Lunar meteorites: witnesses of the composition and evolution of the Moon

MIAO Bingkui[1,2*], CHEN Hongyi[1,2], XIA Zhipeng[1,2], YAO Jie[1,2], XIE Lanfang[1,2], NI Wenjun[1,2] & ZHANG Chuantong[1,2]

[1] Guangxi Scientific Experiment Center of Mining, Metallurgy and Environment, Guilin University of Technology, Guilin 541004, China;

[2] Key Laboratory of Hidden Metallic Ore Deposits Exploration, Guilin 541004, China

Abstract   Lunar meteorites are fragments of the Moon that escaped the gravity of the Moon following high-energy impacts by asteroids, subsequently fell to Earth. An inventory of 165 lunar meteorites has been developed since the discovery and identification of the first lunar meteorite, ALHA 81005, in 1979. Although the Apollo samples are much heavier in mass than lunar meteorites, the meteorites are still an important sample supplement for scientific research on the composition and history of the Moon. Apart from a small amount of unbrecciated crystalline rocks, the majority of lunar meteorites are breccias that can be classified into three groups: highland feldspathic breccia, mare basaltic breccia, and mingled(including fledspathic and basaltic clasts) breccia. The petrography of lunar rocks suggests that there are a series of rock types of anorthosite, basalt, gabbro, troctolite, norite and KREEP in the Moon. Although KREEP is rare in lunar rocks, KREEP components have been found in the increasing number of lunar meteorites. KREEP provides important information on lunar magmatic evolution, e.g., the VHK KREEP clasts in SaU 169 may represent the pristine lunar magma (urKREEP). Six launching pairs of lunar meteorites have been proposed now, along with ten possible lunar launching sites. In addition, symplectite is often found in lunar basalts, which is a significant record of shock metamorphism on the lunar surface. Furthermore, isotopic ages and noble gases not only provide information on crystallization processes in lunar rocks and the formation of lunar crust, but also provide insight into shock events on the lunar surface.

Keywords   lunar meteorites, KREEP rocks, KREEP, launching pair, launching sites

1 Introduction

As we know, meteorites are relics of other planets and asteroids found on the Earth's surface, after they have passed through the Earth's atmosphere. They provide 'fossil evidence' for the different evolutionary stages of the solar system. Obviously, the meteorites are the only easily accessible witnesses to the evolution of the solar system and also an important window to its origin[1]. Based on whether or not magmatic differentiation is experienced, meteorites can be classified either as chondrites or as differentiated meteorites. Chondrites are primitive materials that condensed in the primordial solar nebula, and differentiated meteorites are products of the thermal metamorphism or magmatism that occurred in their parent body asteroids and planets, e.g., Martian meteorites and lunar meteorites. Since the early 1970s, numerous meteorites have been found in the cold and hot deserts[2-3]. Hence, rapid progress has occurred

---

* Corresponding author (email: miaobk@glut.edu.cn)

in meteoritics and cosmochemistry, resulting in great breakthroughs in some fields such as lunar meteorites[1]. Since the first lunar meteorite (ALHA 81005) was discovered[4] in 1982, a collection of 165 lunar meteorites, with a total mass of 65.2 kg and representing 81 pairs, has been catalogued (Table 1). Although these lunar meteorites cannot compete with Apollo and Luna samples in terms of mass, they should have a wider range of sources on the Moon's surface, e.g., the Dho 489 and Y86032 meteorites probably came from marginal areas of the Moon's near side[5-6] which was not a target of lunar landings. Lunar meteorites, therefore, provide supplementary samples that can be used for research on the formation and evolution of the Moon[7]. In addition, in contrast with the Apollo samples, lunar meteorites can be used in other ways to investigate the rock types found in the lunar crust, the noble gases on the Moon's surface, solidification processes in loose lunar soil that somehow enable the formation of meteorites, the impact history of the Moon's surface, and so on[8]. The advances in lunar meteorite research in recent years[9-14], have been summarized in the work of Wang and Lin[7] and Korotev[15].

2 The discovery history and quantity of lunar meteorites

The discovery of lunar meteorites began in the early 1980s. The first lunar meteorite ALHA 81005 was identified in 1982, more than 10 years after samples of the lunar regolith were returned by the Apollo and Luna projects[4]. ALHA 81005 was collected by the American Antarctic Search for Meteorites (ANSMET) program from Allan Hills in Antarctica, and was sent to NASA's Johnson Space Center in Houston for treatment and preservation. The Johnson Space Center is responsible for the treatment and preservation of Apollo lunar samples; its workers are familiar with lunar samples and realized that ALHA 81005 probably came from the Moon owing to similarity in its texture to lunar samples[16]. In fact, a lunar meteorite (Y791197) had been collected prior to the identification of ALHA 81005, but it had been misclassified as a eucrite. Before long, Y791197, Y82192 and Y82193 were identified as the second, third, fourth lunar meteorites, respectively[17]. Meteorites Y793169 and EET87521 were also mistaken for eucrites in their original classification but later identified as lunar meteorites[16].

Lunar meteorites are very rare; hence finding them is difficult and slow. By 1993, only 12 lunar meteorites had been found, of which 11 were from Antarctica. Just one was non-Antarctic, this one from Calcalong Creek in Australia[7,18]. At that time, the asking price for the Calcalong Creek meteorite was up to $40 000 US/g, which created public motivation in the hunt for lunar meteorites[15]. It was not too long before a second non-Antarctic lunar meteorite was found in 1997[19]. By 2000, the global collection of 31 lunar meteorites was still largely from Antarctica. However, after 2000, new successes were made in finding lunar meteorites in the African deserts,

and from then on, the quantity and quality of lunar meteorites has dramatically increased. As of this writing, 165 lunar meteorites have been catalogued with a total mass of 65.2 kg, representing 81 fall events. They include 10 mare basalts, 50 anorthosites, and 21 anorthositic-basaltic mingled breccias (Table 1). The distribution of their collection sites shows that the majority of the lunar meteorites are actually not from Antarctica, but rather from desert areas.

3 Petrologic classification of lunar meteorites

Without the protection of an atmosphere, the Moon has experienced strong impacts throughout its history, resulting in a great number of surface impact craters of all sorts and sizes. Also, a veneer of loose lunar soil, or regolith breccia, ranging in thickness from a few to more than 20 m covers all of the Moon's surface[20]. The Apollo lunar rock sample collection has confirmed that the constituent features of the lunar surface are covered in a loose regolith[21]. Furthermore, the petrography of lunar meteorites also confirms the dominance of regolith features on the lunar surface; with the exception of a small number of unbrecciated basalts, the vast majority of lunar meteorites are breccias. Based on their texture and mineral assemblage, lunar meteorites can be divided into three groups: basalt, anorthosite, and mingled breccias. These groups correspond to three origin regions: the maria, the highlands, and the transitional areas between maria and highland[20]. In addition, based on petrologic characteristics and chemical composition, lunar meteorites should have three lithological end members[15]: (1) brecciated anorthosites, with high Al_2O_3 content (26–31 wt%), low FeO content (3–6 wt%) and a low incompatible element component (e.g., <1 $\mu g \cdot g^{-1}$ Th); (2) basalts and brecciated basalts, with high FeO content (18–22 wt%), medium Al_2O_3 content (8–10 wt%), and medium incompatible element component (e.g., 0.4–2.1 $\mu g \cdot g^{-1}$ Th); (3) impact-melt glasses with a norite composition (16 wt% Al_2O_3, 11 wt% FeO), and a very high incompatible element component (33 $\mu g \cdot g^{-1}$ Th), i.e., the KREEP.

Of the 165 catalogued lunar meteorites, 25 have crystalline and unbrecciated textures that classify them as either basalts or gabbros (Table 2). These 25 meteorites represent 10 pairs in which meteorites NEA 003, Northwest Africa 773/2700/2727/2977/3160/3170/3333/ 6950/7007/ Anoual, and Dhofar 287 are polymict rocks that are composed of basalts+breccias, olivine gabbros+basalts+ferro-gabbro+breccias, and basalts+breccias, respectively. Generally, the unbrecciated basaltic lunar meteorites share the following characteristics. (1) They have the same mineral assemblages as basalts and/or gabbros, consisting mainly of variable amounts of plagioclase, pyroxene, olivine, and ilmenite. (2) They have sub-ophitic and ophitic textures, which vary from fine-grained to coarse-grained, and some are even very coarse-grained, e.g., Asuka 881757 and MIL 05035 which have a coarser-grained gabbro texture[22]. The one

Table 1 The collection of lunar meteorites

Name	Region found	Meteorite types	Year found	Piece number	Number of pairs	Mass/g
Allan Hills A81005	Antarctica	feldspathic regolith breccia	1982	1	1	31.4
Asuka 881757	Antarctica	Gabbro	1988	1	1	442
Calcalong Creek	Australia	Basalt-bearing feldspathic regolith breccia	1990	1	1	19
Dar al Gani (DaG)1042/1048		feldspathic breccia	1999/2001	2	1	802
Dar al Gani (DaG)262/996;400/1058	Libya	feldspathic regolith breccia	1997-1999	4	2	3765.3
Dhofar 925/960/961;1180		basalt-bearing feldspathic impact-melt breccia	2003/2005	4	2	227
Dhofar 1629		mingled breccia	2007	1	1	2.51
Dhofar 1442		Mingled regolith breccia	2005	1	1	106.5
Dhofar 733		feldspathic granulitic breccia	2002	1	1	98
Dhofar 026/457-468		feldspathic granulitic breccia	2000/2001	13	1	708.8
Dhofar 302;303/305-307/309-311/489/730/731/908/909/911/950/1085;1527;1627	Oman	feldspathic impact-melt breccia	2001/2009/2010	18	4	1169.78
Dhofar 1436/1443;1528;1673;1669		feldspathic breccia	2004/2001;2009-2011	5	4	292.3
Dhofar 490/1084;1428		feldspathic fragmental breccia	2001/2003;2006	3	2	337.1
Dhofar 081/280/910/1224		feldspathic fragmental breccia	1999/2001/2003	4	1	571.57
Dhofar 025/301/304/308		feldspathic regolith breccia	2000/2001	4	1	772
Dhofar 287		mare basalt with regolith breccia	2001	1	1	154
Elephant Moraine (EET) 87521/96008	Antarctica	basaltic or gabbroic fragmental breccia	1987/1989	2	1	84
Graves Nunataks (GRA) 6157	Antarctica	feldspathic breccia	2007	1	1	0.8
Jiddat al Harasis (JaH) 348	Oman	feldspathic fragmental breccia	2006	1	1	18.7
Kalahari 008/009	Botswana	mingled breccia	1999	2	1	14098
LaPaz Icefield (LAP) 02205/02224/02226/02436/03632/04841	Antarctica	mare basalt	2002-2004	6	1	1930.3
Larkman Nunataks 06638	Antarctica	feldspathic breccia	2007	1	1	5
Lynch 002	Australia	mingled breccia	2010	1	1	36.5
MacAlpine Hills (MAC) 88104/88105	Antarctica	feldspathic regolith breccia	1989	2	1	724
Meteorite Hills (MET) 01210	Antarctica	basalt-bearing feldspathic regolith breccia	2000	1	1	22.83
Miller Range (MIL) 05035		mare basalt	2005	1	1	142
Miller Range (MIL) 07006	Antarctica	feldspathic regolith breccia	2007	1	1	1.368
Miller Range (MIL) 090034/090036/090070/090075		feldspathic regolith breccia	2009	4	1	721.6
Northeast Africa (NEA) 003	Libya	mare basalt (containing breccia)	2000-2001	1	1	124

(Continued)

Northeast Africa (NEA) 001	Sudan	feldspathic regolith breccia	2002	1	1	262
Northwest Africa (NWA) 4472/4485		Anorthosite-bearing basaltic breccia	2006	2	1	252.3
Northwest Africa (NWA) 3136; 4884		anorthosite-bearing basaltic regolith breccia	2004; 2007	2	2	137.1
Northwest Africa (NWA) 7611		basalt-bearing feldspathic fragmental breccia	2012	1	1	916
Northwest Africa (NWA) 2995/2996/3190/4503/5151/5152/6252/6554/6555		basalt-bearing feldspathic regolith breccia	2005-2010	9	1	1760.7
Northwest Africa (NWA) 773/2700/2727/2977/3160/3170/3333/6950/7007/Anoual		Gabbro (containing basalt and basalt-bearing regolith breccia)	2000/2007/2011	10	1	2967.8
Northwest Africa (NWA) 032/479; 4898; 4734	Northwest Africa	mare basalt	1999/2001; 2006-2007	4	3	1965
Northwest Africa (NWA) 5744; 6578		feldspathic granulitic breccia	2009; 2010	2	2	1808
Northwest Africa (NWA) 482		feldspathic impact-melt breccia	2000	1	1	1015
Northwest Africa (NWA) 2200;3163/4483/4881/6275;2998/7262;5000;4932;4936/5406/6221/6355/6470/6570/6687/7190;7274;7493		feldspathic breccia	2004-2012	19	8	17982.4
Northwest Africa (NWA) 6481;6721;7022; 6888;		feldspathic fragmental breccia	2010-2011	4	4	846.7
Northwest Africa (NWA) 4819		Mingled regolith breccia	2007	1	1	234
Northwest Africa (NWA) 5207;5153		mingled fragmental breccia	2007	2	2	151
Pecora Escarpment (PCA) 02007	Antarctica	feldspathic regolith breccia	2002	1	1	22.4
Queen Alexandra Range (QUE) 94281	Antarctica	anorthosite-bearing basaltic regolith breccia	1994	1	1	23
Queen Alexandra Range (QUE) 93069/94269		feldspathic regolith breccia	1993/1994	2	1	24.5
Sayh al Uhaymir (SaU) 169		basalt-bearing feldspathic regolith breccia	2002	1	1	206
Sayh al Uhaymir (SaU) 449	Oman	feldspathic impact-melt breccia	2006	1	1	16.5
Sayh al Uhaymir (SaU) 300		feldspathic breccia	2004	1	1	153
Shişr 162;166		feldspathic impact-melt breccia	2006;2008	2	2	5658.8
Shişr 161	Oman	feldspathic fragmental breccia	2008	1	1	57
Shişr 160		feldspathic regolith breccia	2008	1	1	101
Yamato 793274/981031		anorthosite-bearing basaltic regolith breccia	1980/1999	2	1	194.7
Yamato 983885		basalt-bearing feldspathic regolith breccia	1999	1	1	290
Yamato 793169	Antarctica	mare basalt	1979	1	1	6.1
Yamato 82192/82193/86032		feldspathic fragmental breccia	1982/1986	3	1	712
Yamato 791197		feldspathic regolith breccia	1979	1	1	52.4
	Total			165	81	65223.758

Data from the website of the Astromaterials Acquisition and Curation Office, NASA (http://curator.jsc.nasa.gov/antmet/lmc/lunar_meteorites.cfm)

exception is meteorite NWA032/479, which has a porphyritic texture[23]. (3) One of the main minerals, plagioclase, is Ca-rich which contrasts strongly with Earth basalts and gabbros. Lunar plagioclase is mostly anorthite, commonly with an An of more than 90, and some feldspar grains are chemically zoned, e.g., NWA4734, Dhofar 287 and Asuka881757[22]. In addition, some lunar anorthosite grains are maskelynized by impact processes. (4) The pyroxene in lunar meteorites is mainly monoclinic, either CaO-rich or FeO-rich. (5) They usually contain the accessary mineral ilmenite, with a typical abundance of about 1% by volume.

Except for the unbrecciated basalts, most lunar meteorites are breccias. Their main protoliths are highland anorthosites and/or mare basalts. Because of the high-energy

Table 2 Petrographic characteristics of unbrecciated basaltic lunar meteorites

Meteorite name	Mass/g	Meteorites types	Petrology	Mineralogy
Yamato 793169	6.1	basalt	A sub-ophitic texture consisting of iron-rich pyroxene and feldspar (partial maskelynization). The mineral assemblage is pigeonite 56 vol%, plagioclase 42 vol%, ilmenite 1 vol%, titanium spinel 1 vol%. Pigeonite is coarse-grained with the size up to 3 × 1mm. Plagioclase is lath in shape,with the size up to 1×0.5 mm.	Plagioclase is Ca-rich with An88-97.5. Pigeonite has a composition of En1.9-53.5, Fs22.2-84.3, Wo9.7-40.7. Olivine is fayalite (Fa98.5).
Asuka 881757	442	gabbro	A coarse-grained sub-ophitic texture that consists of pyroxene, plagioclase, and small amounts of ilmenite, troilite, olivine, apatite, silicon phase (quartz?), Fe-Ni alloy with the grain size of 3-4 mm.	Pyroxene has a wide composition range (En7.8-43.6, Fs30.7-68.2, Wo11.6-40.9) Iron-rich olivine (Fa86.6-94.6) occurs as in symplectite lamellae (10-30 μm). Plagioclase (An88-96) is completely converted to maskelynite.
Northwest Africa 032, 479	~300/156	basalt	A porphyritic texture. The phenocrysts are olivine, pyroxene and chromite. The fine-grained matrix is composed of elongated pyroxene, plagioclase, opaque minerals (ilmenite, troilite, and trace metal). Olivine phenocrysts (12 vol%) is up to 300 μm in size, with chromite inclusions.	Olivine is the most abundant and the largest grain in phenocrysts. Its core is rich in Mg (Fo66), while its rim is rich in FeO (Fo50). It contains chromite inclusions. Olivine in matrix is fine-grained (1-3 μm) and iron-rich (Fo15-30). Pyroxene in phenocrysts has two ranges of composition: En40-50, Wo20-40 and En15-25, Wo10-20. The pyroxene in matrix is relatively rich in FeO (En5-25, Wo15-30). The plagioclase abundance in the matrix is high and rich in CaO (An80-90).
Northeast Africa 003	124	basalt (contain breccia)	It has two portions of 75% unbrecciated mare basalt and 25% basaltic breccia. The mare basalt shows a porphyritic texture in which there are olivine, ilmenite and spinel inclusions embedded in pyroxene. There are many shock melt veins in it. Basaltic breccia contains two basalt clasts which its mineral assemblage is olivine, plagioclase and pyroxene. Plagioclase is shocked into maskelynite.	The pyroxene has a large composition of En5-71, Wo6-38, Fs18-83. Plagioclase is An84-92 in composition. Olivine has Fo73-79.
Northwest Africa 773, 2700, 2727, 2977, 3160, 3170, 3333, 6950, 7007, Anoual	633, 31.7, 191.2, 233, 34, 60, 33, 6, 1649, 91, 5.9	polymict breccia consisting mainly of olivine gabbro	Olivine gabbro and breccia composition. The olivine gabbro consists of olivine (50 vol%) and pyroxene (30-40 vol%). Its pyroxene has two kinds of high-Ca and low-Ca. The breccia contains iron pyroxene. There is olivine-hedenbergite-quartz symplectite in it.	Olivine gabbro : olivine Fo66-72, mean 68. Pyroxene has two composition peaks of Wo36En50 and Wo11En65, and its maximum Fs is 66. Plagioclase has the composition of An90Ab10. Basaltic breccia: plagioclase is An80-96, olivine is Fo55-66, pyroxene Fs is up to 33 with mean Wo20.
Dhofar 287	154	basalt	It has two portions of 95% basalt and 5% regolith breccia. The basalt has a porphyritic texture which has olivine and augite phenocrysts (up to 1mm in size) embedded in the matrix of plagioclase, pyroxene, pyroxferroite, apatite, ilmenite, titanium-rich chromite, titanium spinel, baddeleyite, quartz, Jinghai stone, troilite. Abundances of minerals are pyroxene 49 vol%, maskelynite 26 vol%, olivine 18 vol%, opaque minerals 4 vol%, impact melt 2 vol%.	Basalt parts: Olivine occur as two forms, one is coarse-grained MgO-rich phenocrysts (Fa30-55), another is fine-grained iron olivine (Fa85-100). Pyroxene also has two forms, one is augite phenocrysts Wo30-40, En38-45, the other is fine-grained with Wo10-25, En2-50. All plagioclase is converted into maskelynite (An75-85).

(Continued)

La Paz Icefield 02205, 02224, 02226, 02436, 03632, 04841	1226.3, 252, 244, 59, 93, 56	basalt	A coarse-grained (up to 1.5 mm) sub-ophitic texture consisting mainly of, pyroxene (0.5 mm) and plagioclase (1 mm). The mineral assemblage is pyroxene 55 vol%, plagioclase 30vol%, olivine 3 vol%, ilmenite 5 vol%, iron olivine 5 vol%, cristobalite 2 vol%, and other less amounts of minerals of spinel, troilite, iron-nickel metal and so on. Pyroxene and olivine have wavy extinction. There are shock melt veins and melt pockets in it.	Pyroxene: Fs22-77, En2-55, Wo11-36, Fe/Mn is about 60. Plagioclase: An85-91, Or0-1. Olivine: Fo46-63.
Miller Range 05035	142	gabbro	A coarse-grained gabbro texture consisting of pyroxene (60.2 vol%), plagioclase (27.3 vol%), olivine (6.05 vol%), quartz (4.36 vol%), ilmenite (1.25 vol%) and troilite (0.84 vol%). Symplectite is well developed. Plagioclase is transformed into maskelynite. Quartz is converted partly into silica glass. There are shock veins and melt pockets.	The pyroxene has a chemical zone with the Fe-Ca-poor and Mg-rich core (Fs41.9, Wo 26.3, En31.8) and the Fe-Ca-rich and Mg-poor rim. Plagioclase is An79.8-94.6 with average 91.0. Olivine occurs as two forms, one is coarse mineral crystals (Fa95.5-96.6, mean 97.7), the other is in symplectite (Fa88.9-93.5, mean 90.6).
Northwest Africa 4898	137	basalt	An intergranular texture consisting of plagioclase, pyroxene and bone-like ilmenite. Olivine is euhedral-subhedral often containing Ti-rich chromite inclusions. Ca-rich plagioclase is transformed into maskelynite. Pyroxene has two kinds of Ti-rich pigeonite and augite.	Plagioclase: Calcium-rich, An92.6-96.5; Olivine; it has a chemical zonation with the FeO-poor core (Fa26.3; FeO/MnO=75.8; CaO=0.26-0.82wt%) and the FeO-rich rim (Fa44.1; FeO/MnO=151; CaO=0.28-0.38 wt%); Pigeonite: Fs25.1-44.8, Wo10-19.9; Augite: Fs25-58.7, Wo20.2-38.3; A small amount of iron-rich pyroxene, Fs72.4-75.6Wo10.8-23.9.
Northwest Africa 4734	1372	basalt	A sub-ophitic texture mainly consisting of pyroxene (58.0 vol%), feldspar (30.6 vol%), small amounts of olivine (3.8 vol%), ilmenite (2.2 vol%), silicon phase (1.5 vol%) , chromite (2.2 vol%) and picotite (0.7 vol%).	Pyroxene has a wide range of composition (Fs21-66, Wo10-42, En5-57) that is from pigeonite to augite, as well as a small amount of hedenbergite. Plagioclase is subhedral laths (An79-92, Ab8-18, Or0-3) with chemical zonation of the Ca-rich core and the NaK-rich rim. Partial plagioclase is transformed to maskelynite. Olivine has two occurrences of phenocryst (average Fa50, ~500 μm) and fine-grained inclusion (average Fa57, <100 μm).

Data from the website of the Astromaterials Acquisition and Curation Office, NASA (http://curator.jsc.nasa.gov/antmet/lmc/lunar_meteorites.cfm)

impacts on the Moon's surface that lead to the ejection of material into space, some lunar breccias contain rocks or clasts other than anorthosite and basalt, e.g., KREEP. Generally, lunar meteorite breccias are composed of rock clasts, mineral clasts, impact-melt clasts, and glass clasts in an abundant fine-grained matrix. The rock clasts include various rock types such as anorthosite, basalt, granulite, gabbro, troctolite, pyroxenite, and peridotite, which could be classified by the criteria of Stöffler[24]. As of this writing, records for 140 lunar meteorites breccias from 71 paired meteorites have been updated; the details are as follows:

1. 1 basaltic or gabbroic breccia (2 pieces, 84 g)
2. 50 feldspathic breccias (105 pieces, 38 731.4 g)
(1) 4 feldspathic granulitic breccias (16 pieces, 2 614.8 g);
(2) 8 feldspathic impact-melt breccias (22 pieces, 7 860.1 g);
(3) 17 feldspathic breccias (30 pieces, 19 236.9 g);
(4) 10 feldspathic fragmental breccias (16 pieces, 2 543.1 g);
(5) 11 feldspathic regolith breccias (21 pieces, 6 476.6 g).

3. 20 mingled breccias (33 pieces, 18 677 g)
(1) 4 anorthosite-bearing basaltic regolith breccias (5 pieces, 354.8 g);
(2) 2 anorthosite-bearing basaltic impact-melt breccias (4 piece, 227 g);
(3) 1 basalt-bearing feldspathic fragmental breccias (1 pieces, 916 g);
(4) 6 basalt-bearing feldspathic regolith breccias (14 pieces, 3214.5 g);
(5) 2 mingled fragmental breccias (2 pieces, 151 g);
(6) 2 mingled regolith breccias (2 pieces, 340.5 g);
(7) 3 mingled breccias (4 pieces, 14 137 g).

Based on petrological data, lunar breccia meteorites generally have the following characteristics. (1) The lithology of rock clasts in brecciated lunar meteorites is consistent with lunar rocks, i.e., anorthosite, basalt and mingled basalt-anorthosite. (2) The distributions of the number and mass of lunar meteorites are shown in Figure 1. The ratios of the

number, paired number and mass distribution (except the mingled breccias) of anorthositic lunar meteorites to basaltic lunar meteorites are 3.9∶1, 4.5∶1 and 5∶1, respectively. As the number of lunar meteorites has grown, they gradually show a clear relationship to provenances within lunar highland and mare regions (5∶1); in particular, the mass proportion is identical to that of the landscape areas. However, the paired number rate of anorthositic and basaltic lunar meteorites was only 4.5∶3.5 in the collection of meteorites available in 1993[7]. This indicates that the proportion of anorthositic and basaltic lunar meteorites is related to the landscape source area proportion along with the increasing of lunar meteorite samples in the collection; additionally, this also suggests that lunar meteorites randomly come from locations all over the surface of the Moon. (3) The major element compositions of lunar meteorites agree with the corresponding lunar rock types.
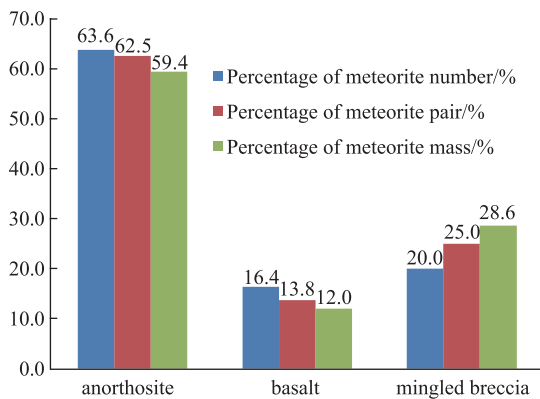
Figure 1 Histogram of anorthositic and basaltic lunar meteorite distributions.

4 The geochemistry of lunar meteorites

Compared with Earth, the structure and composition of the lunar surface is much simpler. Similarly, the mineral assemblages of lunar meteorites are simpler as well. Four main minerals: plagioclase, pyroxene, olivine and ilmenite, along with their relevant glasses formed by shock, account for almost 98% of the mineral components of lunar meteorites[15]. Therefore, the four minerals and their variations play a crucial role in the geochemistry of both the Moon and lunar meteorites. The contents of quartz and orthoclase in lunar meteorites are very low and are closely related to the KREEP component; however, they also have an important influence on lunar geochemistry. The major and trace element geochemical characteristics of lunar meteorites are briefly summarized here.

4.1 Mineral composition

Feldspars: The vast majority of feldspars in lunar meteorites are plagioclase, which is Ca-rich, and largely anorthite. Generally, the An of plagioclase in lunar meteorites ranges from 83 to 99. However, the plagioclase has slight variations in chemical composition with different occurrences. In lunar

breccia meteorites, the plagioclase has a larger compositional range with An ranging from 62 to 98. In basalt, the plagioclase usually has higher An, ranging from 95 to 98. As mentioned above, the other feldspar in lunar meteorites is orthoclase, but this is very rare and commonly occurs as KREEP-rich clasts or glass debris. The orthoclase usually has a relatively high K_2O content (generally Or<5), in which the Or can be up to 60–80.

Pyroxene: The pyroxene in lunar meteorites has assorted compositions, e.g., augite, enstatite, hedenbergite, and pigeonite[9]. In mare basalts, the pyroxene is mainly augite, which usually has compositional zonation with a MgO-rich, FeO-CaO-poor core (En31.8Wo26.3Fs41.9) and a MgO-poor, FeO-CaO-rich rim (En9.10Wo33.4Fs57.5). In feldspathic breccias, there are two kinds of pyroxene: Ca-poor orthopyroxene and Ca-rich augite. Additionally, mineral clasts of pyroxene often have a broader compositional range with two structural styles: one a Ca-rich pyroxene with a homogeneous composition and the other with exsolution lamellae.

Olivine: Olivine in lunar meteorites varies in composition, with various occurrences of basalt, anorthosite clasts, crystal clasts and symplectites, or equilibrated three-phase aggregates (fayalite+hedenbergite+quartz). In basalts, the olivine is usually FeO-rich and has a wide range of compositions with Fa_{20-90}[25]; some olivines in its symplectites are very FeO-rich ($Fa_{>90}$). In feldspathic breccias, the olivine in clasts and the matrix varies greatly in composition and has a greater MgO content (Fo_{60-100}) than in basalts[26]. In addition, another typical feature of olivine in lunar meteorites is that it is Cr_2O_3-CaO-rich[15].

Ilmenite: Although many high-Ti basalts were discovered in the Apollo samples, no high-Ti basalts have been found in lunar meteorites. Even though ilmenite is a common mineral in basaltic lunar meteorites, its content is not high (<5 vol%). It varies in composition between $FeTiO_3$ and $MgTiO_3$, e.g., the ilmenite in MIL 05035 is almost the end member of $FeTiO_3$[22].

In addition to the shock effects resulting from highly fragmented and shocked melt glass, a lot of the plagioclase in lunar meteorites-especially unbrecciated meteorites (e.g., MIL 05035, Yamato 793169 and Asuka 881757) have been shocked into maskelynite by asteroid impacts[22]. Asteroid impacts on the lunar surface also have caused other shock effects, including the multiphase transformations of olivine, ringwoodite and wadsleyite[27]. Furthermore, all lunar meteorites have very trace amounts of primary iron (< 0.1 wt%) and the brecciated lunar meteorites also contain Fe-Ni alloy (<0.7 wt%), which probably originated from chondrites[15].

4.2 Major elements

Since the two main lithologies that occur on the surface of the Moon are highland anorthosites and mare basalts, lunar meteorites originating from the Moon's surface can be classified as anorthosites, basalts or mingled polymicts,

which are caused by mechanical mixing effects as a result of impacts. Therefore, the major element geochemistry of lunar meteorites should be closely related to the lithology of lunar meteorites; i.e., their major element compositions are related to variation in the proportion of anorthosites and basalts. For example, the Al_2O_3, CaO, Na_2O, Cr_2O_3 contents of lunar meteorites are mainly determined by lithology. Feldspathic meteorites are Al_2O_3-rich (20–33 wt%), whereas in basaltic meteorites, the Al_2O_3 content (5–13 wt%) is much lower. However, the Al_2O_3 content of polymict breccias varies depending on the proportion of anorthosites and basalts in the meteorite, with the content (15–33 wt%) balanced between anorthosites and basalts. Owing to CaO and Na_2O mainly occurring in plagioclase, lunar meteorites are CaO-rich and Na_2O-poor (0.3–0.5 wt%), because of the high CaO and Al_2O_3 contents in feldspathic lunar meteorites[15]. Furthermore, most anorthositic lunar meteorites have a relatively high Cr_2O_3 content (0.06–0.15 wt%), which is much higher than that of rocks from Earth. Compared with feldspathic meteorites, basaltic meteorites are depleted in Al, Mg, alkaline earth elements and water (almost 0.00%), but enriched in Fe, Ti and Cr. Their low titanium contents are used as a lithological classification, i.e., they are classified as low titanium (LT) and very low titanium (VLT) basalts[28]. For example, the TiO_2 content of MET 01210, NWA 3136, Yamato 793274/981031, QUE 94281 and EET 87521/96008 ranges from 2 to 3 wt% (LT), and the TiO_2 content of NWA773 is less than 1 wt% (VLT). The value of Fe/Mn is a well-known crucial indicator of lunar rocks. The Fe/Mn ratios of lunar meteorites fall within this lunar range, i.e., the bulk Fe/Mn values for anorthositic (Al_2O_3>20%) and basaltic (Al_2O_3<20%) lunar meteorites are 70±5 (mean±standard deviation) and 72±4, respectively. Also, the $Mg^{\#}$ value (Mg/Mg+Fe, atomic ratio) of lunar meteorites has a wide range, usually between 20 and 80, that is negatively relative to the Al_2O_3 content. In contrast, the $Mg^{\#}$ of basaltic lunar meteorites is generally less than 40, but that of anorthosites is higher, probably as a result of the olivine composition in the anorthosites.

4.3 Trace elements

As for the major element geochemistry described above, the composition of trace elements in lunar meteorites is also closely related to their lithology. First, lunar meteorites generally have much lower abundances of the rare earth elements (REE) compared to rocks from Earth. In feldspathic meteorites, the REE abundance is only 4–10 times that of a CI meteorite (Figure 2). However, in basaltic meteorites, the REE has a higher content than feldspathic meteorites, which is 20–70 times that of CI meteorites. The REE distribution patterns of all lunar meteorites are right-inclined (Figure 2), i.e., more light-REE and less heavy-REE. The feldspathic meteorites have a positive Eu anomaly with a value of 0.7–0.9, which slightly increases as the total REE content increases. In basaltic meteorites, the Eu is a negative anomaly, with a wide range of 0.3–3.0 μg·g^{-1}[15]. SaU169 is

a typical KREEP sample, with a REE content 50 times that of anorthositic lunar meteorites, 7–10 times that of basaltic lunar meteorites, and a strongly negative "*Eu*" anomaly. All mineral grains in lunar meteorites, such as plagioclase and pyroxene, show that the total REE content in the cores is slight higher than that at the rims, however, their distribution patterns are similar[29].

Among incompatible elements, there are some strong correlations. For example, Sm and Th originally were positively correlated to each other, their ratios gradually increase from highland anorthites, and mare basalts to KREEP[15]. The Cr/Sc ratio increases along with an increase in the MgO/FeO ratio in both feldspathic and basaltic lunar meteorites. Furthermore, Cr/Sc has a well correlation to MgO/FeO in both basalts meteorite and anorthositic meteorite.

Similarly, some siderophile elements also correlate with each other. Ni and Ir show a positive correlation, but Ir largely occurs in regolith breccias and its occurrence in primitive anorthosites, olivine cumulate complexes and basalts are very low, suggesting that the vast majority of Ni and Ir are probably from outer space chondrites[15].

In lunar rocks, the Th content is an important indicator of lithology and source region[12]. In the distribution of Th-FeO (Figure 3), the mare basalts, highland anorthosites, Apollo 16 samples, and rocks from Procellarum show distinct positions. However, Th-FeO plots of lunar meteorites are obviously dispersed and random, some in expected lunar rock areas, others not, which was probably caused by the random generation of sources of the lunar meteorites and/or the mixture of different terrane rocks. Anyway, the Th content is still a crucial parameter in the identification of the origins or source areas of lunar meteorites.
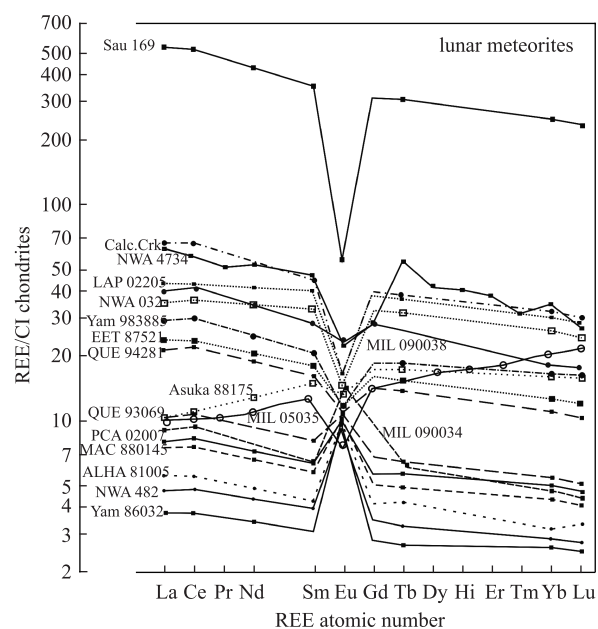

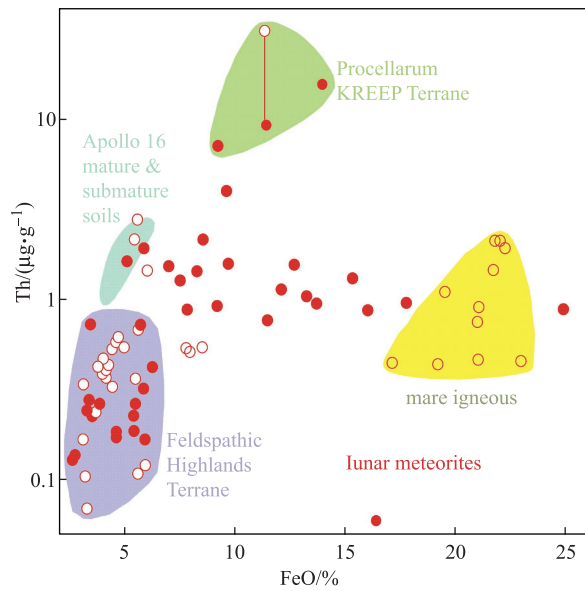**Figure 2** REE patterns for lunar meteorites[15]. Data from References[16, 23, 29-37].

Figure 3 Th and FeO plots of lunar meteorites[12].

5 KREEP in lunar meteorites

KREEP, referred to as a lithology enriched in K, REE, P and other incompatible elements, was one of the great discoveries made by Apollo lunar sample research[38]. No unbrecciated original lunar rocks have been found with a KREEP component, so the KREEP therefore occurs as either impact-melt glass or K-rich norite clasts. KREEP can be considered a conceptual composition, representing a third type of lunar magma in addition to highland anorthosites and mare basalts. However, KREEP rocks provide significance insight into the magmatic evolution and crust-mantle formation on the Moon[20,38]. Additionally, KREEP may have an influence on future exploitations of lunar resources because of its richness in REE, Th and U[38]. The genesis and origin of KREEP has been a contentious issue[38]. Based on its occurrence, some have suggested that KREEP is the product of splashing mixtures resulting from great impacts or volcanism[39]. Others argue that it consists of melt from a late stage in magmatic evolution, e.g., the pristine lunar magma, or urKREEP[40]. More lines of evidence now show that the KREEP in Apollo lunar samples probably originated from the Procellarum[41]. In recent years, along with the increasing number of lunar meteorites, more KREEP components have been found and studied in lunar meteorites (Table 3). This can be summarized as follows. (1) KREEP components have been discovered in 11 lunar meteorites. (2) They occur mainly in anorthosites and less commonly in basalts. (3) A very high KREEP (VHK)-meteorite SaU169 probably represents an urKREEP[11,30]. (4) Dhofar 287 is the lunar meteorite that richest in KREEP[30,42]. (5) Pb-Pb dating (3921 Ma) of KREEP in SaU 169 indicates that the KREEP component was formed in the final melt of the lunar magma ocean, likely resulting from the Great Impact, 3.9 billion years ago[11]. That said, lunar meteorites incorporating KREEP are not only from the vicinity of the Procellarum, but can come from any part of the Moon's surface, so the KREEP in lunar meteorites has great significance for exploring and understanding the genesis of the Moon's crust[15].

Table 3 KREEP components found in lunar meteorites

Meteorites	Meteorites types	Rock types of KREEP	Petrology and mineralogy	Reference
Calcalong Creek	basalt-bearing feldspathic regolith breccia	basaltic clast	Glass clasts, K-rich glass and SiO_2 glass with spherical-like texture and ophitic texture consisting of 52% pyroxene (pigeonite and iron pigeonite), 43% plagioclase (An91-97Or0.1-3.0), 5% olivine (Fo45-78), and a small amount of 4% of K-feldspar and phosphorite, whitlockite, zircon.	[31, 43]
Dhofar1180	basalt-bearing feldspathic impact-melt breccia	impact-melt glass	30 μm glass clast which has two portions of different chemical compositions. Rich in K_2O (0.7%-3.08%) and P_2O_5 (1.61%-3.08%).	[44]
SAU169	basalt-bearing feldspathic regolith breccia	VHK gabbro clast	Impact-melt clasts with coarse-grained crystalline texture consisting of pyroxene (60.8 vol%), Ba-rich feldspar (27.9 vol%), apatite (5.6 vol%), Nb-rich ilmenite (4.0 vol%), zircon (1.2 vol%) and small amounts of sulfides (0.6 vol%).	[11]
NWA2995/2996	basalt-bearing feldspathic regolith breccia	(1) graphic texture K feldspar clast; (2) quartz monzobiorite clast	(1) One orthoclase clast with a graphic porphyritic texture, containing rounded quartz grains bedded in feldspar (Ab21Or73). (2) Another quartz monzobiorite clast is a coarse-grained exsolution pyroxene (mg# 20-40) with inclusions of iron olivine (Fo18-30), alkali feldspar, albite, quartz (or quartz glass), apatite and ilmenite etc.	[10, 45]
Y-793274	anorthosite-bearing basaltic regolith breccia	(1) gabbroic anorthosite clast, (2) anorthositic grbbro clast	(1) Granulitic basaltic texture mainly composed of plagioclase and minor olivine-pyroxene. There are a lot of fractures broken by the impact. (2) It shows a complete gabbro texture mainly composed of plagioclase, pyroxene and olivine.	[46]

(Continued)

Y-983885	basalt-bearing feldspathic regolith breccia	basalt clast	One lithic clast has a sub-ophitic texture consisting of plagioclase (64.1 vol%), pyroxene (pigeonite+augite) (20.1 vol%), Si,Al,K-rich glass (10.9 vol%), whitlockite (2.8 vol%), K-feldspar (<0.1 vol%) etc.	[47]
NWA7493	feldspathic regolith breccia	graphic texture quartz k-feldspar clast	Graphic texture composed of k-feldspar and quartz.	[48]
NWA7022	feldspathic fragmental breccia	quartz +k-feldspar clast?	An intergrowth of quartz and feldspar.	[49]
Dhofar287A	basalt	late interstitial matrix	Mainly composed of olivine, Si- and K-Ba-rich glass, ilmenite, apatite and whitlockite etc.	[42]
Dhofar1442	mingled regolith breccia	granophyer clast	Quartz+K-feldspar+Na-rich plagioclase clasts.	[50]
NWA 4472/4485	anorthosite-bearing basaltic breccia	phosphorite-bearing basic rock clast	Mainly composed of pyroxene, apatite, ilmenite, spinel and SiO_2-rich phase.	[13]
NWA 773	basalt (partly breccias)	late interstitial matrix	Mainly composed of K-Ba plagioclase, apatite, ilmenite and SiO_2 glass, and the characteristics of REE contents and patterns are similar to KREEP.	[51]

6 Launching pairs and ejecting sites of lunar meteorites

Lindstrom et al.[52] argue that ALHA81005 and Y791197 probably came from the same impact crater when the second lunar meteorite (Y791179) was confirmed. Their suggestion, without strong evidence, is not widely accepted[53], but it at least highlights the significance of launching pairs and ejecting sites for lunar meteorites. So far, six launching pairs for lunar meteorites proposed: (1) YAMM: Y793169/A881757/MET 01210/MIL 05035 (unbrecciated mare basalts)[22], (2)NWA 032 and LAP 02205 (unbrecciated mare basalts)[59]; (3)QUE 94281 (anorthosite-bearing basaltic regolith breccia), Y793274/Y981031 (anorthosite-bearing basaltic regolith breccia), and EET 87521/96008 (basaltic or gabbroic fragmental breccia)[33,37,58,60-61]; (4) A81005 (feldspathic regolith breccia), Y791197 (feldspathic regolith breccia) and Dhofar 081 (feldspathic fragmental breccia)[53,57-58]; (5) Calcalong Creek (basalt-bearing feldspathic regolith breccia) and Y983885 (basalt-bearing feldspathic regolith breccia)[14]; (6) MAC 88104/88105 (feldspathic regolith breccia) and NWA 482 (feldspathic impact-melt breccia) [58]. However, there are strong arguments for some launching pairs, e.g., A81005, Y791197 and Dhofar 081; MAC 88104/88105 and NWA 482[15].

For unbrecciated lunar basalts, research on launching pairs of lunar meteorites includes: (1) the similarity of chemical compositions among meteorites, (2) the compositional difference from other lunar basalts, (3) the similarity of their cosmic rays exposure (CRE) history and ages; (4) the similarity of crystallization ages[37, 54-56]. However, for lunar meteorite breccias, the identification of launching pairs is much more difficult. Their identification criteria mainly includes CRE history and launching ages[53,57-58], and also lithology, petrography and chemical composition. The identification of launching pairs for breccias is much more complex because it is difficult to exclude the possibility of launching pairs for different rock types. This is because different rocks are likely to have formed at the same site on the lunar surface, e.g., at the Apollo 17 landing site in the Taurus-Littrow highlands[15].

In addition, on the basis of the above launching pairs, some possible ejecting sites for lunar meteorites are also suggested. Most lunar meteorites are considered to have come from the near side of the Moon (Figure 4). In detail, there are 10 possible launching regions proposed for lunar meteorites. Region A is the Schickard impact crater-4 YAMN meteorites[22]. Region B is Mare Imbrium and Mare Serenitatis-meteorite NWA 003. Both areas (Figure 4) are possible launching sites[62]. Region C is in the east near side, near Mare Crisium-Dhofar 301[63]. Region D is the northern maria-Yamato 981031[64]. Area E is Laland crater-SaU 169[65]. Region F is near to the SPA basin on the northwest nearside of the Moon-SaU449, Dhofar 925/960/961, NWA 2996[10,66]. Region G is the west nearside of the Moon-Dhofar 302[63]. Region H is the Oceanus Procellarum-NWA 3163, GRA 06157, Y 983885, NWA 4472[13,47,67,68]. Area I is the north far side of the Moon-SaU 300[69]. The launching region distribution indicates that lunar meteorites have come from all over the Moon's surface.

7 The symplectites in lunar meteorites

A symplectite is a kind of microgranular mineral intergrowth forming as a result of a secondary reaction or alteration processes. Generally, symplectites are the products of geological processes that occur at high temperatures and pressures; hence, they are a good geothermobarometer for indicating the thermodynamic and dynamic conditions of geological process[70].
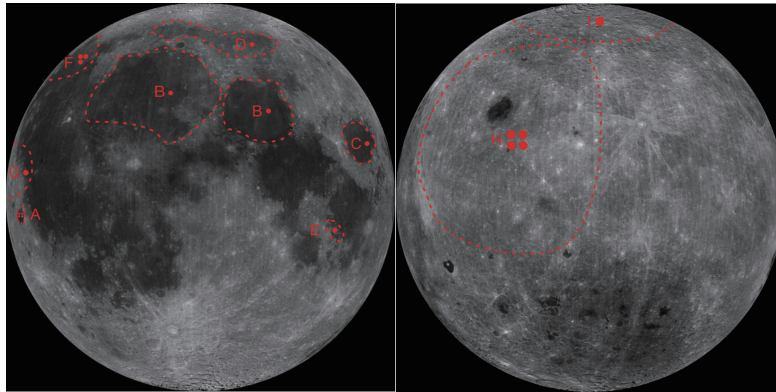
Figure 4 Possible launching sites for lunar meteorites

Many symplectites are found in lunar rocks. The first symplectite in lunar rocks, which was found in the Apollo 11 samples, is a sub-micron-grained worm-like intergrowth composed of monoclinic pyroxene, fayalite, and cristobalite[71]. Later, another kinds of symplectites, such as olivine+inclusions, olivine+feldspar, chromium spinel-diopside-bronzite, and chromium spinel-diopside-bronzite, were also discovered in lunar rocks; these all vary greatly in occurrence and shape[72-73]. To explain how these symplectites formed, a variety of hypotheses have been posed: olivine-feldspar reactions, captured crystals in a residual melt, trace element diffusion in olivine, decomposition of the original chrome garnet, high-pressure solid phase reaction, among others. However, none of the hypotheses is widely accepted (e.g., Reference[72-73]).

Along with the increasing number of lunar meteorites, some symplectites have also been discovered in lunar meteorites, e.g., MIL 05035, MET 01210, Yamato 82193, Y 79319, A881757, EET 96008, NWA 773[22,51,74-76]. However, the types of symplectites seem to be simpler than in lunar rocks. The most common symplectite is ferroaugite-fayalite-SiO_2, and the second most abundant is olivine+quartz, usually accompanied by a few grains of pyroxene, plagioclase, Fe-Ni metals, or phosphorite[77]. Generally, the formation of symplectite is thought to result from the decomposition of pyroxferroite; low-pressure and high-temperature experiments support this claim[78-79]. However, others argue that symplectite should crystallize from a residual magmatic melt since some late-stage minerals such as plagioclase and phosphorite occur in symplectites[77]. The low formation pressure of < 1.15 GPa for the 'hedenbergite+olivine+quartz' symplectite, indicates that lunar symplectites should have formed on or near the surface of the Moon. Other explanations for lunar meteorite symplectites are possible, e.g., reaction results[72] and high-pressure solid phase reactions[73]. However, the discovery of strong shock effects in rocks (e.g., plagioclase maskelynization) and relict pyroxferroite in symplectites indicate that the symplectites in lunar meteorites are closely related to shock metamorphism[76]. Further research on symplectites in lunar meteorites will help to understand shock metamorphism and the history of the Moon's surface.

8 Age and evolutionary history of lunar meteorites

In general, lunar meteorites may experience a long history spanning many stages from rock formation to falling to Earth. Accordingly, the time series of lunar meteorites should represent this multistage history, e.g., crystallization age of lunar rocks, noble gas preservation (giving the age of lunar meteorites), duration of regolith exposure to cosmic rays, launching time resulting in the ejection of the sample from the Moon's surface, the duration of flight between the Moon and Earth, and the terrestrial age after falling to Earth[7]. The crystallization age of Apollo samples is about 4.5–3.9 Ga, which is consistent with that of lunar meteorites, and constrains the timing of lunar crustal formation[80]. In addition, the distribution of the Rb-Sr internal isochron line age, and the K-Ar and Ar-Ar age of lunar meteorites, records the lunar cataclysm events of 3.9 Ga, which spanned short time intervals. Additionally, the $^{40}Ar/^{36}Ar$ ratios of lunar soil particles correspond well to lunar soil brecciation ages, e.g., the $^{40}Ar/^{36}Ar$ value of MAC88104/88105 is 5.7±1.0, and its breccia formation age is more than 20 Ga; the $^{40}Ar/^{36}Ar$ value of Y791179, ALHA81005, Y793274 is about 2, and its breccia formation age is 1 Ga; the $^{40}Ar/^{36}Ar$ value of Y793274 is about 10, and its breccia formation age is about 4–3 Ga[81]. Additionally, the CRE age and terrestrial ages provide proof of different lunar meteorite launching events: 0.06 Ma, 0.25–0.30 Ma, 8±3 Ma, <0.04 Ma; 0.05–0.11 Ma, 0.35±0.10 Ma, 1±0.20 Ma and 3±1 Ma. These ages provide important criteria for assessing launching pairs of lunar meteorites [57].

9 Conclusions

Because of the discovery of lunar meteorites in Earth's deserts, the number of lunar meteorites available for study has dramatically increased in recent years. The lunar meteorite collection provides important scientific samples for research. As the catalogue of samples increases, the ratios of the number, paired number and mass distribution (except the

mingled breccias) of anorthositic lunar meteorites to basaltic lunar meteorites have been updated to 3.9∶1, 4.5∶1 and 5∶1 respectively. These ratios obviously tend to the highland and mare lunar landscape areas (5∶1). The mass rate, especially, is exactly the same as that of the lunar landscape area proportion, suggesting that the lunar meteorites came from all over the Moon's surface. With the exception of a small number of unbrecciated crystalline rocks, the vast majority of lunar meteorites are breccias that can be divided into three main types: highland feldspathic, mare basaltic, and mingled breccias. According to petrographic analyses, especially of rock clasts, lunar meteorites are observed to have a variety of lithologies such as anorthosite, basalt, gabbro, troctolite, norite and KREEP. The geochemistry of lunar meteorites also shows correlations with lithology, such as REE, Th, and Sm. Abundant KREEP components are found in lunar meteorites. In particular, the VHK KREEP clasts in SaU 169 may represent a primordial (urKREEP) magma, which provides important information of the origin of the KREEP. Based on comprehensive comparisons, six launching pairs of lunar meteorites and ten launching sites from the Moon are proposed. The discovery of lunar symplectites provides significant insight into the history of shock metamorphism on the lunar surface. Furthermore, research on isotopic ages and the composition of noble gases not only provides information on crystallization processes in lunar rocks and the formation of lunar crust, but also gives insight into the history of shock events on the lunar surface.

References

1   Lin Y T, Miao B K, Xu L, et al. Research progress in meteoritics and Cosmochemistry (2001-2010). Bulletin of Mineralogy, Petrology and Geochemistry, 2013, 32(1): 40-55 (Chinese Edition).

2   Harvey R , The origin and significance of Antarctic meteorites. Chemie der Erde Geochemistry, 2003, 63:93-147.

3   Miao B K, Lin Y T, WangD D, et al. Progress of antarctic meteorite collection in China (2000-2010). Bulletin of Mineralogy, Petrology and Geochemistry, 2012, 31(6): 565-574 (Chinese Edition).

4   Bogard D. A Meteorite from the Moon. Geophysical Research Letters, 1983, 10:773-774.

5   Takeda H, Yamaguchi A, Bogard D D, et al. Magnesian anorthosites and a deep crustal rock from the farside crust of the moon. Earth and Planetary Science Letters, 2006, 247:171-184.

6   Yamaguchi A, Karouji Y, Takeda H, et al. The variety of lithologies in the Yamato-86032 lunar meteorite: Implications for formation processes of the lunar crust. Geochimica et Cosmochimica Acta, 2010, 74:4507-4530.

7   Wang D T, Lin Y T. Inspiration from study of antarctic meteorites III: Overview on antarctic lunar meteorites and their evolution history. Antarctic Research, 1993, 5 (2): 1-20(Chinese Edition).

8   Warren P H, Ryder G. A brief review of the scientific importance of lunar meteorites//Workshop on New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets. 1998:74.

9   Zeigler R A, Jolliff B L, Korotev R L. Lunar meteorites sayh al uhaymir 449 and dhofar 925, 960, and 961: windows into South Pole Aitken Basin?//Proceedings of the 44th Lunar and Planetary Science Conference. The Woodlands: LPI, 2013: 2437.

10 Mercer C N, Treiman A H, Joy K H. New lunar meteorite Northwest Africa 2996: A window into farside lithologies and petrogenesis. Meteoritics and Planetary Science, 2013, 48(2): 289-315.

11 Lin Y, Shen W, Liu Y, et al. Very high-K KREEP-rich clasts in the impact melt breccia of the lunar meteorite SaU 169: New constraints on the last residue of the Lunar Magma Ocean. Geochimica et Cosmochimica Acta, 2012, 85: 19-40.

12 Korotev R L, Jolliff B L, Zeigler R A. What lunar meteorites tell is about the lunar highlands crust. LPI Contributions, 2012: 35-36.

13 Joy K H, Burgess R, Hinton R, et al. Petrogenesis and chronology of lunar meteorite Northwest Africa 4472: A KREEPy regolith breccia from the Moon. Geochimica et Cosmochimica Acta, 2011, 75(9): 2420-2452.

14 Lorenzetti S, Busemann H, Eugster O. Regolith history of lunar meteorites. Meteoritics and Planetary Science, 2005, 40(2): 315-327.

15 Korotev R L. Lunar geochemistry as told by lunar meteorites. Chemie der Erde/Geochemistry, 2005, 65(4): 297-346.

16 Korotev R L, Zeigler R A, Jolliff B L. Compositional constraints on the launch pairing of LAP 02205 and PCA 02007 with other lunar meteorites//Proceedings of the 35th Lunar and Planetary Science Conference. The Woodlands: LPI, 2004.

17 Yanai K, Kojima H, Katsushima T. Lunar meteorites in Japanese collection of the Yamato meteorites. Meteoritics, 1984, 19: 342.

18 Hill D H, Boynton W V, Haag R A. A lunar meteorite found outside the Antarctic. Nature, 1991, 352(6336): 614-617.

19 Bischoff A, Weber D. Dar AL Gani 262: the first lunar meteorite from the Sahara. Meteoritics & Planetary Science, 1997,32(S1): 13-14.

20 Ouyang Z Y. Introduction to lunar science. Beijing: Chinese Aerospace Press, 2005: 362.

21 Institute of Geochemistry of Chinese Academy of Sciences. Progress of study on lunar geology. Beijing: Chinese Science Press. 1977: 327.

22 Arai T, Hawke B R, Giguere T A, et al. Antarctic lunar meteorites Yamato-793169, Asuka-881757, MIL 05035, and MET 01210 (YAMM): Launch pairingand possible cryptomare origin. Geochimica et Cosmochimica Acta, 2010, 74(7): 2231-2248.

23 Fagan T J, Taylor G J, Keil K, et al. Northwest Africa 032: Product of lunar volcanism. Meteoritics & Planetary Science, 2002, 37(3): 371-394.

24 Stöffler D, Knoell H D, Marvin U B, et al. Recommended classification and nomenclature of lunar highland rocks-A committee report//Confence on the Lunar Highlands Crust. New York and Oxford: Pergamon Press, 1980: 51-70.

25 Xia Z P, Miao B K, Chen H Y, et al. Petrology and mineralogy of lunar meteorite EET 96008 from antarctica. Chinese Journal of Polar Scienc, 2013. 25 (4): 352-361(Chinese Edition).

26 Yao J, Miao B K, Chen H Y, et al. Petrology and Mineralogy of a new lunar meteorite MIL 090070 found in Antarctica. Chinese Journal of

Polar Scienc, 2013, 25 (4): 329-341 (Chinese Edition).

27　Barrat J A, Chaussidon M, Bohn M, et al. Lithium behavior during cooling of a dry basalt: An ion-microprobe study of the lunar meteorite Northwest Africa 479 (NWA 479). Geochimica et Cosmochimica Acta, 2005, 69(23): 5597-5609.

28　Papike J J, Ryder G, Shearer C. Lunar Samples// Paul H R. Planetary Materials. Mineralogical Society of America. 1998, 36: 5-1-5-234..

29　Wang Y, Hsu W B, Guan Y B, et al. Petrogenesis of the Northwest Africa 4734 basaltic lunar meteorite. Geochimica et Cosmochimica Acta, 2012, 92: 329-344.

30　Gnos E, Hofmann B A, Al-Kathiri A, et al. Pinpointing the source of a lunar meteorite: Implications for the evolution of the Moon. Science, 2004, 305(5684): 657-660.

31　Hill D H, Boynton W V. Chemistry of the Calcalong Creek lunar meteorite and its relationship to lunar terranes. Meteoritics and Planetary Science, 2003, 38(4): 595-626.

32　Jolliff B L, Korotev R L, Haskin L A. A ferroan region of the lunar highlands as recorded in meteorites MAC88104 and MAC88105. Geochimica et Cosmochimica Acta, 1991, 55(11): 3051-3071.

33　Jolliff B L, Korotev R L, Rockow K M. Geochemistry and petrology of lunar meteorite Queen Alexandra Range 94281, a mixed mare and highland regolith breccia, with special emphasis on very-low-Titanium components. Meteoritics and Planetary Science, 1998, 33(4): 581-601.

34　Jolliff B L, Zeigler R A, Korotev R L. Petrography of Lunar Meteorite LAP 02205, A New Low-Ti Basalt Possibly Launch Paired with NWA 032//Proceedings of the 35th Lunar and Planetary Science Conference. The Woodlands: LPI, 2004.

35　Korotev R L, Lindstrom M M, Lindstrom D J, et al. Antarctic meteorite ALHA81005-Not just another lunar anorthositic norite. Geophysical Research Letters, 1983, 10(9): 829-832.

36　Korotev R L, Jolliff B L, Rockow K M. Lunar meteorite Queen alexandra range 93069 and the iron concentration of the lunar highlands surface. Meteoritics and Planetary Science, 1996, 31(6): 909-924.

37　Korotev R L, Jolliff B L, Zeigler R A, et al. Compositional constraints on the launch pairing of the three brecciated lunar meteorites of basaltic composition. Antarctic Meteorite Research, 2003, 16: 152-175.

38　Zou Y L, Xu L, Ouyang Z Y. KREEP rocks. Chinese Journal of Geochemistry, 2004, 23(1): 65-70.

39　Hawke B R, Head J W. Lunar KREEP volcanism-Geologic evidence for history and mode of emplacement//Proceedings of the 9th Lunar and Planetary Science Conference Proceedings. New York, Pergamon Press, 1978: 3285-3309.

40　Warren P H, Wasson J T. The origin of KREEP. Reviews of Geophysics and Space Physics, 1979, 17(1): 73-88.

41　Wieczorek M A, Phillips R J. Thermal modeling of mare volcanism and the "Procellarum KREEP Terrane"//Proceedings of the 30th Annual Lunar and Planetary Science Conference. Houston: LPI, 1999.

42　Anand M, Taylor L A, Misra K C, et al. KREEPy lunar meteorite Dhofar 287A: A new lunar mare basalt. Meteoritics and Planetary Science, 2003, 38(4): 485-499.

43　Marvin U B, Holmberg B B. Highland and mare components in the callcalong creek lunar meteorite. Lunar and Planetary Science Conference, 1992, 23: 849.

44　Zhang A, Hsu W. A KREEP clast in the lunar meteorite dhofar 1180//Lunar and Planetary Science Conference. Houston: LPI, 2007.

45　Mercer C N, Treiman A H. New lunar meteorite NWA 2996: A window into highland plutonic processes and KREEP metasomatism//Proceedings of the 42nd Lunar and Planetary Science Conference.

The Woodlands: LPI, 2011.

46　Koeberl C, Kurat G, Brandsätter F. Lunar meteorite Yamato-793274: Mixture of mare and highland components and barringerite from the Moon//Proceedings of the 15th Symposium on Antarctic Meteorites. Tokyo: National Institute of Polar Research, 1991, 4: 33-55.

47　Arai T, Otsuki M, Ishii T, et al. Mineralogy of Yamato 983885 lunar polymict breccia with a KREEP basalt a high-Al basalt, a very low-Ti basalt and Mg-rich rocks. Antarctic Meteorite Research, 2005, 18: 17-45.

48　Agee C B, Korotev R L, Irving A J. Petrology and bulk composition of two lunar fragmental breccias: Northwest africa 7493 and Northwest Africa 7611//Proceedings of the 44th Lunar and Planetary Science Conference. The Woodlands: LPI, 2013: 2692.

49　Kuehner S M, Irving A J, Korotev R L. Petrology and composition of lunar meteorite Northwest Africa 7022: An unusually sodic anorthositic gabbroic impact melt breccia with compositional similarities to miller range 090036//Proceedings of the 43rd Lunar and Planetary Science Conference. The Woodlands: LPI, 2012: 1524.

50　Zeigler R A, Korotev R L, Jolliff B L. Petrography and geochemistry of lunar meteorite dhofar 1442//Proceedings of the 42nd Lunar and Planetary Science Conference. The Woodlands: LPI, 2011: 1012.

51　Fagan T J, Taylor G J, Keil K, et al. Northwest Africa 773: Lunar origin and iron-enrichment trend. Meteoritics and Planetary Science, 2003, 38(4): 529-554.

52　Lindstrom M M, Lindstrom D J, Korotev R L, et al. Lunar meteorite Yamato-791197: A polymict anorthositic norite breccia//Proceedings of the 10th Symposium on Antarctic Meteorites. Tokyo: National Institute Polar Research, 1986, 41: 58-75.

53　Warren P H. Lunar and martian meteorite delivery services. Icarus, 1994, 111(2): 338-363.

54　Fernandes V A, Morris A A, Burgess R, et al. New Ar-Ar age determinations for the Lunar Mare basalts asuka 881757 and Yamato 793169//Proceedings of the 36th Annual Lunar and Planetary Science Conference. The Woodlands: LPI, 2005.

55　Thalmann C, Eugster O, Herzog G F, et al. History of lunar meteorites Queen Alexandra Range 93069, Asuka-881757, and Yamato-793169 based on noble gas isotopic abundances, radionuclide concentrations, and chemical composition. Meteoritics and Planetary Science, 1996, 31(6): 857-868.

56　Warren P H, Kallemeyn G W. Geochemical investigation of two lunar mare meteorites: Yamato-793169 and Asuka-881757//Proceedings of the 17th Symposium on Antarctic Meteorites. Tokyo: National Institute Polar Research, 1993, 6: 35-57.

57　Eugster O. Cosmic-ray exposure ages of meteorites and lunar rocks and their significance. Chemie der Erde/Geochemistry, 2003, 63(1): 3-30.

58　Nishiizumi K, Caffee M W, Jull A J T, et al. Exposure histories of lunar meteorites (abstract)//Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo: National Institute of Polar Research, 2003: 104.

59　Nyquist L E, Shih C Y, Reese Y, et al. Age of lunar meteorite LAP02205 and implications for impact-sampling of planetary surfaces//Proceedings of the 36th Annual Lunar and Planetary Science Conference. The Woodlands: LPI, 2005.

60　Lorenzetti S, Eugster O. Noble gas characteristics of lunar meteorite Yamato981031 paired with basaltic-anorthositic breccia Yamato-793274//Proceedings of the 27th Symposium on Antarctic Meteorites. Tokyo: NIPR, 2002: 75-76.

61　Arai T, Warren P H. Lunar meteorite QUE 94281: Glass compositions and other evidence for launch pairing with Yamato-793274. Meteoritics and Planetary Science, 1999, 34(2): 209-234.

62   Haloda J, Fernandes V A, Burgess R, et al. Lunare mare basalt meteorite NEA003-A: Chronology, chemical and petrological composition//AGU Fall Meeting Abstracts. San Francisco: American Geophysical Union, 2007, 23: 1440.

63   Nazarov M A, Demidova S I, Patchen A, et al. Dhofar 301, 302 and 303: Three new lunar highland meteorites from oman//Proceedings of the 33rd Annual Lunar and Planetary Science Conference. Texas: LPI, 2002.

64   Sugihara T, Ohtake M, Owada A, et al. Petrology and reflectance spectroscopy of lunar meteorite Yamato 981031: Implications for the source region of the meteorite and remote-sensing spectroscopy. Antarctic Meteorite Research, 2004, 17: 209.

65   Zeigler R A, Korotev R L, Jolliff B L. Geochemistry and petrography of high-Th, mafic impact-melt breccia from Apollo 12 and Sayh Al Uhaymir 169//Proceedings of the 37th Annual Lunar and Planetary Science Conference. Texas: LPI, 2006.

66   Demidova S I, Nazarov M A, Kurat G, et al. New lunar meteorites from oman: Dhofar 925, 960 and 961//Proceedings of the 36th Annual Lunar and Planetary Science Conference. Texas: LPI, 2005.

67   Shafer J, Brandon A, Lapen T, et al. Trace element geochemistry of a lunar granulite: Evidence from Northwest Africa 3163//Proceedings of the 42nd Lunar and Planetary Science Conference. Texas: LPI, 2011: 1508.

68   Zeigler R A, Korotev R L, Korotev R L. Fieldpath Lunar Meteorite Graves Nunataks 06157, a Magnesian Piece of the Lunar Highlands Crust//Proceedings of the 2nd Conference on the Lunar Highlands Crust. Bozeman, MT, 2012.

69   Hsu W B, Zhang A C, Bartoschewitz R, et al. Petrography, mineralogy, and geochemistry of lunar meteorite Sayh al Uhaymir 300. Meteoritics and Planetary Science, 2008, 43(8): 1363-1381.

70   Elvevold S, Gilotti J A. Pressure-temperature evolution of retrogressed kyanite eclogites, Weinschenk Island, North-East Greenland Caledonides. Lithos, 2000, 53(2): 127-147.

71   Ware N G, Lovering J F. Electron-microprobe analyses of phases in lunar samples. Science, 1970, 167(3918): 517-520.

72   Bell P M, Mao H K, Roedder E, et al. The problem of the origin of symplectites in olivine-bearing lunar rocks//Proceedings of the 6th Lunar and Planetary Science Conference. New York: Pergamon Press, 1975: 231-248.

73   Albee A L, Dymek R F, Depaolo D J. Spinel symplectites: high-pressure solid-state reaction or late-stage magmatic crystallization? Lunar and Planetary Science Conference, 1975, 6: 1.

74   Anand M, Taylor L A, Neal C R, et al. Petrogenesis of lunar meteorite EET 96008. Geochimica et Cosmochimica Acta, 2003, 67(18): 3499-3518.

75   Yanai K, Kojima H. Yamato-82193 meteorite: the third lunar meteorite collected at the Yamato mountains, antarctica. Meteoritics, 1985, 20: 790.

76   Liu Y, Floss C, Day J, et al. Petrogenesis of lunar mare basalt meteorite Miller Range 05035. Meteoritics & Planetary Science, 2009, 44(2): 261-284.

77   Oba T, Kobayashi Y. The mineral assemblage of symplectites in lunar meteorite Asuka-881757. Antarctic Meteorite Research, 2001, 14: 21-27.

78   Burnham C W. The crystal structure of pyroxferroite from Mare Tranquillitatis//Proceedings of the Lunar and Planetary Science Conference, The MIT Press, 1971, 2: 47-57.

79   Lindsley D H, Papike J J, Bence A E. Pyroxferroite: breakdown at low pressure and high temperature. Lunar Science, 1972, 3: 483-485.

80   Eugster O, Niedermann S, Burger M, et al. Preliminary report on the Yamato-86032 lunar meteorite: III. Ages noble gas isotopes, oxygen isotopes and chemical abundances//Proceedings of the 13th Symposium on Antarctic Meteorites. Tokyo: National Institute of Polar Research, 1989, 2: 25-35.

81   Eugster O, Geiss J, Grogler N. Dating of early regolith exposure and the evolution of trapped $^{40}AR/^{36}AR$ with time. Lunar and Planetary Science Conference Abstracts, 1983, 14: 177-178.