 belts or zones composed of blue ices and nunataks (Figure 2) (Liu et al., 2003; Ju and Liu, 2000). The glaciers of the ice sheet flow over the Gale Escarpment into the Grove Mountains region and then travel in a zigzag pattern among the nunataks. The ice flows much slower owing to the block of nunataks, which drives ablation due to katabatic wind. As a result, meteorites embedded in the ice layer remain exposed and stranded on the surface of the blue ice field. Seven field seasons of meteorite surveys and substantial collection of meteorites in the Grove Mountains verify that this region is a new and important meteorite concentration area in Antarctica (Ju and Liu, 2002, 2000; Liu and Ju, 2002).

Figure 1 Landscape of the central region of Grove Mountains.

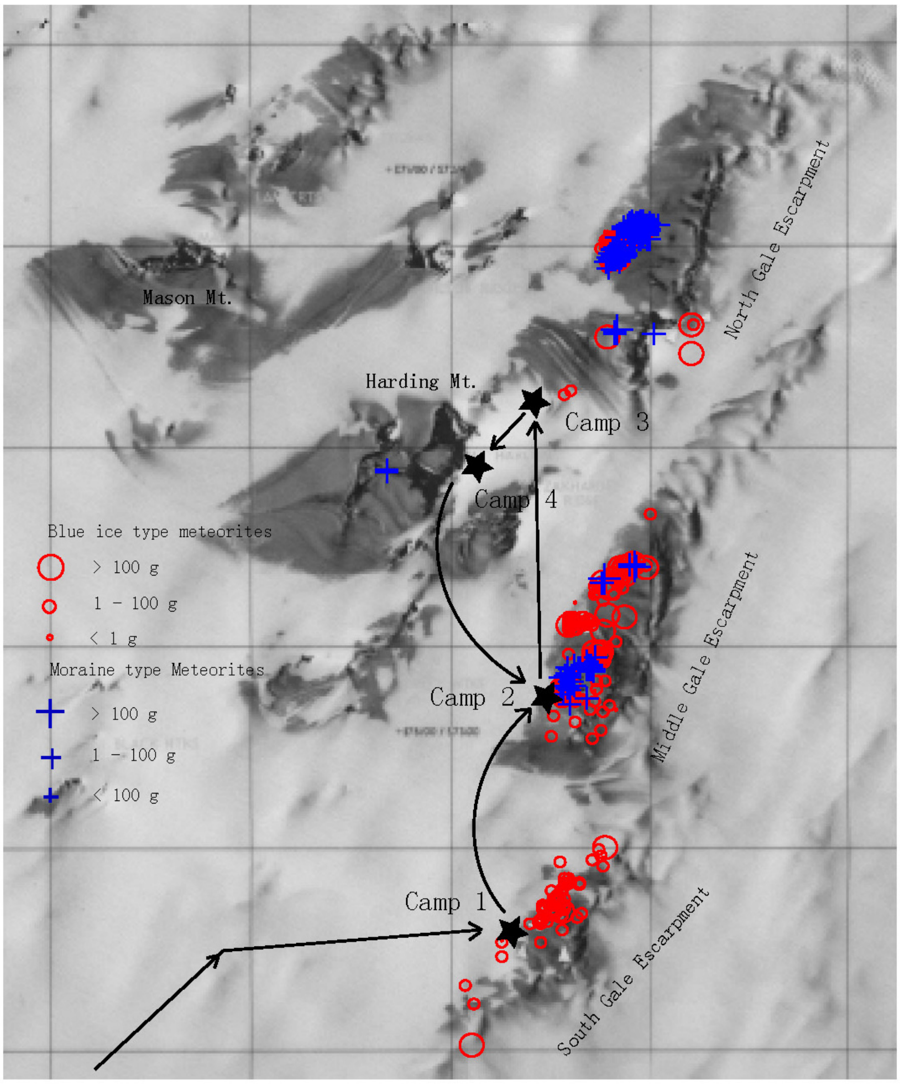

Figure 2 The core area in Grove Mountains is composed mainly of nunataks (black) and blue ice fields (dark grey). The distribution of blue ice type meteorites and moraine type meteorites is represented by red circles and blue crosses, respectively (Qin et al., 2008).

2.2 Meteorite survey history and collection

In the early 1990s, Chinese meteoritists paid great attention to international progress and achievements in Antarctic meteorite studies, investigated the meteorite concentration mechanism in Antarctica, and then proposed a meteorite search program in Antarctica to CHINARE (Wang, 1990). During the 1998/1999 field season, CHINARE began its first inland expedition in the GRV with a field team of only four members and a snowmobile (Ju and Liu, 2000). Four meteorites were discovered unexpectedly during this initial field survey, which was a prelude to Chinese Antarctic meteorite collection (Chen et al., 2001; Ju and Liu, 2000). In the next austral summer season, a larger Grove Mountains team of eight members conducted a more comprehensive expedition with a focus on the Geology, Glaciology, Mapping, and Climate. The team spent two weeks to search for meteorites. As a result, 28 meteorites were found in the blue ice field below the south segment of the Gale Escarpment (Ju and Liu, 2000), bringing the total of GRV meteorites found at that time to 32 and confirming this location as a new Antarctic meteorite concentration (Ju and Liu, 2002; Liu and Ju, 2002). In 2002/2003 austral summer, the third team to the Grove Mountains achieved a remarkable breakthrough in meteorite collection with a total of 4448 recovered samples (Ju and Miao, 2005; Miao et al., 2004a). Four additional expeditions were carried out in the GRV region with collections of 5354, 1618, 583, and 630 meteorites, respectively (Miao et al., 2012, 2004a; Miao and Lin, 2010; Lin et al., 2006a). Detailed information regarding the Grove Mountains expeditions is listed in Table 1. In summary, the Chinese collection of more than 12000 is now the third largest in the world, following Japan and the United States, which also clearly confirms that the Grove Mountains is an important meteorite concentration area (Miao et al., 2012; Miao and Lin, 2010).

Table 1 Summary of the Grove Mountains expeditions and meteorite collection

CHINAREs	Field time	Team members	Equipment & Task	Meteorite collection
No. 15	1998/1999	4	Equipment: One snow mobile & one sleigh Task: geology, glaciology, mapping, weathering	4
No. 16	1999/2000	8	Equipment: Two snow mobiles & three sleighs Task: meteorite survey, geology, glaciology, mapping, weathering	28
No. 19	2002/2003	8	Equipment: Two snow mobiles & three sleighs Task: meteorite survey, geology, glaciology, mapping, weathering	4448
No. 22	2005/2006	11	Equipment: Two snow mobiles & three sleighs Task: meteorite survey, geology, glaciology, mapping, weathering	5354
No. 25	2009/2010	10	Equipment: Two snow mobiles & three sleighs Task: meteorite survey, geology, glaciology, mapping, weathering	1618
No. 30	2013/2014	9	Equipment: Two snow mobiles & three sleighs Task: geology, glaciology, mapping, weathering meteorite survey	583
No. 32	2015/2016	10	Equipment: Two snow mobiles & three sleighs Task: geology, glaciology, mapping, weathering meteorite survey	630
Total meteorite collection				12665

2.3 Basic classification of meteorites

2.3.1 Grove Mountains meteorite classification history

Basic classification and nomenclature are the first step and preliminary work for Antarctic meteorite curation (Miao and Wang, 2008). With the increasing size of the meteorite collection, classification has become a routine and daily component of Chinese Antarctic meteorite curation. All the GRV meteorites samples are curated by Polar Research Institute of China (PRIC). The classified meteorites and the thin sections are kept in drying boxes, while the meteorite samples just returned from Antarctica before their classification are stored in the ice house. Meteorite classification and sample curation in China is generally classified into three stages (Miao and Wang, 2008): (1) meteorites that were first classified by individual meteoritists before 2000; (2) GRV meteorites that were classified by university and institutional groups of the Chinese Academy of Sciences in 2000–2006; (3) Since 2006, Antarctic meteorites have been curated in PRIC with systematic classification supervised by the China's Antarctic Meteorite Expert Committee (CAMEC). After more than a decade of effort, more than 3000 meteorites have been classified (Table 2) and a matured classification procedure has been development by the CAMEC.

2.3.2 New meteorite classification method

Meteorite classification is a challenging task for the curation of PRIC, owing to the large GRV collection, so a quick and efficient classification method is required. Magnetic susceptibility is an important physical feature related to a meteorite's Fe-Ni alloy content and is therefore a potentially useful parameter for meteorite classification. Luo et al. (2009) measured the magnetic susceptibility of 613 classified GRV meteorites and found that the mass normalized magnetic susceptibility (log$X$, 10^{-9} $m^3 \cdot kg^{-1}$) shows a very good correlation between ordinary chondrite groups. Most ordinary chondrites of the H, L, and LL groups can be classified according to magnetic susceptibility, which has also been found to be a more reliable classification parameter for unequilibrated ordinary chondrites (Hu et al., 2013; Luo et al., 2009).

2.3.3 Type features of GRV meteorites

The meteorite concentration mechanism in glaciers results in the accumulation of abundant meteorites exposed in some narrow bare ice regions, inevitably leading to a certain degree of meteorite pairing (Harvey, 2003), which must be considered in order to assess the number of meteorite falls (Miao et al., 2003). Based on a comparison of petrology and mineral chemistry, five possible pairings were identified in the first 32 meteorites collected during the first two expeditions in the Grove Mountains region (Miao et al., 2003). Additional pairing studies suggested that relatively higher proportions of meteorite pairing in some localities may be caused by meteorite rain and/or brecciation of some larger meteorites (Miao et al., 2008d). Based on pairing analyses of 100 classified meteorites, the distribution of GRV meteorite types has been shown to have the following features (Miao et al., 2008d): (1) Almost all meteorite types are found in the Grove Mountains collection with the exception of lunar meteorites; (2) The type distribution is very uneven with a particularly high proportion of L6 meteorites; (3) GRV meteorites are relative fresh with weathering degrees of W1 and W2; (4) Meteorites masses are relatively smaller than American Antarctic Search for Meteorites (ANSMET) samples.

Table 2 Summary of classified GRV meteorites

Meteorite type		Number	Meteorite name
Non-ordinary chondrites	Martian meteorites	2	GRV 99027, GRV 020090
	HEDs clan	3	GRV 99018, GRV 051523, GRV 13001
	Winonaite	2	GRV 022890, GRV 021663
	Mesosiderites	12	GRV 020124, GRV 020171, GRV 020175, GRV 020281, GRV 021525, GRV 021553, GRV 050212, GRV 054854, GRV 055055, GRV 055153, GRV 055364, GRV 090994
	Pallasites	1	GRV 020099
	Iron meteorites	4	GRV 98003, GRV 090018, GRV 090327, GRV 090333
	Ureilites	11	GRV 021512, GRV 021729, GRV 021788, GRV 022835, GRV 022888, GRV 022931, GRV 024237, GRV 024516, GRV 052382, GRV 052408, GRV 090312
	Carbonaceous chondrites	21	GRV 020005, GRV 020015, GRV 021579, GRV 021710, GRV 021769, GRV 021865, GRV 023154, GRV 023155, GRV 050179, GRV 13051, etc.
	Enstatite chondrites	2	GRV 021692, GRV 13100
	Sum	58	-
Ordinary chondrites	H-melt breccia	3	GRV 053644, GRV 054336, GRV 055356
	H3	39	GRV 020016, GRV 020044, GRV 020162, GRV 021481, GRV 022552, GRV 022907, GRV 024063, GRV 050009, GRV 090313, GRV 090324, etc.
	H4	340	GRV 99006, GRV 020004, GRV 020216, GRV 020219, GRV 020251, GRV 052288, GRV 053039, GRV 090316, GRV 13035, GRV 13132, etc.
	H5	402	GRV 98004, GRV 020009, GRV 020076, GRV 050076, GRV 051779, GRV 052204, GRV 053171, GRV 053788, GRV 090243, GRV 090301, etc.
	H6	127	GRV 99009, GRV 020031, GRV 022245, GRV 022551, GRV 022570, GRV 022833, GRV 053065, GRV 054098, GRV 090304, GRV 090389, etc.
	L-melt breccia	4	GRV 052483, GRV 055152, GRV 090407, GRV 13136
	L3	33	GRV 99001, GRV 020006, GRV 020011, GRV 050002, GRV 050006, GRV 050015, GRV 050018, GRV 052696, GRV 090306, GRV 091001, etc.
	L3-6	1	GRV 050202
	L4	112	GRV 99003, GRV 020001, GRV 020029, GRV 021583, GRV 021643, GRV 051657, GRV 051658, GRV 054955, GRV 090001, GRV 090011, etc.
	L5	1026	GRV 98002, GRV 020039, GRV 020040, GRV 020047, GRV 051668, GRV 051674, GRV 051691, GRV 090110, GRV 090111, GRV 090112, etc.
	L6	987	GRV 99007, GRV 020132, GRV 020134, GRV 051562, GRV 051582, GRV 051590, GRV 090660, GRV 090666, GRV 13080, GRV 13082, etc.
	L7	1	GRV 052969
	LL3	6	GRV 020010, GRV 020032, GRV 020034, GRV 020036, GRV 020104, GRV 020105
	LL4	11	GRV 99015, GRV 020014, GRV 020021, GRV 020028, GRV 020033, GRV 020037, GRV 020041, GRV 022096, GRV 050004, GRV 050017, GRV 090748.
	LL4-6	2	GRV 020013, GRV 99002
	LL5	13	GRV 99004, GRV 99005, GRV 99013, GRV 020002, GRV 020003, GRV 020012, GRV 020019, GRV 022021, GRV 024066, GRV 024245, GRV 050007, GRV 090326, GRV 090591
	LL6	12	GRV 021496, GRV 022018, GRV 022462, GRV 022793, GRV 022909, GRV 023590, GRV 050003, GRV 050014, GRV 052356, GRV 052729, GRV 053978, GRV 13071
	Ungrouped	1	GRV 98001
	Sum	3120	-
Total		3178	-

3 Research on Antarctic meteorites

3.1 Ordinary chondrites

3.1.1 Petrography and mineral chemistry

Ordinary chondrites are the most common meteorite type and have three chemical groups and different petrologic types with a range of physical and petrologic properties (Wang and Wang, 2011), which are significant for understanding the evolution of the early solar nebula and ordinary chondrite classification (Wang and Wang, 2011; Wang et al., 2009). Ordinary chondrites are the most abundant in the Antarctic meteorite collection (Wang and Wang, 2011; Harvey, 2003) as well as the Chinese Antarctic meteorite collection, accounting for about 97% of classified GRV meteorites (Miao et al., 2012). In addition to basic classification work, Chinese meteoritists have conducted further studies on ordinary chondrites since the discovery of the first four meteorites in 1998 (Li et al., 2014; Shang et al., 2013; Dai et al., 2008; Miao et al., 2008d, 2002a, 2002b; Dai, 2007; Tao et al., 2005, 2002; Liu et al., 2002; Wang et al., 2002b; Chen et al., 2001).

Three of the first four GRV meteorites discovered in 1998/1999 were identified as ordinary chondrites, with detailed petrologic and mineral chemistry characteristics indicating that they were indeed different meteorites (Chen et al., 2001; Ju and Liu, 2000). In the next field season, the 28 collected meteorites attracted sufficient attention such that the Chinese Antarctic Meteorite Workshop (CAMW) was set up to develop a meteorite classification procedure for Antarctic meteorite nomenclature. Comparative research on the petrology of these 28 meteorites was completed by different Chinese geochemistry institutes and colleges, and the reported petrological and mineral chemistry features made an important contribution to the late GRV meteorite classification procedure and meteorite sample management (Liu et al., 2002; Miao et al., 2002a, 2002b; Tao et al., 2002; Wang et al., 2002b).

Under the financial support of the National Infrastructure Natural Resource Platform for Science and Technology (Grant no. 2005DKA2146), PRIC constructed a Resource-sharing Platform for Polar Samples including Antarctic meteorites in 2006–2008. During its development, the CAMW group classified 2350 GRV meteorite samples. As a result, further and more detailed petrological and mineral chemistry data from the GRV ordinary chondrites were reported (Dai et al., 2009, 2008; Jiang and Xu, 2009; Hu et al., 2008; Li et al., 2008; Miao and Wang, 2008; Miao et al., 2008d; Dai, 2007; Wang et al., 2007; Liang et al., 2006b). The work described here yielded the following achievements and information with regard to GRV ordinary chondrites. (1) More petrologic and mineral chemistry data were added to the sharing platform of Chinese Antarctic meteorites. (2) The proportions of different meteorite types were assessed by pairing results. (3) GRV meteorites were found to have relatively high shock metamorphic characteristics. (4) Different classification methods were tested and assessed, especially pertaining to unequilibrated chondrites. (5) The type distribution of various meteorites provides evidence for the meteorite concentration mechanism in the GRV.

3.1.2 Refractory inclusions of ordinary chondrites (OC)

It is well known that refractory inclusions are common in carbonaceous chondrites while rare in ordinary chondrites (MacPherson et al., 1988). On the basis of a series of studies on refractory inclusions on carbonaceous and enstatite chondrites (Lin et al., 2004a, 2003a; Lin and Kimura, 2003, 1997a, 1997b), Lin et al. (2004a) studied refractory inclusions in Antarctic ordinary chondrites. Through *X*-ray mapping and electronic scanning spectroscopy, 24 refractory inclusions (i.e., CAIs) were found in 18 ordinary chondrites (Lin et al., 2006b).

Features of the ordinary chondrites CAIs include their substantially lower abundance and the fact that their type is simple and apparently different from carbonaceous chondrites, with only two types identified among the 24 CAIs (A-type and spinel-pyroxene). Another feature is that the ordinary chondrite CAIs consist of fine-grained feldspathoids, spinel, and Ca-pyroxene with minor ilmenite but lack primary melilite, which is a main phase of carbonaceous chondrites CAIs, suggesting that they are heavily altered. However, further and more comprehensive comparisons show that the ordinary chondrites CAI types and size distributions are similar to other chondrite types. This suggests that CAIs in various chondrite groups primarily formed under similar processes and conditions, and were transported to different chondrite-accreting regions. The heterogeneous abundance and distinct alteration assemblages of CAIs from various chondrites may be due to transport processes and secondary reactions under different conditions (Lin et al., 2006b).

3.1.3 Chemical composition of metallic Fe-Ni components of ordinary chondrites

Chondrites formed directly from the condensation and accretion of the solar nebula. They did not undergo later fractionation and therefore recorded information about the formation and evolution of the solar nebula during the early stages of solar system. In order to better understand their formation within the solar nebula and evolution processes of their parent bodies, Xu et al. (2009) analyzed the bulk composition of metallic Fe-Ni from ordinary chondrites, including two GRV unequilibrated ordinary chondrites, using inductively coupled plasma mass spectrometry (ICP-MS). Their analyses show that the refractory siderophile elements (Re, Au, Ni, Co) display a flat pattern

(1.01 × CI Co-normalized), moderate elements (As, Cu, Ag, Ga, Ge, Zn) decrease with volatility from 0.63 × CI (Co-normalized, As) to 0.05 × CI (Co-normalized, Zn), and Cr and Mn are relatively depleted, probably owing to their main proportion in silicates and sulfides (nonmagnetic). Conclusively, the abundances of siderophile and chalcophile elements of metallic Fe-Ni from the ordinary chondrites correlate with the 50% condensation temperatures (i.e., volatility) of the elements (Xu et al., 2009). In addition, equilibrated and unequilibrated ordinary chondrites share similar siderophile and chalcophile element patterns in the metallic Fe-Ni portions, but the metallic Fe-Ni of equilibrated ordinary chondrites display a strong deficit of Cr, Mn, Ag and Zn, suggesting that these elements were almost all partitioned into silicates and/or sulfides during thermal metamorphism (Xu et al., 2009).

3.1.4 Oxygen isotopic compositions, cosmic ray exposure (CRE) ages, and weathering degrees of ordinary chondrites

Additional studies on Antarctic meteorites have been carried out to measure oxygen isotopes, cosmic ray exposure (CRE) ages, and weathering degrees. Oxygen isotopes are an important indicator for understanding the origin and relation among different meteorites (Clayton, 2003), including its main components (Xu et al., 2009). Aluminum-rich chondrules (ARCs) are a rare constituent in primitive chondrites that condensed in the early solar nebula, but their mineralogic and chemical composition properties are intermediate between CAIs and chondrules, which provides important information regarding their temporal and petrogenetic relationships. Jiang et al. (2015) surveyed ARCs in three OCs from the GRV 022410 (H4), GRV 052722 (H3.7) and Julesburg (L3.6) and analyzed their oxygen isotopic compositions using *in situ* nanoscale secondary ion mass spectrometry (NanoSIMS).

The seven ARCs contained bulk Al_2O_3 of ~17%−33% and exhibited igneous textures composed of olivine, high-Ca and low-Ca pyroxenes, plagioclase, spinel, and glass. Based on the analyses, the ARCs have oxygen isotopic compositions ($\delta^{18}O$=−6.1‰ ~ −7.1‰, $\delta^{17}O$=−4.5‰ ~ −5.1‰) close to ferromagnesian chondrules but are far more depleted in ^{16}O than CAIs ($\delta^{18}O$=−40‰, $\delta^{17}O$=−40‰). Most ARCs oxygen isotopic compositions plot close to the terrestrial mass fractionation (TF) line, and a few between the TF and carbonaceous chondrites anhydrous mixing (CCAM) lines. However, different minerals have different oxygen isotopic features. Plagioclase, nepheline, and glass suffered O-isotopic exchange during metamorphism in the parent body. Spinel, olivine, and pyroxene represent the primary O-isotopic compositions of the ARCs and define a fitted line with a slope of ~0.7±0.1. This shallower slope, as well as more depleted ^{16}O compositions, indicates that ordinary chondrites ARCs probably experienced a higher degree of oxygen isotope exchange with a ^{16}O-poor nebular gas reservoir during multiple melting episodes (Jiang et al., 2015).

In order to study the CRE ages and thermal history of OC, Chinese and Swedish researchers determined the mineralogical and chemical characteristics and the He, Ne, and Ar isotopic abundances of two meteorite falls from China, and of two Antarctic meteorites recovered by the 15th Chinese National Antarctic Research Expedition (Lorenzetti et al., 2003; Wang et al., 2003). Three meteorites of Guangmingshan (H5), Zhuanghe (H5), and GRV 98002 (L5) were reported to have CRE ages of 68.7 ± 10.0 Ma, 3.8 ± 0.6 Ma, and 17.0 ± 2.5 Ma, respectively, which are within the range typically observed for the respective meteorite types. However, these authors found that GRV 98004 had an extremely short parent body-Earth transfer time of 0.052 ± 0.008 Ma and proposed that several asteroids in Earth-crossing orbits or in the main asteroid belt with orbits close to an ejection resonance are spectral-match candidates and may represent immediate precursor bodies of meteorites with CRE ages ≤ 0.1 Ma.

Furthermore, during the classification of GRV ordinary chondrites, some contradictory problems on weathering degree criteria were observed; e.g., some silicates were partly altered along cracks while only minor portions of metal or troilite (< 20%) were weathered. Shang et al. (2013) therefore proposed a new criteria to categorize the weathering degree for ordinary chondrites that accounts for the weathering features of both metal/troilite and silicates, e.g., W_m3-W_s0, where subscripted *m* and *s* represent weathering of the metal and silicate, respectively .

3.2 Carbonaceous chondrites

Carbonaceous chondrites are the most primitive condensates in the solar nebula. They are unequilibrated, minimally affected by parent body processes, and record important information regarding the nebular condition, physical process, and time scale of formation events in their source regions (Dai et al., 2013). At present, there are 12 classified carbonaceous chondrites collected from the Grove Mountains: CM (GRV 020017, 020025, 021536, 050179, 050384); CO (GRV 021579); CV (GRV 023155, 022459); and CR (GRV 021710, 021767, 021768, 021769) (Dai et al., 2015, 2013, 2006, 2004; Zhao et al., 2013; Zhang et al., 2010a; Wang et al., 2008b). On the basis of their classification and petrographic characteristics, several studies on CAIs, presolar grains, and other special components have been carried out on these GRV carbonaceous chondrites, as described below.

3.2.1 Refractory inclusions in carbonaceous chondrites

Refractory inclusions (mainly CAIs) are the products of high-temperature thermal events and represent the first solid condensate from the cooling protoplanetary disk.

Investigation of these materials therefore provides insight into the origin and evolution of solar nebula (Lin et al., 2006b). Additionally, CAIs are an important component of carbonaceous chondrites. In order to explore the origin of carbonaceous chondrites and evolution of the solar nebula, the CAIs from different GRV carbonaceous chondrites have been studied (Dai et al., 2015, 2013, 2006, 2004) with results summarized as follows. (1) The GRV carbonaceous chondrites experienced terrestrial weathering to a certain degree, but the CAI mineral assemblages indicate that alteration occurred during formation in the nebula rather than during weathering. (2) CAIs are mainly found in CM, CV, and CO chondrites, but their abundances are variable among the different groups (e.g., CR chondrites contain fewer CAIs) (Dai, 2007). (3) Statistical analysis of GRV Carbonaceous Chondrites indicates that the A-type and spinel-pyroxene-rich type CAIs dominate the CAI population, as has been reported in Allende and Murchison carbonaceous chondrites (Dai et al., 2015, 2013). (4) Different CAI types share similar petrographic and mineral chemistry features, which suggest that all CAIs may have a similar origin in the same region of the solar nebula (Dai, 2007).

3.2.2 Presolar grains in CR carbonaceous chondrites

Presolar grains from primitive chondrites (e.g., CR) are small circumstellar dust grains that survived homogenization in the solar nebula and can provide information regarding stellar nucleosynthetic processes and the physical and chemical conditions of condensation (Zinner et al., 2005). GRV 021710 is a CR2 chondrite and one of the most presolar-grain-enriched primitive chondrites found to date (Miao et al., 2007). Zhao et al. (2013) used *in situ* NanoSIMS ion imaging to investigate presolar grains in GRV 021710 and found high abundances of C- an O-anomalous grains, with concentrations of 236 ± 40 and 189 ± 18 ppm, respectively (Zhao et al., 2013). Important points achieved in the work include the following. (1) The abundance of O-enriched presolar grains of supernova origin in GRV 021710 is about twice higher than other chondrites, suggesting that supernova material is unevenly distributed in the original solar nebula. (2) The first discovery of presolar SiO_2 grains provides direct evidence for the presence of SiO_2 presolar grains in supernova ejecta. (3) NanoSIMS ion imaging of S isotopes shows that the abundance of sulfide presolar grains is up to 2 ppm. (4) GRV 021710 underwent only a very low degree of late alteration history compared with other primitive type 3 carbonaceous chondrites.

3.2.3 Exotic components in carbonaceous chondrites

Unequilibrated chondrites are mainly composed of chondrules, metal/sulfides, refractory inclusions, and a fine-grained matrix; these components are thought to have formed directly in the early solar system. However, other exotic components, such as lithic clasts, occur in some unequilibrated chondrites (Sokol et al., 2007; Bischoff et al., 2006). In general, more igneous-textured lithic clasts have been discovered in ordinary chondrites but are rare in carbonaceous chondrites. These lithic clasts provide important evidence for the existence of planetesimals formed prior to the accretion of chondrite parent bodies (Zhang et al., 2010a). Zhang et al. (2010a) found a metamorphosed lithic clast in CM chondrite GRV 021536, composed mainly of Fe-rich olivine (Fo_{62}) with minor diopside ($Fs_{9.7–11.1}Wo_{48.3–51.6}$), plagioclase ($An_{43–46.5}$), nepheline, merrillite, Al-rich chromite (21.8 wt% Al_2O_3, 4.43 wt% TiO_2), and pentlandite. The mineral chemistry and oxygen isotopic composition suggest that this lithic clast could be derived from an exotic primitive CV asteroid, different from the CM chondrite parent body. The apparent lack of hydration indicates that the lithic clast accreted onto the CM chondrite parent body after hydration of the CM components (Zhang et al., 2010a).

3.3 Shock metamorphism

Shock metamorphism is one of the most important physical features of meteorites, which records the parent body impact history, and is also of great significance for studies on the formation and evolution of the planets (Sharp et al., 2006). The GRV chondrites have relatively higher shock metamorphic effects, which makes them good objects for studying the impact history of certain asteroids that may be the source region of chondrites (Feng et al., 2008). Shock features from a few hundred GRV chondrites were studied in order to assess the different stages of shock metamorphism (Wang et al., 2010a; Feng et al., 2008). It was found that different chemical groups of chondrites have different shock stages, and H group chondrites have substantially higher shock stages than L and LL group chondrites, which possibly reflects different physical properties of their parent-body asteroids (Wang et al., 2010a; Feng et al., 2008).

In order to investigate phase transformation processes under high pressure, transformed olivine in shock veins of GRV chondrites was carefully studied (Feng et al., 2012; Feng and Lin, 2008). Observations and analyses reveal the transformation mechanism of olivine to ringwoodite. Shocked olivine generally displays zonation with a ringwoodite crust and olivine core. The crustal ringwoodite, with great variation of Fa values (27.8–81.6 mol%), is relatively richer in FeO than the olivine core, and the Fa value of ringwoodite has good linear correlation with its Raman peaks. The composition of ringwoodite can therefore be speculated by its Raman shifts with analysis precision of better than 5 mol% (Feng et al., 2012; Feng and Lin, 2008).

Martian meteorites usually display strong shock metamorphic effects (Miao et al., 2004b). Martian shergottites share common features, including the presence of maskelynite, indicating that they originated from heavy impact events. GRV 99027 is the first GRV Martian lherzolitic meteorite found with strong shock effects (Wang et al., 2006a; Lin et al., 2003b) and complicated mineralogical features (e.g., shock, melting, and recrystallization), and it contains lamellae of pyroxene, olivine, and minor ilmenite (<1 μm wide), suggesting that the plagioclase in GRV 99027 is not maskelynite but rather recrystallized plagioclase from the shock melt. These findings suggest that the meteorite experienced slower cooling than maskelynite-bearing meteorites. The shock and thermal metamorphic features therefore indicate that the parent rock of GRV 99027 could have been embedded in hot rocks, which facilitated a more protracted cooling history (Wang and Chen, 2006).

3.4 Martian meteorites

3.4.1 Petrology of Martian meteorites

Two Martian meteorites (GRV 99027 and GRV 020090) were found in the Grove Mountains; both are lherzolitic shergottites and share similar petrographic textures consisting of interstitial and poikilitic regions (Jiang and Hsu, 2012; Wang et al., 2006a; Miao et al., 2004b; Lin et al., 2003b). However, some differences in mineral composition have been reported (Jiang and Hsu, 2012; Wang et al., 2006a; Miao et al., 2004b; Lin et al., 2003b). (1) GRV 020090 contains the characteristic low olivine of lherzolitic shergottites and distinctly higher maskelynite (19 vol%) than GRV 99027. (2) Poikilitic pyroxene in GRV 020090 shows chemical zonation with a pigeonite core and augite rim, while the same is not observed in GRV 99027. (3) Olivine and pyroxene of GRV 020090 are more ferroan than GRV 99027, e.g., the olivine of GRV 020090 (poikilitic $Fa_{28–30}$, interstitial $Fa_{36–45}$) has higher FeO contents than GRV 99027 (poikilitic $Fa_{23–30}$, interstitial $Fa_{30–42}$) within different structural regions, and the pyroxenes in GRV 020090 also have higher FeO contents than GRV 99027. (4) Chromite in GRV 020090 has higher TiO_2 contents than GRV 99027. The above petrographic comparison suggests that the two specimens are not paired meteorites and likely experienced different magmatic crystallization conditions.

An Antarctic Martian meteorite (Yamato 984028) from the Japanese collection has also been studied (Hu et al., 2011). Yamato 984028 is a lherzolitic shergottite and shares a similar petrography with GRV 99027. But Yamato 984028 is not paired with GRV 99027 and other lherzolitic shergottites owing to different shock metamorphic features. Yamato 984028 was severely shocked, producing melt veins and transforming plagioclase to glass. Its melt veins are characterized by the absence of any high-pressure polymorphs, the presence of abundant small mineral fragments, and prevailing granulation textures of olivine and chromite. These features are consistent with adiabatic melting during the release of shock-induced high pressures, and quenching at ambient pressure. Hence, Yamato 984028 serves as a probe for the study of meteorite impact processes on terrestrial surfaces (Hu et al., 2011).

3.4.2 Geochemistry and petrogenesis of lherzolitic Martian meteorites GRV 99027 and GRV 020090

The trace element contents of GRV 99027 and GRV 020090 were measured and their petrogeneses are discussed on the basis of the previously described petrographic and mineralogical observations. The bulk compositions of 50 elements, including rare earth elements (REEs) and platinum group elements (PGEs), were determined using ICP-AES, ICP-MS, and the Carius-tube technique combined with ICP-MS (Lin et al., 2013a, 2008; Jiang and Hsu, 2012). GRV 99027 has a relatively lower bulk ΣREE content with a smooth and hump-shaped pattern and no Ce and Eu anomalies, which is nearly parallel to other lherzolitic shergottites (Lin et al., 2008; Wang et al., 2008a). Furthermore, its primary minerals exhibit lower ΣREE contents but olivine and pyroxene grains are enriched in heavy REE (HREE) and the plagioclase is enriched in light REE (LREE) with a large positive δEu. On the other hand, whitlockite in this sample has high ΣREE contents with a negative δEu anomaly. These REE compositions suggest that GRV 99027 is not paired with other lherzolitic shergottites, but may originate from the same Martian igneous unite (Lin et al., 2008; Wang et al., 2008a). Additionally, the bulk PGE contents of GRV 99027 are low with an unfractionated distribution pattern (except for Pd) and are not depleted in W or Ga relative to lithophile element trends. Fractionation between siderophile and lithophile elements becomes less pronounced with increasing volatility, except for high Ni and Co abundances. These characteristics are likely representative of the Martian mantle, which is consistent with previous work suggesting that the Martian mantle formed in a deep magma ocean followed by later accretion of chondritic material (Wang et al., 2008a).

Differing from GRV 99027 and other lherzolitic shergottites, GRV 020090 is relatively enriched in LREE, suggesting that GRV 020090 is an enriched lherzolitic shergottite (Lin et al., 2013a; Jiang and Hsu, 2012). However, REE patterns from the cores of pigeonite oikocrysts and olivine chadacrysts are indistinguishable from those of GRV 99027 and other moderately depleted lherzolitic shergottites and reveal the LREE-depleted pattern of a primordial parent magma. Based on the petrography and bulk composition, Lin et al. (2013a) proposed a two-stage formation model with the primordial parent magma of GRV 020090 derived from a moderately depleted Martian upper mantle reservoir and a residual melt that was later contaminated by oxidized and enriched Martian crustal materials as it ascended to the subsurface.

3.4.3 Isotopic compositions of GRV 99027 and GRV 020090 Martian meteorites

Liu et al. (2011) measured the Rb-Sr and Sm-Nd isotopic compositions of the lherzolitic shergottite sample GRV 99027 and reported a Rb-Sr mineral isochron age of GRV

99027 of 177 ± 5 (2σ) Ma with an initial $^{87}Sr/^{86}Sr$ ratio (I_{Sr}) of 0.710364 ± 0.000011 (2σ). This age is consistent with most lherzolitic shergottite ages of about 180 Ma, and also fills the small gap of I_{Sr} values between Allan Hills A77005 and Lewis Cliff 88516. These results further suggest that all lherzolitic shergottites probably come from a single igneous source on Mars (Liu et al., 2011).

H isotopic composition is an important feature of Martian meteorites (Watson et al., 1994). So the H isotopes receive particular attention upon discovery of the first Martian meteorite in the Grove Mountains (GRV 99027) (Wang et al., 2008a). Based on analyses of apatite, the δD value and H_2O contents of GRV 99027 are +1300‰ ~ +4700‰ and 0.04 ~ 0.43 wt%, respectively, and do not show a clear correlation (Wang et al., 2008a, 2006b). In contrast, Hu et al. (2014) reported a strong correlation between measured water contents and H isotopic compositions of GRV 020090 magmatic apatite inclusions using NanoSIMS. A strong logarithmic correlation indicates that Martian magma contains appreciable water that exchanges with the Martian atmosphere (Hu et al., 2014). Based on H diffusion rates, the lifetime of liquid water is estimated to be 150 thousand years. The estimated water contents of the parent magma and Martian mantle are 380–450 ppm and 38–45 ppm, respectively, which indicates that the Martian mantle is relatively water-poor relative to the Earth (Hu et al., 2014).

3.4.4 Cosmic exposure age

The abundances of cosmic nuclides ^{10}Be and ^{26}Al in GRV 99027 were measured by accelerator mass spectrometry (AMS) with obtained values of 14.1 ± 0.6 dpm·kg^{-1} and 67.5 ± 3.4 dpm·kg^{-1}, respectively (Ping et al., 2007). The cosmic-ray exposure age of GRV 99027 is therefore 4.4 ± 0.6 Ma according to ^{10}Be concentration calculations. However, the ^{26}Al concentration is too high to match with the ^{10}Be exposure age, indicating additional solar ray production. Combined with the petrologic and geochemical characteristics, the lherzolitic Martian meteorites GRV 99027, LEW 88516, Y-793605, NWA 1950 and ALHA77005 have very similar exposure ages, suggesting that these meteorites were probably ejected from Mars in the same impact event.

3.5 Lunar meteorites

Although the Apollo samples are much larger in mass than lunar meteorites, lunar meteorites provide more information on the chemical composition and evolution of the Moon because they were derived randomly from the lunar surface, and probably represent 10 possible lunar launching sites (Miao et al., 2014; Wang and Lin, 1993). The majority of lunar meteorites are breccias, aside from a small number of unbrecciated crystalline rocks. Based on their petrography, lunar meteorites can be classified into three groups: highland anorthosite, mare basalt, and mingled breccia (including feldspathic and basaltic clasts) (Miao et al., 2014).

At present, no Antarctic lunar meteorites have been discovered by Chinese expeditions, but an Antarctic lunar meteorite study has been conducted by means of international collaboration and sample loans (e.g., MIL 05035, MIL 090036, MIL 090070, EET 96008, LAP 02224). Both MIL 05035 and LAP 02224 are unbrecciated lunar basalts. MIL 05035 has a typical gabbro texture and consists mainly of coarse-grained pyroxene and plagioclase without olivine. Its important feature is the occurrence of symplectite of fayalite-hedenbergite-silica, which formed by a shock-induced transformation (Chen et al., 2015; Zhang et al., 2010b). LAP 02224 is the typical subophitic basalt consisting dominantly of pyroxene, plagioclase, and ilmenite with small amounts of magnesian olivine.

Zhang et al. (2010b) measured the zircon ages of MIL 05035 and LAP02224 and reported a Pb/Pb age of 3851 ± 8 Ma (2σ), suggesting that this sample could be paired with Asuka 881757. The magmatic event related to MIL 05035 was probably due to the late heavy impact bombardment on the Moon around 3.9 Ga. One baddeleyite grain in LAP 02224 shows a large variation of Pb/Pb ages, from 3109 ± 29 to 3547 ± 21 Ma (2σ), much older than the whole-rock age of the same meteorite (~3.02 ± 0.03 Ga). Another baddeleyite grain in LAP 02224 has an age of 3005 ± 17 Ma (2σ). This result indicates that the minimum crystallization age of LAP 02224 is ~3.55 Ga and the younger ages may reflect late thermal disturbances in the U-Pb system (Zhang et al., 2010b).

The other three meteorites, EET 96008, MIL 090036, and MIL 090070, are lunar breccias. EET96008 is a basaltic breccia, while MIL 090036 and MIL 090070 are feldspathic breccias (Xia et al., 2013; Xie et al., 2013; Yao et al., 2013). EET 96008 consists of sub-angular clasts (50.2 vol%) and matrix (49.8 vol%). The majority of clasts are crystalline, including pyroxene, olivine, feldspar, and quartz. EET 96008 has three typical shock-induced darkened areas and a considerable number of glassy clasts and shock pockets, suggesting that it experienced strong shock events above the shock stage of S5. In the shock-induced darkened area, many granulitic aggregates share the same mineral assemblage of fayalite-hedenbergite-silica with the symplectite in MIL 05035, suggesting that they probably decomposed from pyroxene under shock metamorphism (Xia et al., 2013).

MIL 090070 has a brecciated texture with many cm-sized anorthosite clasts, indicative of a typical highland anorthosite breccia (Yao et al., 2013). The lithic clasts are mainly anorthositic, primarily composite anorthositic breccia. This sample also contains a small proportion of other lithologies including gabbro, gabbroic norite, gabbroic troctolite, gabbroic, and anorthosite. The composite breccia indicates that MIL 090070 experienced many shock events and is cemented by shock-induced glassy breccias. Its composite-brecciated texture provides evidence for the process of lunar regolith formation (Yao et al., 2013). MIL 090036 has a similar brecciated texture as found in MIL 090070 and EET 96008, but with a clast component ratio of anorthosite and basalt intermediate between these two samples (Xie et al., 2013). The volume ratio of anorthositic and basaltic clasts suggests that MIL 090036 belongs to a feldspathic breccia (Xie et al., 2013).

3.6 Other meteorite types

3.6.1 Ureilites

Ureilites are special primitive achondrites, which have both "primitive" and "igneous" characteristics. Ureilite petrology and geochemistry show typical igneous features (e.g., coarse-grained crystalline texture, highly fractionated lithophile elements, *V*-shaped REE patterns), as well as primitive chondritic features including high abundances of carbon and noble gases and relatively high abundances of unfractionated siderophile elements. These complicated features have therefore led to considerable controversy regarding their origin and formation history (Miao et al., 2008b). Since the discovery of two ureilites in the Grove Mountains (GRV 021512 and GRV 022931) (Miao et al., 2008c), a total ten ureilites have been found and studied (GRV 021512, GRV 021729, GRV 021788, GRV 022408, GRV 022835, GRV 022888, GRV 022931, GRV 024237, GRV 024516, GRV 052382). Most are ordinary ureilites with a coarse-grained ureilitic texture composed of olivine and pigeonite with carbon interstitials of graphite and diamond, but others (GRV 052382, GRV 052408, GRV 022931, GRV 022888) are highly shocked or reduced ureilites.

GRV 052382 is a ureilite with strong shock effects including a fine-grained granulitic olivine texture, interstitial melt among round olivine grains, pigeonite with a large number of vesicles, kamacite veins filling fractures and vesicles, and diamond transformed from graphite. These effects suggest that GRV 052382 is likely a very heavily shocked ureilite (Miao et al., 2010, 2008a). The other three samples (GRV 052408, GRV 022931, GRV 022888) are highly reduced ureilites with cataclastic porphyritic textures composed of olivine and pigeonite relicts embedded in high volume carbonaceous interstitial material and/or reduction products, indicating they were highly reduced under high temperatures for a long period of time (Huang et al., 2014; Miao et al., 2008b).

The other six GRV ordinary ureilites share the following similar petrological features (Huang et al., 2014; Jiang et al., 2010; Miao et al., 2008b; Liang et al., 2006a): (1) a mineral assemblage consisting of olivine, pigeonite, and carbon polymorphs of graphite and diamond; (2) coarse-grained olivine and pigeonite textures usually with 120° junctions; (3) a reduction zone of olivine with higher Fa core contents and near forsterite rims; and (4) various volumes of carbonaceous interstitial material. Based on the Fa composition of olivine cores, some GRV ureilites (GRV 024516, GRV 022888, GRV 052382, GRV 052408) are classified into type I ($Fa_{15–18}$) while others (GRV 021512, GRV 021729, GRV 021788, GRV 022931) are classified into type II ($Fa_{>18}$).

The temperatures estimated by mineral pairs show that ureilites, regardless of the degree of reduction, generally have similar reduced temperatures of 1217–1229°C, which suggests that the reduction degree may result from the high temperature duration (Huang et al., 2014; Miao et al., 2008b). Ureilites are generally believed to have complicated histories involving evolving partial melts, possibly carbon-rich magma, magmatic crystallization with graphite as the liquidus phase, impact events (e.g., diamond transformation), thermal retrograde metamorphism (e.g., recrystallization of fractured olivine), and ejection away from the parent body as result of an impact (Huang et al., 2014; Jiang et al., 2010; Miao et al., 2008b; Liang et al., 2006a). In addition, noble gases analyses suggest that the GRV 024516 ureilite has a CRE age of 33.3 Ma and gas retention age of 1936.8 Ma (Wang et al., 2007), indicating that GRV 024516 is one of the ureilites with the largest cosmic-ray exposure ages. The K-Ar gas retention age 1936.8 Ma of GRV 024516 is far less than the crystallization age of ureilites, indicating that it has experienced severe thermal events (possibly a strong impact event) that caused the loss of ^{40}Ar.

3.6.2 Iron and stony iron meteorites

Seventeen iron and stony iron meteorites were among the classified GRV meteorites. Most are small with masses less than 10 g, while five are relatively large with masses greater than 10 g. The identified types include one iron (GRV 98003, 282.2 g), one pallasite (GRV 020099, 23.5 g), 12 mesosiderites, and three ordinary chondritic metal nuggets. At present, the petrology and geochemistry have only been investigated on the iron meteorite GRV 98003 and mesosiderite GRV 020175.

The iron meteorite GRV 98003 was found in the 1st expedition in the Grove Mountains and contains a complete fusion crust (Ju and Liu, 2000). GRV 98003 has a bulk (wt) composition of 82.28% Fe, 15.31% Ni, 0.31% Co, 0.02% Cu, 0.09% Zn, and 0.18% P. The kamacite is 92.4 wt% Fe, 6.80 wt% Ni, and 0.81 wt% Co; the taenite is 61.8 wt% Fe, 37.1 wt% Ni, and 0.13 wt% Co. Although GRV 98003 classified as a very fine octahedrite only by its kamacite texture (Chen et al., 2001) and as an ungrouped iron meteorite (Wang and Lin, 2002) in the earlier work, its INAA composition such as Ga, Ge, Ir suggests that GRV 98003 is an IAB (Wang and Lin, 2005). GRV 98003 contains similar texture and metallic phases as NWA 468 as well as comparable Pt, Ni, Co, Au, As, and Cu abundance patterns, although Re, Ir, Ga, Ge, and Cr concentrations are significantly lower in the former. Wang and Lin (2005) therefore proposed that GRV 98003 and NWA 468 have the same origin and probably formed on metal-rich carbonaceous chondrite parent bodies by impact melting.

Mesosiderite GRV 020175 weighs 1.54 g and is weathered significantly (Wang et al., 2010b). Wang et al. (2010b) investigated the petrology of GRV 020175 and reported roughly equal portions of silicates (43 vol%) and Fe-Ni metal phases (57 vol%). Fe-Ni metals occur in a variety of textures from irregular large masses to veins penetrating silicates to fine matrix grains. The metallic portions contain kamacite, taenite, and troilite, of which kamacite is dominant followed by troilite and taenite (Wang et al., 2010b). Silicate phases exhibit a porphyritic texture composed of a fine-grained matrix and phenocrysts of pyroxene, plagioclase, silica, and olivine. The matrix is ophitic and consists of pyroxene and plagioclase grains. Some orthopyroxene phenocrysts occur as euhedral crystals with chemical zoning from a magnesian core to a ferroan rim, while others are characterized by many fine inclusions of plagioclase composition. Pigeonite has almost inverted to its orthopyroxene host with augite lamellae enclosed by more magnesian rims. All petrographic and geochemical characteristics suggest that GRV 020175 is a mesosiderite. Based on its matrix texture and relatively abundant plagioclase, this specimen is further classified as a type 3A mesosiderite.

Mineralogical, petrological, and geochemical features of GRV 020175 imply a complex formation history. Wang et al. (2010b) proposed formation from rapid crystallization of a surface lava flow or as a shallow intrusion followed by reheating of the primary silicate minerals to 1000°C, rapid cooling to 875°C, which subsequently mixed metal with silicate. During or after this mixing, a reduction of the silicates occurred likely by a redox reaction with sulfur, and the rock underwent thermal metamorphism, which produced coronas on the olivines, rims on the inverted pigeonite phenocrysts, overgrowths on the orthopyroxene phenocrysts, and homogenized the matrix pyroxenes. In any case, metamorphism was not sufficiently extensive to completely re-equilibrate GRV 020175 (Wang et al., 2010b).

3.6.3 HED clan meteorites

Although HED clan meteorites are the most abundant among the achondrite family, only three eucrites have classified in the GRV meteorites (GRV 99018, GRV 051523, GRV 13001). GRV 13001 weighs 1299.1 g, but GRV 99018 and GRV 051523 are much smaller with masses of 0.23 g and 0.8 g, respectively. The petrology of GRV 99018 and GRV 051523 has been studied, while information on GRV 13001 has not yet been reported in the literature.

GRV 99018 is a monomict eucrite breccia consisting mainly of pyroxene (50.5 vol%) and plagioclase (37.2 vol%) with minor silica phases (7.0 vol%) and opaque minerals (5.2 vol%). The specimen is heavily shocked with the occurrence of shock veins and pockets. However, melt crystallization of shock veins and pockets indicate that the eucrite experienced thermal metamorphism after the impact event. The subsequent strong thermal metamorphism suggests that impact heating may play an important role in the differentiation of asteroids such as Vesta (Lin et al., 2004b).

GRV 051523 is a heavily shocked eucrite composed of two textures of coarse-grained gabbro and shock melt (Liu et al., 2008). The gabbroic area consists mainly of coarse- grained pyroxene and plagioclase, while the shocked melt area is a fine-grained texture composed of pyroxenes, plagioclase, and other opaque minerals. The whole rock mineral assemblage is pyroxene (62.9 vol%), plagioclase (34.2 vol%), opaque minerals (2.7 vol%), minor silica, and tiny FeO-rich olivine. The coarse-grained pyroxenes show exsolution of augite lamellae (1–3 μm in width) in pigeonite or *Cvice versa*. The pyroxene compositions are $Wo_{1.7–11.1}Fs_{48.1–59.9}$ in the gabbroic region and $Wo_{1.5–2.5}Fs_{56.8–59.2}$ in the shocked region. The plagioclase compositions are $An_{90.2–92.2}$ in the gabbroic region and $An_{85.7–90.8}$ in the shocked region. These texture features, tiny or needle-like oriented chromite inclusions, and occurrence of homogeneous pyroxene compositions indicate that GRV 051523 experienced intense thermal metamorphism after the main shock event. This specimen can therefore provide additional constraints on the chemical composition, magmatic differentiation, multi-stage shock history, and thermal evolution of Vesta (Liu et al., 2008).

3.6.4 Winonaite

GRV 021663 is the only winonaite meteorite found in the GRV and is highly weathered (W3) and weakly shocked (S2). GRV 21663 has an equigranular texture in which 120° junctions occur commonly. Its mineral assemblage is olivine ($Fa_{5.4}$), orthopyroxene ($Fs_{4.7}Wo_{3.0}$), chromian diopside ($En_{53.6}Fs_{2.4}Wo_{44}$), troilite, kamacite, and plagioclase ($Ab_{74.5}Or_4An_{21.5}$). Minor phases include schreibersite and *K*-feldspar. The bulk oxygen isotopic composition is $\delta^{18}O$ (7.50 ‰) and $\delta^{17}O$ (3.52 ‰). GRV 021663 was originally classified as an acapulcoite but comparisons of these data with other primitive achondrites resulted in its reclassification as a winonaite (Li et al., 2011a).

The occurrence of troilite, metal, and schreibersite in GRV 021663 indicate that these minerals were once completely molten. Euhedral inclusions of pyroxene within plagioclase further suggest crystallization from a silicate melt, while the depletion of plagioclase, metal, and troilite indicates that GRV 021663 could represent a residuum following partial melting on its parent asteroid. Trace element distributions in silicate minerals do not, however, confirm this scenario. The formation of GRV 021663, as well as other winonaite meteorites, has been proposed to likely relate to brecciation and mixing of heterogeneous lithologies, followed by varying degrees of thermal metamorphism on the parent body asteroid. Peak metamorphic conditions may have resulted in localized partial melting of metal and silicate mineralogies, but the data remain inconclusive (Li et al., 2011a).

3.6.5 E/H meteorites

GRV 020043 is a possible transition chondrite between the E and H groups, and has the same mineral assemblage as ordinary chondrites (Li et al., 2011b). This specimen has a typical chondritic texture and similar mineral assemblage as H chondrite, composed of low-Ca pyroxene (40 vol%), olivine (24 vol%), diopside (8 vol%), plagioclase (10 vol%), Fe-Ni metal (14 vol%), troilite (4 vol%), and trace amounts of chromite and apatite. The main silicates are compositionally homogeneous, e.g., olivine ($Fa_{10.4–12.4}$) and low-Ca pyroxene ($Fs_{10.1–11.6}$). Some chondrules in this meteorite are well defined with sharp edges and an abundance of 37 vol%. The matrix is moderately recrystallized. However, the chemical compositions of minerals in GRV 020043 are beyond those of OC and very near enstatite chondrite. Based on its mineral chemistry, olivine model abundance, and oxidation intensity, Li et al. (2011b) suggested a transition classification for this chondrite between E and H groups with a type 4 petrologic type.

4 Discussion and conclusions

4.1 Status and problems of the Antarctic meteorite survey

Since the discovery of the first four meteorites in the Grove Mountains in 1998/1999, CHINARE has carried out a meteorite survey in Antarctica for 20 years. At present, CHINARE has collected a vast number of meteorites and identified a new meteorite concentration region: the Grove Mountains. At the same time, China has also conducted several studies of Antarctic meteorites and made a considerable contribution to meteorite science. These achievements can be summarized as follows. (1) The Antarctic meteorite collection now contains more than 12000 samples, making China a leading country in Antarctic meteorites. (2) A new inland Antarctic meteorite concentration site has been identified, which may be one of the richest meteorite sites in Antarctica. (3) The Antarctic meteorite depository and its resource-sharing platform have been established and PRIC is responsible for the curation of Antarctic meteorites. (4) More than 3400 meteorites have been classified using nomenclature of the international meteorite society. (5) A series of studies on the petrology and geochemistry of Antarctic meteorites have been conducted with substantial contributions made to the field (e.g., Martian meteorites and ureilites).

Nevertheless, some problems or shortcomings exist in the undertaking of this meteorite work, compared to ANSMET and JARE (Japanese Antarctic Research Expedition):

(1) Because of its limited logistics support system, the Chinese meteorite survey is presently constrained to the Grove Mountains region. As seven surveys continue to look for meteorites in the Grove Mountains, the number of collected meteorites is annually declining and the general masses of meteorite samples are becoming considerably smaller.

(2) In the last seven field seasons of expeditions in the Grove Mountains, the meteorite survey has only been a supplementary task alongside the main geology and glaciology survey, and a professional meteorite search team has not yet been set up. In order to develop Antarctic meteorite study for long term, a professional team for meteorite expeditions is necessary.

(3) Since 1999, meteorite classification has been on-and-off work. During the construction of the Resource-sharing Platform of Polar Samples, including the meteorite depositary in 2006–2008, the classification of 2450 meteorites was completed by eight scientific groups under a project involving the Experimental Standardization and Sharing of Polar Region Biological and Geological Samples (No. 2005DKA21406). Since 2011, small numbers of meteorite samples, usually a few hundred samples a year, have been classified by Guilin University of Technology, which, for more a >20000-piece inventory, is far too slow.

(4) Although Antarctic meteorites have been curated and managed in the meteorite depositary by PRIC since 2000, there are presently no professional workers for the daily curation of the meteorite depositary.

(5) Because of historical reasons involving national development in cosmochemistry and planetary sciences, Chinese research teams within meteorite research and cosmochemistry remain relatively small.

4.2 Prospect for Antarctic meteorites

Antarctic meteorites are not only a precious scientific research resource for cosmochemistry and planetary sciences but also of great significance for witnessing the evolution of the Antarctic ice sheet. Antarctic meteorite studies are undoubtedly an important field within Antarctic sciences, which is fully illustrated by the sustained meteorite survey and achievements of the United States for more than 30 years (Righter et al., 2014). In order to better promote the development of space science research and Antarctic scientific research, China will need to increase its funding into the field survey of Antarctic meteorites and draw a road map for future decades. According to the long-term development goals of CHINARE, some preliminary ideas about the development of China's Antarctic meteorite program are suggested as follows.

(1) Researchers should be encouraged to apply for National Natural Science Foundation of China (NSFC) for projects related to Antarctic meteorites in order to increase the intensity on their search, recovery, and study. Especially, NSFC should be used to not only support research but also fund for meteorite survey in Antarctic or Gobi desert. Since the Antarctic meteorite concentration operates under two main factors of meteorite accumulation (e.g., direct infall over a long period of time and the glacial movement

mechanism that concentrates meteorites in the ice sheet), the Antarctic meteorite survey should pay particular attention to the relation between Antarctic meteorites and the evolution of the Antarctic ice sheets.

(2) Antarctica is a very special geographical albeit dangerous place with complicated conditions for work and expedition. In order to promote efficiency and ensure success, a special meteorite expedition team should be established. Certain experiences of an Antarctic meteorite survey have been mastered after seven expeditions; however, a stable and professional team is lacking. The field work involved in an Antarctic meteorite search includes challenging exploration and danger, such that team staff should possess appropriate field experience and ability in Antarctica. A professional meteorite search team should therefore be organized as soon as possible.

(3) In order to obtain deeper insight into the meteorite concentration mechanism, it is of great importance to conduct a comparative study of different meteorite concentration sites. After more than 30 expeditions in Antarctica, China has established a relatively complete logistics system, including five Antarctic stations and one ice breakers. During the 13th five-year plan (2016–2020), CHINARE will also set up an air transportation system to support and serve field expeditions, which will be a good opportunity to search for meteorites in areas beyond the GRV region, such as the Charles Prince Mountains and Victoria Lands.

(4) Cosmic dust is a type of very fine extraterrestrial material, generally smaller than 2 mm, which can be classified as micrometeorites (50 μm to 2 mm) and interplanetary dust particles (<50 μm) (Taylor et al., 2016). Cosmic dust is of great scientific value. Many of such dust particles are unique samples of asteroid bodies unlike any meteorite; they include the least processed remnants of the Solar System's starting materials. Some primitive particles contain interstellar dust grains and primordial organic matter, while other particles retain evidence of the inner workings of minor planets and the dynamical evolution of the asteroid belt (Taylor et al., 2016). In recent decades, a substantial amount of cosmic dust has been collected in Antarctic ice, snow, and glacial sediments and will hence become an important aspect of future Antarctic expeditions (Ventura Bordenca et al., 2015; Yada and Kojima, 2000; Wang and Dai, 1995). Chinese participation in the study on Antarctic comic dusts is therefore suggested.

(5) Antarctic meteorites are a precious scientific resource. Therefore, in order to make best use of the GRV meteorite collection, publicity aimed towards developing international collaboration into GRV meteorite research should be increased.

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