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INVITED REVIEW

Lunar geochemistry as told by lunar meteorites

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Abstract

About 36 lunar meteorites have been found in cold and hot deserts since the first one was found in 1979 in Antarctica. All are random samples ejected from unknown locations on the Moon by meteoroid impacts. Lithologically and compositionally there are three extreme types: (1) brecciated anorthosites with high Al_2O_3 (26–31%), low FeO (3–6%), and low incompatible elements (e.g., $<1\,\mu g/g$ Th), (2) basalts and brecciated basalts with high FeO (18–22%), moderately low Al_2O_3 (8–10%) and incompatible elements (0.4–2.1 μg/g Th), and (3) an impact-melt breccia of noritic composition (16% Al_2O_3, 11% FeO) with very high concentrations of incompatible elements (33 μg/g Th), a lithology that is identified as KREEP on the basis of its similarity to Apollo samples of that designation. Several meteorites are polymict breccias of intermediate composition because they contain both anorthosite and basalt. Despite the large range in compositions, a variety of compositional parameters together distinguish lunar meteorites from terrestrial materials. Compositional and petrographic data for lunar meteorites, when combined with mineralogical and compositional data obtained from orbiting spacecraft in the 1990s, suggest that Apollo samples identified with the magnesian (Mg-rich) suite of nonmare rocks (norite, troctolite, dunite, alkali anorthosite, and KREEP) are all products of a small, geochemically anomalous (noritic, high Th) region of crust known as the Procellarum KREEP Terrane and are not, as generally assumed, indigenous to the vast expanse of typical feldspathic crust known as the Feldspathic Highlands Terrane. Magnesian-suite rocks such as those of the Apollo collection do not occur as clasts in the feldspathic lunar meteorites. The misconception is a consequence of four

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historical factors: (1) the Moon has long been viewed as simply bimodal in geology, mare or highlands, (2) one of the last, large basin-forming bolides impacted in the Procellarum KREEP Terrane, dispersing Th-rich material, (3) although it was not known at the time, the Apollo missions all landed in or near the anomalous Procellarum KREEP Terrane and collected many Th-rich samples formed therein, and (4) the Apollo samples were interpreted and models for lunar crust formation developed without recognition of the anomaly because global data provided by orbiting missions and lunar meteorites were obtained only years later.

Keywords: Meteorites; Moon; Basalt; Impact-melt breccia; Anorthosite; Antarctica; Impact; Crater; KREEP; Lunar rock

1. Lunar meteorites

1.1. Background

A lunar meteorite is a rock that was ejected from the Moon by the impact of a meteoroid and was subsequently captured by the Earth's gravitational field. Although it is now apparent that rocks from the Moon must have been dropping from the sky throughout geologic history, the first lunar meteorite was not recognized until 1982, 9 years after the last Apollo mission to the Moon. The meteorite, a 31-g stone known as ALHA (Allan Hills) 81005, was one of 315 meteorites collected in Antarctica during the sixth field season (1981–82) of the ANSMET (Antarctic Search for Meteorites) program (Bogard, 1983; Harvey, 2003; Cassidy, 2003). More than 25,000 meteorite specimens have been collected in the cold desert of interior Antarctica and as of 1999, 85% of all known meteorites had been found in Antarctica (Harvey, 2003). The 1981–82 ANSMET field team recognized that ALHA 81005 was as an unusual meteorite. It had a greenish, vesicular fusion crust (Fig. 1); most meteorite fusion crusts are darker and not vesicular. Where the fusion crust was missing, white clasts in a dark matrix were exposed, a feature unlike that of any previously known meteorite.

The ANSMET program is sponsored by the US government. All ANSMET meteorites are first examined at the NASA Johnson Space Center in Houston, Texas, in the same facilities used to house and curate the Apollo lunar sample collection. Curators there had seen many Moon rocks and suspected that the meteorite originated from the Moon. After numerous scientific studies, aided by the fact that planetary scientists had also already seen and studied Apollo moon rocks, the identification of ALHA 81005 as a lunar meteorite was uncontroversial (Cassidy, 2003).

In hindsight, it is remarkable that it took so long to recognize the first lunar meteorite. At the time that ALHA 81005 was found, several thousand classified meteorites existed in the world's collections. Among them were eight that, around 1980, were just being recognized to have most likely originated from Mars (Wasson and Wetherill, 1979; Nyquist et al., 1979; McSween and Stolper, 1979). Four or five

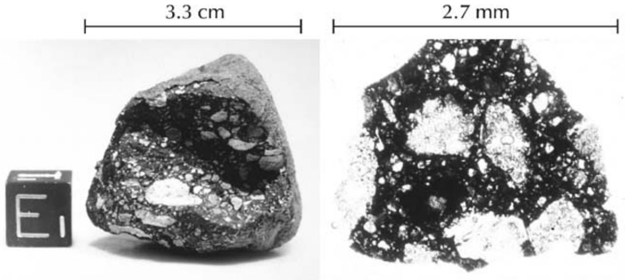

Fig. 1. Lunar regolith breccias, such as meteorite ALHA 81005 depicted here, are fractal objects with a great range in clast sizes. The texture is similar regardless of scale. Left: Broken surface of the whole meteorite (NASA photo S82-35865). Right: Photomicrograph of a thin section of a subsample (fragment 2M1 of Korotev et al., 1983). The light clasts are anorthositic breccias. The dark matrix is lithified fine-grained regolith with a composition very similar to the average of the large clasts. Despite the apparent heterogeneity, the bulk compositions of small subsamples such as that on the right from a given meteorite are all very similar for most of the lunar-meteorite regolith breccias.

of the eight martian meteorites – the achondrites known as SNC meteorites (Shergotty, Nakhla, Chassigny) – were falls that existed in the pre-Antarctic collection (Chassigny, fell in 1815; Shergotty, 1865; Nakhla, 1911; Zagami, 1962; and possibly Lafayette, sometime before 1931). Two of the others were finds that had been collected on previous ANSMET excursions (ALHA 77005, Elephant Moraine 79001). We can speculate that the reason it took so long to recognize the first lunar meteorite is that in addition to being rare among meteorites (0.1%), lunar meteorites resemble unremarkable terrestrial rocks more so than do asteroidal meteorites (e.g., texture, density), stones tend to be small (median mass: ~50 g), and no recovered meteorite fall has yet been from the Moon.

The second lunar meteorite to be recognized, Yamato 791197 (Yanai and Kojima, 1984), followed closely by the third, Yamato 82192 (Yanai et al., 1984) and fourth, Yamato 82193 (Yanai and Kojima, 1985), were announced in 1984 and 1985. The Yamato meteorites are collected on expeditions to Antarctica by the NIPR (National Institute of Polar Research) of Japan. The 1979–80 NIPR field season had netted more than 4000 meteorite specimens and processing of the collection required several years. In fact, there were three lunar meteorites in the Yamato 79 collection, but Yamato 793274 (Yanai and Kojima, 1987) and Yamato 793169 (Takeda et al., 1992) were not recognized to be lunar meteorites for several more years. Yamato 793169, a lunar basalt, had originally been classified as a eucrite (Takeda et al., 1992). Similarly, EET (Elephant Moraine) 87521 was collected by ANSMET in 1987 and initially classified as a brecciated eucrite. It required two more years to recognize its lunar heritage (Warren and Kallemeyn, 1989; Delaney, 1989).

In 1990, the count of lunar meteorites stood at seven, consisting of 10 stones, all collected in Antarctica. MAC (MacAlpine Hills) 88104 and 88105 are paired, that is, two stones from a single fall that were found close together in the field (Jolliff et al., 1991b). Likewise, Yamato 82192, 82193, and 86032 are pieces of a single meteoroid (Eugster et al., 1989). The first lunar meteorite to be found outside of Antarctica and the first acquired by a private collector was Calcalong Creek, found in the desert of western Australia (Hill et al., 1991). Because it is small (19 g) and the first piece of the Moon legally available for sale, advertised market prices for small samples of the meteorite have been in the $40,000/g range. Such prices have provided incentives to dealers and collectors to find more rare types of meteorites. In 1997 the second lunar meteorite from a hot desert, Dar al Gani 262, was found in Libya (Bischoff and Weber, 1997). At least 10 lunar meteorites are now known from the deserts of Africa, including Kalahari 009, the largest single stone among the lunar meteorites (13.5 kg; Russell et al., 2005). In 2000, Dhofar 025 was the first of more than 40 numbered lunar meteorite stones to be found in the Sultanate of Oman. As with the Antarctic meteorites, each stone is given its own alphanumeric designation. Pairing relationships among the various Dhofar lunar stones are not well established, but they probably represent about nine different meteorite falls (Nazarov et al., 2004). At this writing, samples of hot-desert meteorites are typically selling for $1500–$5000/g, which compares with ~$13/g for gold.

At this writing, about 82 stones from about 36 lunar meteorites have been found, identified, analyzed, and described (Table 1). Others are offered for sale on the Internet and at least several of these are legitimate but have not been announced in the *Meteoritical Bulletin* (e.g., Russell et al., 2005). The number of known martian meteorites is about 35. The numbers of both have increased dramatically over the past few years because of continued success in Antarctica (15 lunar and 12 martian) of the ANSMET and NIPR programs (Harvey, 2003; Imae et al., 2002) and the diligence of private collectors and dealers who are scouring hot deserts and desert bazaars in search of rare types of meteorites.

In this paper I review compositional aspects of lunar meteorites with emphasis on "How do we know that it is a rock from the Moon?" on the basis of a rock's composition. This discussion is directed largely at persons with a knowledge of terrestrial mineralogy and geochemistry. The author maintains an Internet web site on lunar meteorites and has been contacted by more than 400 people over the past several years, most of whom think that they have found a meteorite, often a lunar meteorite. Although the differences are well understood by lunar geochemists and petrologists, there is little information readily available even to terrestrial geochemists about how to distinguish an Earth rock from a Moon rock by composition. I also consider a Gedanken experiment – What if, as with Mars, lunar meteorites and global geochemical and mineralogical data had been acquired from orbit before samples were collected on the lunar surface and brought to Earth by spacecraft and astronauts? I contend that our geochemical view of the Moon has been distorted by a preconception, unlikely events, coincidences, and the order of discovery. In order to help make that case, I present most of the information in Sections 1–3 without reference to information obtained by the Apollo missions. When that approach may be misleading, I include information derived from Apollo in square brackets.

Table 1. List of lunar meteorites, as of June, 2005, in approximate order of decreasing Al_2O_3 abundance

N	Meteorite Name (with mass of individual stones of pairs)	When found[a]	Lunar rock type	Mass[b] (g)	Where found[a]	Al_2O_3 (%)	Th (μg/g)	Notes
Feldspathic breccias								
1	Dhofar 081/280/910/1224[c] (174 + 251 + 142 + 5 g)	1999–2003	Feldspathic fragmental breccia	572	Oman	081: 31	0.2	1,2,3
2	Dhofar 302/303/305/306/307/309/310/311/730/731/908/909/911/950/1085 (15 stones: 4–245 g)	2001–2003	Feldspathic (impact-melt?) breccia	1007	Oman	27–33	n.d.[d]	1,2,3,4,13
3	Dhofar 026/457–468 (14 stones: 19–148 g)	2000–2001	Feldspathic granulitic breccia	709	Oman	29	0.4	2
4	Dar al Gani (DaG) 400	1998	Feldspathic regolith breccia	1425	Libya	29	0.3	
5	Northwest Africa (NWA) 482	2000	Feldspathic impact melt breccia	1015	Algeria?	29	0.2	
6	MacAlpine Hills (MAC) 88104/88105 (61 + 663 g)	1989	Feldspathic regolith breccia	724	Antarctica	29	0.4	
7	Yamato 82192/82193/86032 (37 + 27 + 648 g)	1982/86	Feldspathic fragmental breccia	712	Antarctica	82192: 27 86032: 29	0.2	5
8	Kalahari 008	1999	Feldspathic regolith breccia	598	Botswana	28	n.d.	1,2,12
9	Queen Alexandra Range (QUE) 93069/94269 (21.4 + 3.1 g)	1993/94	Feldspathic regolith breccia	24	Antarctica	28	0.5	
10	Dar al Gani (DaG) 262	1997	Feldspathic regolith breccia	513	Libya	28	0.4	

Table 1. (*continued*)

N	Meteorite Name (with mass of individual stones of pairs)	When found[a]	Lunar rock type	Mass[b] (g)	Where found[a]	Al_2O_3 (%)	Th (μg/g)	Notes
11	Dhofar 489	2001	Feldspathic crystalline-matrix breccia	34	Oman	27	0.06	1,4,5
12	"specimen 1153"	<2000	Feldspathic regolith breccia	n.d.	Antarctica	27	n.d.	1,6
13	Dhofar 025/301/304/308 (751 + 9 + 10 + 2 g)	2000–2001	Feldspathic regolith or impact-melt breccia	772	Oman	025: 27	0.6	2,3,4
14	Northeast Africa (NEA) 001	2002	Feldspathic regolith breccia	262	Sudan	27	0.3	1
15	Pecora Escarpment (PCA) 02007	2003	Feldspathic regolith breccia	22	Antarctica	26	0.4	
16	Yamato-791197	1979	Feldspathic regolith breccia	52	Antarctica	26	0.3	
17	Allan Hills 81005	1982	Feldspathic regolith breccia	31	Antarctica	26	0.3	
18	Dhofar 733	2002	Feldspathic granulitic breccia	98	Oman	n.d.	n.d.	1,8
19	Dhofar 490/1084 (34 + 90 g)	2001/2003	Feldspathic fragmental breccia	124	Oman	n.d.	n.d.	1,2,3
20	Dhofar 925/960/961 (49 + 35 + 22 g)	2003	Feldspathic (impact-melt?) breccia	106	Oman	n.d.	n.d.	1,2,4
21	Dar al Gani (DaG) 996	1999	Feldspathic (?) fragmental breccia	12	Libya	n.d.	n.d.	1,4
Mingled (basaltic-feldspathic), basaltic, and other mafic breccias								
22	Yamato 983885	1999	Basalt-bearing feldspathic regolith breccia	290	Antarctica	22	2	

23	Calcalong Creek	~1990	Basalt-bearing feldspathic regolith breccia	19	Australia	21	4	
24	Yamato 793274/981031 (8.7 + 186 g)	1980/1999	Anorthosite-bearing basaltic regolith breccia	195	Antarctica	18	1.1	9
25	Sayh al Uhaymir (SaU) 169	2002	Th-rich mafic impact-melt breccia & regolith breccia	206	Oman	IMB: 16 RB: 18	IMB: 33 RB: 8	10
26	Meteorite Hills (MET) 01210	2001	Anorthosite-bearing basaltic breccia	23	Antarctica	17	1	
27	Queen Alexandra Range (QUE) 94281	1994	Anorthosite-bearing basaltic regolith breccia	23	Antarctica	16	0.9	
28	Northwest Africa (NWA) 3136	2004	Anorthosite-bearing basaltic regolith breccia	95	NW Africa	14	1	
29	Elephant Moraine (EET) 87521/96008 (31 + 53 g)	1987/1996	Basaltic or gabbroic fragmental breccia	84	Antarctica	14	0.9	11
30	Kalahari 009	1999	Basaltic fragmental breccia	14,100	Botswana	13	n.d.	1,2,12
31	Northwest Africa 773	2000	Basaltic regolith breccia with clasts of cumulate olivine gabbro	633	NW Africa	RB: 9 OG: 5	RB: 0.6 OG: 0.3	10
Unbrecciated mare basalts								
32	Yamato 793169	1979	Mare basalt	6	Antarctica	11	0.7	
33	LaPaz Icefield (LAP) 2205/02224/02226/02436/03632 (1226 + 252 + 244 + 59 + 93 g)	2002/2003	Mare basalt	1875	Antarctica	10	10	

Table 1. (*continued*)

N	Meteorite Name (with mass of individual stones of pairs)	When found[a]	Lunar rock type	Mass[b] (g)	Where found[a]	Al_2O_3 (%)	Th (μg/g)	Notes
34	Asuka 881757	1988	Mare basalt	442	Antarctica	10	2	
35	Northwest Africa 032/479 (~300 + 56 g)	1999/2001	Mare basalt	~456	Morocco	9	2	2
36	Dhofar 287	2001	Mare basalt, with regolith breccia	154	Oman	MB: 8 RB: n.d.	MB: 1 RB: n.d.	10

[a]Year or location found or purchased.

[b]Total mass of all stones.

[c]Numbers on the same line separated by a slash (/) indicate that the meteorite consists of two or more stones, each of which has a number.

[d]Not determined or reported.

Notes column: 1—Not well characterized; 2—Detailed compositional and petrographic data are not available or are not available for all stones; 3—On the basis of appearance of sawn faces, the different stones appear similar to each other; the stones were found near each other; it is otherwise not well established, however, that both or all stones are paired; 4—Lunar rock type uncertain; classification is based on thin section(s) that may have been small compared to the clast size; not all stones are similarly described; 5—The Yamato 82 stones are more mafic (lower Al_2O_3) than the Yamato 86 stone because they contain a greater proportion of mare volcanic material (Korotev et al., 1996, 2003b); 6—Dhofar 489 may be paired with Dhofar 302, although it was found 24 km away; 7—Few details available; the only information is that of Yanai (2000); may be paired with another meteorite in the list; 8—Possibly paired with another Dhofar stone, although no other lunar meteorite stone has been found within 22 km of Dhofar 733; 9—On the basis of available data, the Yamato 79 stone is more mafic than the Yamato 98 stone because it contains a greater proportion of mare volcanic material (Korotev et al., 2003a); 10—Dilithologic; the meteorite consists of a small portion of regolith breccia attached to the predominant lithology; 11—The meteorite is highly heterogeneous at the scale of analyzed subsamples because it consists of a solidified differentiated magma; on the basis of available data, the EET 96 stone is slightly more mafic than the EET 87 stone because it contains a greater proportion of a high-Fe, evolved differentiate (Korotev et al., 2003a); 12—The two Kalahari stones were allegedly found 50 m apart and there is some petrographic evidence that they are paired, despite that the two lithologies are distinctly different; 13—Shukolyukov et al. (2004) argue that Dhofar 303 is from a different fall than Dhofar 305, 307, and 731.

1.2. Ejection and delivery

Most lunar meteorites derive from craters on the order of a few km in diameter (Warren, 1994; Head, 2001). Warren's (1994) argument is elegant in its simplicity: there haven't been enough large impacts on the Moon in past few Ma to account for all the meteorites, given, as summarized below, that the meteorites likely derive from many craters and all left the Moon in the past 20 Ma. It is not known from which crater on the Moon any of the lunar meteorites originates, although it is possible to speculate that certain meteorites might come from certain regions or even specific craters (Fagan et al., 2002; Jolliff et al., 2003; Gnos et al., 2004; Nyquist et al., 2005). Lunar escape velocity averages 2.38 km/s, 2–4 times the muzzle velocity of rifles used for big-game hunting. Lunar material accelerated to escape velocity or higher will assume an orbit around the Earth or Sun. Atmospheric entry velocities for lunar meteorites are less than those of other meteorites (Nishiizumi, 2003), presumably because they are not accelerated by solar gravity to the extent that meteoroids from the asteroid belt are. All lunar meteorites for which cosmic-ray exposure data are available were launched from the Moon in the past 20 Ma; most were ejected in the past 0.5 Ma. Lunar meteorites that remained in space for a long time before being captured by Earth's gravitational field were likely in heliocentric orbit; those with short Moon–Earth transit times were in geocentric orbit. Terrestrial ages range from too short to measure ($<$30,000 years) to about half a Ma (Nishiizumi, 2003; Lorenzetti et al., 2005). Nazarov et al. (2004) estimate, on the basis of the Dhofar stones, that the annual mass flux of lunar material in the 10–1000 g range "is most likely to be equal to several tens or few hundred kilograms for the entire Earth's surface." Thus far, however, all lunar meteorites have been found only in deserts where meteorites of several different types are concentrated (Schlüter et al., 2002; Imae et al., 2002; Harvey, 2003; Russell et al., 2005).

1.3. Lithological types

Five lunar meteorites are unbrecciated basalts, Yamato 793169, Asuka 881757, LAP (LaPaz Icefield) 02205 et al. (five stones), NWA (Northwest Africa) 032/479 (two stones), and Dhofar 287. Another lunar meteorite, NWA 773, consists mainly of an olivine cumulate from a fractionated basaltic magma chamber (Fagan et al., 2003; Jolliff et al., 2003). Crystallization ages for these rocks are great by terrestrial standards, 2.8 Ga for NWA 032 (^{40}Ar–^{39}Ar; Fernandes et al., 2003), 3.02 ± 0.03 and 2.95 ± 0.02 Ga for LAP 02205 (^{87}Rb–^{87}Sr and ^{40}Ar–^{39}Ar; Nyquist et al., 2005), 2.9 Ga for NWA 773 (^{40}Ar–^{39}Ar; Fernandes et al., 2003; Sm–Nd; Borg et al., 2004), $\sim$3.9 Ga for Yamato 793169 (Fernandes et al., 2005), and 3.8–3.9 Ga for Asuka 881757 (Fernandes et al., 2005). Despite their great age, the basaltic lunar meteorites appear very fresh in thin section because there have been no fluids on the Moon to alter them and no processes other than meteoroid impacts to metamorphose them. Shock features and veins of melt glass occur, reflecting their abrupt expulsion from the Moon (Yanai, 1991; Fagan et al., 2002; Anand et al., 2003; Jolliff et al., 2003, 2004).

All other lunar meteorites are polymict breccias – rocks made up of bits and pieces of different kinds of older rocks that have been lithified by heat and shock as a result of meteoroid impacts on the lunar surface. Four of the brecciated meteorites are dominated by basalt, 70–95%, on the basis of compositional mass balance. These are EET 87521/96008 (paired stones found 9 years apart; Warren and Kallemeyn, 1989; Delaney, 1989; Nishiizumi et al., 1980; Korotev et al., 2003a), the regolith breccia portion of NWA 773 (Fagan et al., 2003; Jolliff et al., 2003); NWA 3136 (Kuehner et al., 2005), and Kalahari 009 (Russell et al., 2005). Five brecciated lunar meteorites contain subequal amounts of basaltic and feldspathic material (i.e., ~30–70% basalt). These meteorites are Yamato 793274/981031 (paired stones; Takeda et al., 1992), QUE 94281 (Jolliff et al., 1998; Arai and Warren, 1999), MET (Meteorite Hills) 01201 (Zeigler et al., 2005; Korotev and Irving, 2005), Calcalong Creek (Hill and Boynton, 2003), and Yamato 983885 (Kaiden and Kojima, 2002; Arai et al., 2004).

Most of the brecciated lunar meteorites, however, are dominated (>90%) by feldspathic materials. All of the feldspathic lunar meteorites are polymict rocks that are composed mainly of anorthositic lithologies as clasts and glass but which also contain uncommon or rare norites, troctolites, and sometimes a minor to trace component of basalt. Most lithic clasts in the feldspathic lunar meteorites are themselves breccias. (''Feldspathic lunar meteorite'' is preferable to ''highlands lunar meteorite'' or ''lunar highlands meteorite'' because it objectively describes the mineralogy while making no assumptions about where on the Moon a rock originates. As argued below, a lunar rock that is not a mare basalt does not necessarily come from the feldspathic highlands.)

The components of the breccias are old. Cohen et al. (2000, 2005) obtained ages ranging from 1.0 to 3.9 Ga for clasts of impact-melt breccias in five feldspathic lunar meteorites. In similar studies, the youngest ages observed in clasts and glass from five feldspathic lunar meteorites are 1.6, 1.7, 2.3, 3.3, and 3.6 Ga (Fernandes et al., 2000, 2004). Again, the ages represent impact events, thus the target rocks are even older. The impact melt breccia composing SaU (Sayh al Uhaymir) 169 crystallized 3.9 Ga ago (Gnos et al., 2004). Few igneous crystallization ages are available for components of feldspathic lunar meteorites. Such ages are difficult to obtain because concentrations of the geoclock elements K, Rb, Sm, etc., are low in feldspathic materials of the lunar crust and because impacts can reset ages in some isotopic systems. Bogard et al. (2000) obtain an age of about 4.4 Ga for a feldspathic (igneous?) clast in Yamato 86032. A spinel troctolite clast in Dhofar 489 has a crystallization age of 4.27 ± 0.13 Ga old (Takeda et al., 2004).

Most brecciated lunar meteorites are regolith and fragmental breccias. Such breccias are the closest lunar analogs to terrestrial sedimentary rocks. They consist of material from near the surface of the Moon that has been fractured and pulverized by many impacts over 4.5 Ga and then lithified in a final impact, possibly the same one that launched the breccia from the Moon. The matrix of a regolith or fragmental breccia typically consists of fine-grained crystalline material but it may be glassy. Clasts in the regolith and fragmental breccias are unsorted with respect to grain-size distribution because there is no wind or water on the Moon. The breccias are typically fractal in that they appear similar regardless of scale (Fig. 1). Three of the lunar meteorites are dilithologic; they are dominated by one lithology but contain a small portion of regolith breccia attached to the main lithology (e.g., Fig. 2). The three meteorites are Dhofar 287, a basalt (Anand et al., 2003; Demidova et al., 2003), NWA 773, an olivine cumulate (Fagan et al., 2003; Jolliff et al., 2003), and SaU 169, an impact-melt breccia (Gnos et al., 2004). Each of the three meteorites can be interpreted as an unrepresentative sample of a regolith breccia that contains one anomalously large clast. For the other regolith and fragmental breccias, the lithologies of the matrix are essentially the same as those of the clasts (but with two important exceptions noted below for the regolith breccias) and the distinction between clasts and matrix is somewhat arbitrary.

Clasts in regolith and fragmental breccias are typically angular but may be rounded slightly from abrasion associated with impacts. Clasts are never as rounded as those in terrestrial stream conglomerates, however. Aspects ratios of clasts are typically small; elongated clasts are rare. There is no preferred orientation of the clasts nor any hint of layering. Vesicles occur, but are rare, except in fusion crusts and relict agglutinates (below). The regolith and fragmental breccias are extremely coherent rocks, and indeed they must be in order to have survived the launch from the Moon and hard landing on Earth (Warren, 2001a). [Some regolith breccias collected on the Apollo missions are very friable.] Clasts and matrix have similar hardness, and on broken surfaces clasts have no relief with respect to the matrix.

Regolith breccias differ from fragmental breccias in that regolith breccias, by definition, contain lithic components that can only be produced at or above the lunar surface (Stöffler et al., 1980). Typically, regolith breccias contain glass spherules of

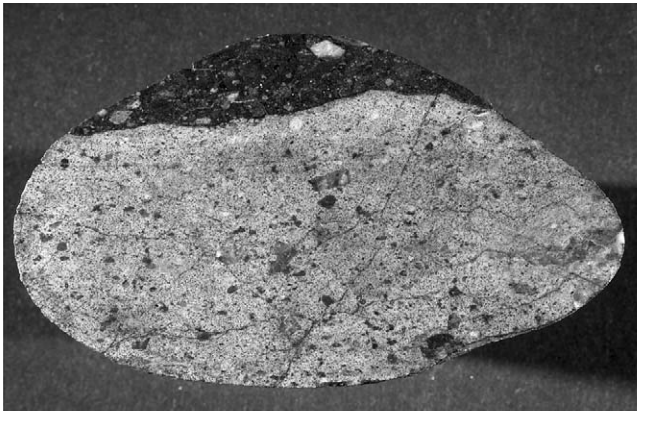

Fig. 2. Face of a sawn slab of lunar meteorite Sayh al Uhaymir (SaU) 169 (Gnos et al., 2004). The predominant lithology (bottom) is a KREEP (Th-rich) impact-melt breccia generally similar in composition to those collected on the Apollo 12 and 14 missions, but with greater concentrations of incompatible elements. The dark lithology (top) is regolith breccia somewhat similar in composition to the soil of the Apollo 14 site. Maximum width: ~6 cm. Photo courtesy of Peter Vollenweider/Natural History Museum Bern.

impact or pyroclastic origin (e.g., Delano, 1991; Arai and Warren, 1999; Arai et al., 2004). Some contain small (<1 mm), glassy, vesicular breccias called agglutinates or glass-welded aggregates that are produced during micrometeoroid impacts into fine-grained regolith. Glass spherules and agglutinates are the only lithologies that occur in the nominal matrix of regolith breccias that do not also occur as large clasts. Most regolith breccias consist of material that was within the upper few meters of the lunar surface (Warren, 1994, but see Nishiizumi, 2003). As a consequence, regolith and fragmental breccias contain gases such as H, He, N, Ne, Ar, Xe derived from solar-wind implanted ions and cosmic-ray reactions (Bogard and Johnson, 1983; Eugster, 2003). The regolith breccias contain the greatest proportion of asteroidal material and even the silicate portion of a small chondrite-like meteorite has been found in PCA (Pecora Escarpment) 02007 (Taylor et al., 2004).

An agglutinate is vesicular because the solar-wind implanted gases are released when gas-rich surface regolith is heated and fused during a micrometeoroid impact on the Moon. Similarly, many of the lunar meteorites, most notably QUE (Queen Alexandra Range) 93069/94269 (paired stones; cover photo) and PCA 02007, have highly vesicular fusion crusts because the solar-wind implanted gases are released from the ablation melt during atmospheric entry of the meteor. Gas-rich regolith breccias occur among asteroidal meteorites, but lunar meteorites are richer in solar-wind-implanted gases by factors of 10–100 (Bogard and Johnson, 1983) because the lunar regolith is deeper than asteroidal regoliths (greater lunar gravity) and because the Moon is closer to the sun than most asteroids. Because most of the regolith breccias are feldspathic, clasts are typically feldspathic and light colored. The matrix is usually dark. The material of the fine-grained matrix is largely the same as that of the coarse-grained clasts, however.

[Many samples of regolith breccias and unconsolidated regolith or ‘‘soil’’ were collected on the Apollo and Luna missions. Thus it has been easy to interpret observations made on those lunar meteorites that are regolith breccias. It would have been more difficult without the Apollo advantage. For example, as a result of Apollo we know that material at the surface of the Moon is subject to ‘‘maturation’’ or ‘‘space weathering’’ effects and that some of the processes involved are surface correlated and, therefore, more effective on fine-grained material. The mean grain size of freshly excavated and deposited ‘‘bedrock’’ decreases with time as a result of micrometeoroid impacts. Other space weathering effects lead to darkening and spectral reddening with time. In a mature regolith formed from anorthosites, the fine-grained material (<1 mm) is darker than the coarse crystalline material from which it formed, despite having the same composition. This is one reason that the matrix of many feldspathic lunar meteorites is darker than the clasts (Fig. 1).

Apollo regolith samples are rich in agglutinates, a lithology that is not formed on Earth and is rare in other types of meteorites. Agglutinates are fragile, and those that survive as clasts in the lunar meteorites have lost some of their characteristic morphology and character. Their origin would have been difficult to correctly interpret without the samples of Apollo regolith fines. Some aspects of space weathering and its effects on lunar regolith are described in Adams and McCord

(1973), McKay et al. (1974), Morris (1980), Keller and McKay (1997), Pieters et al. (2000), and Noble et al. (2001).]

A few lunar meteorites are impact-melt breccias. They are essentially igneous rocks in which angular or partially resorbed mineral and lithic clasts are suspended in a matrix of crystallized impact melt (Stöffler et al., 1980). At least one lunar meteorite, Dhofar 026, is a granulitic breccia (Cohen et al., 2004). Granulitic breccias are metamorphic rocks presumably formed at depth from older breccias by prolonged heating associated with a large impact. [Impact-melt and granulitic breccias are common in the Apollo collection.] There has been some inconsistency in application of the term impact-melt breccia when applied to lunar meteorites (Korotev et al., 2003b; Cohen et al., 2004) and it is possible that some lunar meteorites that have been classified as impact-melt breccias would have been classified as other types of breccias had they been samples in the Apollo collection. A related problem is that for some of the hot-desert meteorites, few petrographic thin sections have been available for study and classifications have been made using sections that are small in area with respect to the grain size of the clasts.

1.4. Mineralogy and compositional systematics

Lunar meteorites consist mainly ($>98\%$) of four minerals and glass derived from melting of the four minerals. These are plagioclase feldspar, mainly anorthite ($CaAl_2Si_2O_8$), pyroxenes ($[Mg,Fe,Ca]Si_2O_6$), olivine ($[Mg,Fe]_2SiO_4$), and ilmenite ($FeTiO_3$). Ilmenite is considerably less abundant ($\leqslant 5\%$) than the three silicate minerals. Minor and trace minerals reported from lunar meteorites include, in approximate decreasing order of importance, various spinels (Fe, Mg, Al, and Cr oxides), ülvospinel ($TiFe_2O_4$, but often Cr rich), kamacite and taenite (metallic FeNiCo), K feldspar ($KAlSi_3O_8$), tridymite and cristobalite (SiO_2), troilite (FeS), RE(rare-earth)-merrillite ($Ca_{16}[Y,REE]_2Mg_2[PO_4]_{14}$; the mineral is sometimes identified as whitlockite), apatite ($Ca_5[PO_4]_3[Cl,F]$), armalcolite ($[Mg,Fe]Ti_2O_5$) and tranquillityite ($Fe_8[Zr,Y]_2Ti_3Si_3O_{24}$) [both minerals were first discovered in the Apollo 11 basalts], baddeleyite (ZrO_2), pyroxferroite ($[CaFe]_6[SiO_3]_7$), rutile (TiO_2), zircon ($ZrSiO_4$), barringerite ($[Fe,Ni]_2P$), pentlandite ($[Fe,Ni]_9S_8$), zirconolite ($CaZrTi_2O_7$), monazite ($[Y,REE,Th]PO_4$), and hapkeite (vapor deposited Fe_2Si) (Marvin, 1983; Treiman and Drake, 1983; Koeberl et al., 1991; Yanai, 1991; Marvin and Holmberg, 1992; Takeda et al., 1993; Anand et al., 2003, 2004b; Demidova et al., 2003; Jolliff et al., 2003; Arai et al., 2004; Cohen et al., 2004; Gnos et al., 2004; Kuehner et al., 2005). In addition to impact glass, lunar meteorites contain maskelynite – vitrified plagioclase from shock melting. Shock also leads to the high-pressure polymorphs of olivine, ringwoodite and wadsleyite (in NWA 479; J.-A. Barrat, pers. comm.). All lunar meteorites contain trace ($\leqslant 0.1\%$) amounts of indigenous metallic iron. The brecciated lunar meteorite also contain FeNi ($<0.7\%$) derived from asteroidal meteorites, mainly chondrites. Nonetheless, using simple field techniques used to assess magnetism, all lunar meteorites are functionally nonmagnetic compared to chondrites.

The only Fe^{3+} minerals in lunar meteorites are terrestrial weathering products. Except for troilite, sulfide minerals are absent. Carbonate and sulfate minerals are absent, except as secondary minerals in hot-desert meteorites. Quartz has not been reported and tridymite and cristobalite are rare. [These generalizations are true of Apollo and Luna samples, too.]

Plagioclase, pyroxene, olivine, and ilmenite are the most common lunar minerals because lunar minerals are largely of igneous or metamorphic origin and the most common chemical elements in lunar meteorites are, in decreasing order of abundance, O, Si, Al, Ca, Fe, Mg, and Ti, which account for 99% of the mass of any lunar meteorite. [The observation that these seven elements were the "principal chemical elements" of the Moon was first made by Turkevich (1971) on the basis of results from the Surveyor and early Apollo and Luna 16 missions.] Each element occurs at concentrations of 1% or greater in the meteorites, except for Ti, which is $<1\%$ in all but a few basaltic meteorites. [Basalts in the Apollo collection have up to 11% TiO_2 ("high-Ti basalt"), corresponding to up to 20% normative ilmenite.] The next most common element is Na (0.3–0.5% as Na_2O), which is carried by the minor albite ($NaAlSi_3O_8$) component of the plagioclase, typically, $Ab_{3–6}$ in feldspathic meteorites and $Ab_{4–20}$ in mare basalts. Lithologies with more albitic plagioclase are rare (e.g., Arai et al., 2004). [Alkali anorthosites and alkali gabbronorites with plagioclase of $An_{65–85}$ and $Or_{2–20}$ are somewhat more common in the Apollo collection, but are still $<1\%$ of the mass of the regolith, except at Apollo 12 and 14 sites where they might be a few percent.] The Moon is depleted, compared to the Earth, in all volatile elements, including the alkalis. As a consequence, lunar meteorites have lower concentrations of Na, K, Rb, and Cs than most terrestrial igneous rocks (Fig. 3). Other elements in the 0.1–1% range in some meteorites are P, K, Cr, and Mn. The only important anion on the Moon is oxygen, thus when the metallic elements are expressed as oxides, the sum-of-oxides for the major and minor elements is 99–100%.

Because silica minerals are only trace phases, ilmenite is a minor phase, and the three silicate minerals each have approximately the same concentration of SiO_2, there is little variation in SiO_2, 43–48%, among lunar meteorites. [Some rare lithologies of the Apollo collection contain substantial free silica as glass, cristobalite, or tridymite, leading to enrichment in SiO_2 (Fig. 4).] This small range contrasts strongly with that of terrestrial rocks, which range from essentially 0% to 100% SiO_2. There is a wide range in other major elements in lunar meteorites, however. For example, Al_2O_3 concentrations range over a factor of 6.6, from 4.7% to 31.2%, which corresponds to a range in normative plagioclase from 13% (NWA 773, olivine cumulate) to 88% (Dhofar 81, brecciated anorthosite). In each case, the Al-poor phases are mainly pyroxene and olivine. Because most lunar meteorites are polymict breccias, that is, mechanical mixtures, and all first-order variation in major element concentrations among lunar meteorites results from variation in the ratio of plagioclase to the sum of the three iron-bearing minerals, the concentrations of FeO, MgO, and FeO + MgO each strongly anticorrelate with those of Al_2O_3, CaO, and Al_2O_3 + CaO (e.g., Fig. 4). In effect, on a plot of FeO + MgO vs. Al_2O_3 or CaO (Fig. 4; or FeO vs. Al_2O_3, e.g., Korotev et al., 2003b), all lunar meteorites plot on a

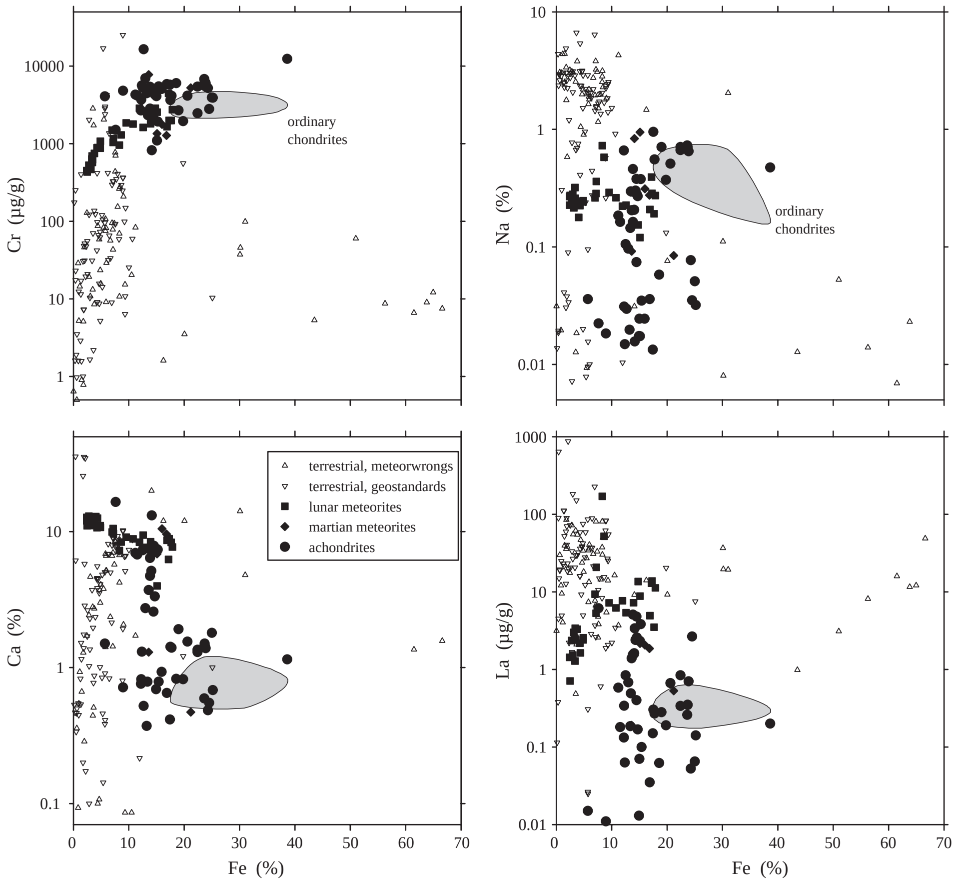

Fig. 3. Comparison of the compositions of lunar meteorites to asteroidal achondrites and terrestrial rocks. Points for "terrestrial, meteorwrong" ($N = 57$) represent rocks submitted to the author as a possible meteorite or lunar sample by amateurs. Points for "terrestrial, geostandard" ($N = 82$) are for international geochemical reference standards; all represent common terrestrial rock types (Korotev, 1996; excludes minerals, monomineralic rocks, ores, and unconsolidated sediments). The gray fields comprise ordinary chondrites, which represent 96% of all asteroidal stony meteorites. Chondrite data from Wasson and Kallemeyn (1988); achondrite data from Mittlefehldt et al. (1998), McSween and Treiman (1998), and sources cited therein.

mixing line between anorthite and the mean composition of the Fe- and Mg-bearing minerals. [This observation is true of all polymict and many monomict Apollo samples, too.] Because of their simple mineralogy, there is no mechanism for lunar rocks to plot off the trend of Fig. 4a. [Some rare monomict lithologies in the Apollo collection represented only by very small samples do not plot on the trend.] As a result of the correlation of Fig. 4a, Al_2O_3 concentrations serve as first-order

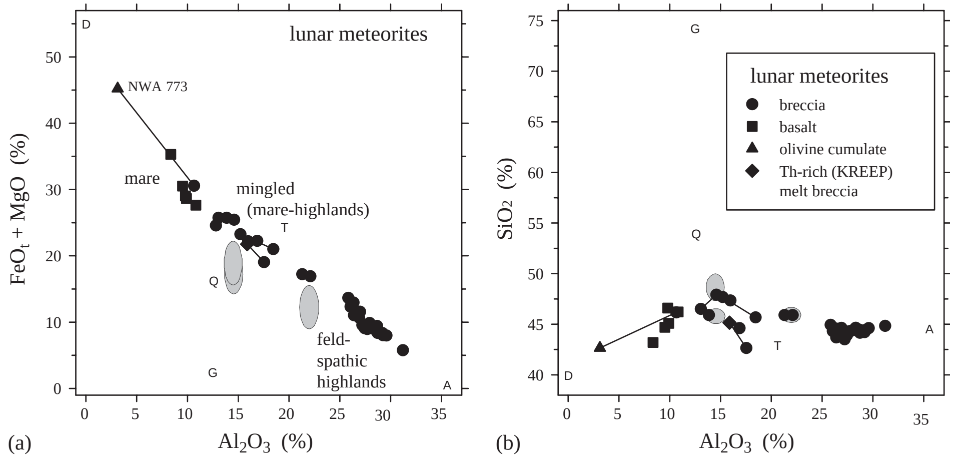

Fig. 4. Variation in $FeO_t + MgO$ (total Fe as FeO, mass percent) and SiO_2 with Al_2O_3 among lunar meteorites (solid symbols). In this and some other figures, lines connect (1) different stones of paired meteorites for which the different stones have different compositions or (2) the different lithologies of dilithologic meteorites. (a) Most of the variation in major-elements involves variation in the ratio of plagioclase to pyroxene-plus-olivine, with breccias from the feldspathic highlands being at one extreme and basalts from the maria at the other. Most, but not all (Fig. 10b), of the meteorites of intermediate composition are breccias composed of subequal amounts of material from the feldspathic highlands and the basaltic maria. (b) Because the three main minerals of the lunar crust (plagioclase, pyroxene, olivine) all have similar SiO_2, there is little variation in bulk SiO_2 among lunar meteorites. The letter symbols represent lithologies of extreme composition in the Apollo collection not represented among the lunar meteorites. These include highly feldspathic ferroan anorthosite (A, 269-g sample 15415; Ryder, 1985), dunite (D, 59-g samples 72415–8; LSPET, 1973), granite (G, 1.8-g sample 14321,1028; Warren et al., 1983b), quartz monzogabbro (Q, 0.023-g sample 14163,7069; Jolliff, 1991), and troctolite (T, 156-g sample 76535; Rhodes et al., 1974). Except for ferroan anorthosite, these lithologies are all rare in the Apollo collection. The three ellipses represent the composition of the regoliths at the landing sites of Surveyors 5 (mare), 6 (mare), and 7 (highlands), with the highest-Al_2O_3 point (22%) representing Surveyor 7 (Turkevich, 1971, converted to oxide percentages assuming that the sum of the measured element oxides total 99% of the mass of the regolith; the ellipses are sized to represent the reported 90% confidence levels).

compositional classification parameters for lunar meteorites, much in the way SiO_2 concentration is used to classify lunar igneous rocks. To a good first approximation, the proportion of normative plagioclase in a lunar meteorite can be obtained by dividing the Al_2O_3 concentration by 35.5%, the concentration in An_{96} plagioclase.

All lunar meteorites with low Al_2O_3 (<15%) are basalts, breccias dominated by basalt, or, in one case, an olivine cumulate from a basaltic magma (NWA 773). Compared to terrestrial basalts, lunar basalts are poor in Al, alkali elements, and water (0.00% H_2O) and are rich in Fe, Ti, and Cr (Fig. 5). SiO_2 ranges from 43% to 46% among the basaltic lunar meteorites. [When Apollo and Luna basalts are

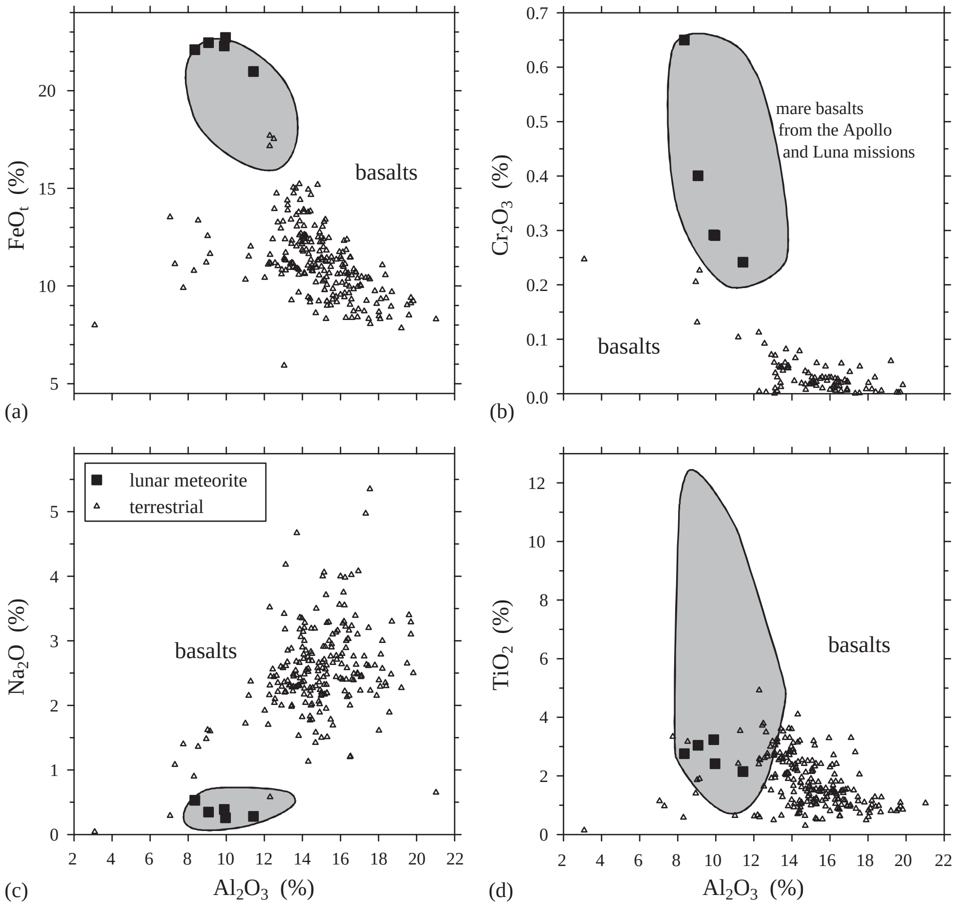

Fig. 5. Comparison of the compositions of the five unbrecciated basaltic lunar meteorites to mare basalts from the Apollo and Luna missions (gray fields) and terrestrial basalts (triangles). Lunar mare basalts have high FeO_t (total Fe as FeO), Cr_2O_3, and TiO_2, low Al_2O_3, and very low Na_2O compared to terrestrial basalts. Only some Archean basalts are similar. Terrestrial data from BVSP (1981). In (b), points for NWA 032 and LAP 02205 overlap; the two meteorites are similar in composition because they derive from the same source crater.

considered, the range extends from 38% to 48%. The low-Si Apollo basalts are ilmenite rich, "high-Ti basalts" (6–14% TiO_2) in the compositional classification system used for Apollo and Luna basalts (e.g., Papike et al., 1998). High-Ti basalt has not yet occurred among the lunar meteorites although it was the principal type of basalt acquired on the Apollo 11 and 17 missions. With 2–3% TiO_2, the five lunar meteorites that are unbrecciated basalts, as well as the basalt component of breccias MET 01210 and NWA 3136, are all "low-Ti basalts" (1–6% TiO_2) in the Apollo classification system, despite that they are high in Ti compared to terrestrial basalts

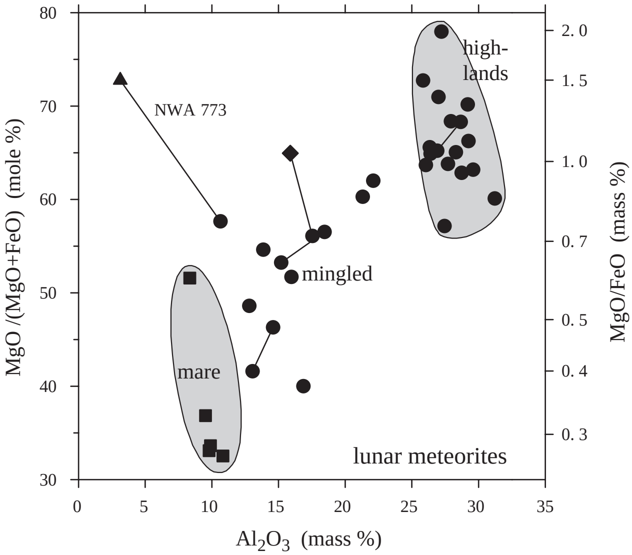

Fig. 6. Variation in the MgO/FeO ratio with Al_2O_3 concentration in lunar meteorites. Although the feldspathic lunar meteorites (highlands) are all similar in composition, MgO/FeO varies considerably and the variability is not correlated with Al_2O_3 ($R^2 = 0.01$). Meteorites from the feldspathic highlands have greater MgO/FeO ratios than those from the maria. The gray fields encompass the crystalline basaltic (mare) and the feldspathic (highlands) meteorites.

(Fig. 5d). The basalt component of the other basalt-rich breccias (Yamato 793274/981031, QUE 94281, EET 87521/96008, and NWA 773) is "VLT (very-low-Ti) basalt" (<1% TiO_2).]

At the other extreme, approximately half of the lunar meteorites are highly feldspathic (26–31% Al_2O_3, i.e., 73–88% normative plagioclase). All feldspathic lunar meteorites are breccias. Normatively, they are noritic and troctolitic anorthosites, although a few correspond to anorthositic norites or troctolites (Stöffler et al., 1980). The feldspathic meteorites have a wide range of MgO/FeO or Mg' (mole % Mg/[Mg + Fe]), but all have greater Mg' than the basalts (Fig. 6). After Al_2O_3/(FeO + MgO), Mg' is next most variable major-element parameter among lunar meteorites. In the feldspathic meteorites, Mg' correlates with normative olivine abundance (Korotev et al., 2003b) and, thus, reflects the olivine to pyroxene ratio. Because Sc is carried mainly by pyroxene and Cr is carried mainly by chromite associated with olivine, Cr/Sc increases with MgO/FeO among both feldspathic and basaltic lunar meteorites (Fig. 7). This relationship is useful because Cr/Sc can be measured with a precision of 1% by INAA (instrumental neutron activation analysis). Most terrestrial rocks have lower Cr (Fig. 3) and lower Cr/Sc than any lunar rock (Fig. 7). Even the feldspathic lunar meteorites (~80% plagioclase) have high Cr (0.06–0.15% as Cr_2O_3) compared to most terrestrial igneous rocks that are considerably more mafic.

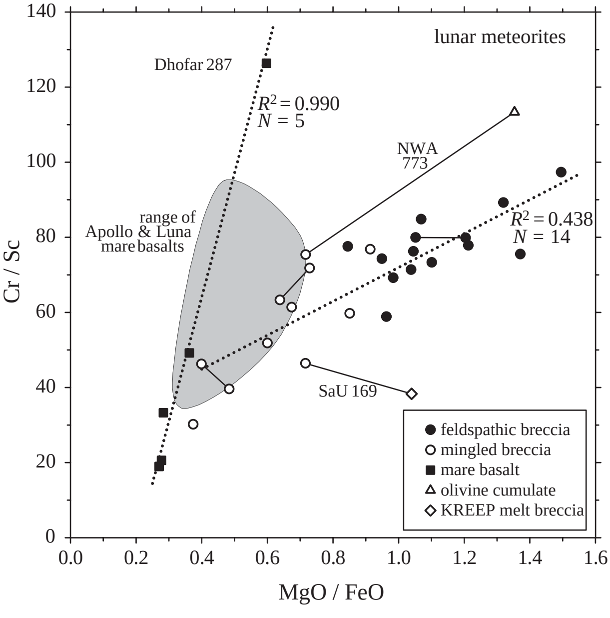

Fig. 7. Among the five lunar mare-basalt meteorites, Cr/Sc correlates strongly with MgO/FeO, although the correlation is weak if the Apollo and Luna basalts (gray field) are included. Among feldspathic lunar meteorites (filled circles), there is also a weak correlation between the two ratios, but with a different slope. The dotted regression lines are defined by the filled symbols. Mingled breccias are those with <25% Al_2O_3 that contain both mare and highlands materials. Cr/Sc is high on the Moon compared to the Earth. Of the 138 terrestrial samples of Fig. 3, only 9 (6.5%) have Cr/Sc ratios lying within the range (19–126) of the lunar meteorites of this figure. For most (116), Cr/Sc is lower; for a few (13, mostly ultramafic), it is have higher.

Feldspathic lunar meteorites consistently have low concentrations of incompatible elements by terrestrial standards, typically 4–10 times the concentrations in ordinary chondrites. All feldspathic lunar meteorites have strong positive Eu anomalies (Fig. 8), i.e., they are enriched in Eu with respect to the other (trivalent) REEs. Because of the low oxygen fugacity of the Moon, virtually all Eu is divalent. Divalent Eu substitutes for Ca in plagioclase. On the Moon, Eu is a compatible trace element whereas the other REE are incompatible. Basaltic lunar meteorites have concentrations of incompatible elements several times greater than those of the feldspathic meteorites and all have negative Eu anomalies.

In this paper I use the term "mingled" meteorites to include all the brecciated meteorites that are not highly feldspathic, i.e., those with ⩽22% Al_2O_3. Many dealers and collectors of lunar meteorites use a classification system in which most lunar meteorites are categorized as either LUN A (anorthosite) or LUN B (basalt). This system is overly simple in that there is no reason to believe [largely on the basis of our Apollo experience] that the anorthosite:basalt ratio in lunar breccias cannot

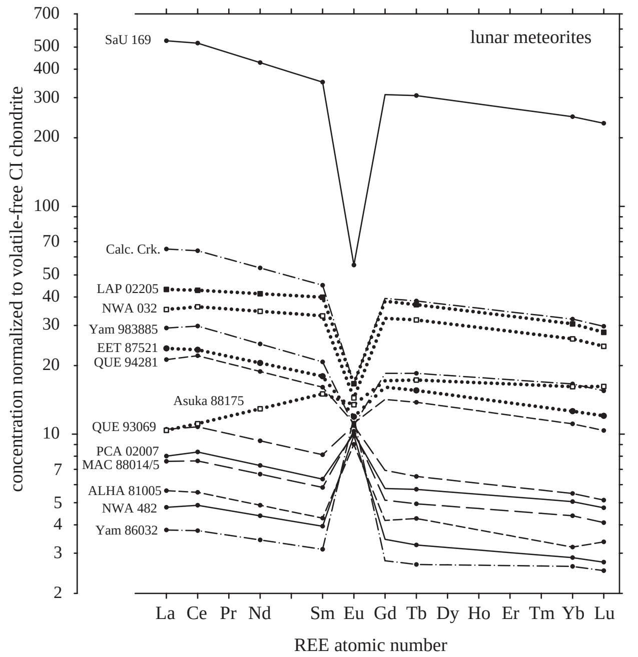

Fig. 8. All feldspathic (⩾25% Al_2O_3) lunar meteorites have low concentrations of trivalent REEs and positive Eu anomalies. The crystalline basalts (square symbols, dotted lines) and basaltic breccias (circle symbols, dotted lines) have negative Eu anomalies as does the KREEP-rich breccia, SaU 169. The basalts are relatively depleted in light REE compared to the REE-rich nonmare meteorites. Concentrations are normalized to $1.36C_{REE}$, where C_{REE} are the concentrations of "mean C1 chondr." from Table 1 of Anders and Grevesse (1989). This normalization yields REE concentrations equivalent to those in ordinary chondrites. For simplicity, only those elements determined precisely by INAA are plotted (points); normalized concentrations other elements are interpolated. This plot also demonstrates the constancy of divalent Eu (Fig. 11) compared to the range for trivalent REE. Data are from Fagan et al. (2002), Gnos et al. (2004), Hill and Boynton (2003), Jolliff et al. (1991b, 1998, 2004), and Korotev et al. (1983, 1996, 2003a, b, 2004).

cover the complete range of 0:100 to 100:0. At this writing there is a compositional gap between the feldspathic lunar meteorites with the lowest Al_2O_3 (ALHA 81005 and Yamato 791197, with 26%) and the mingled meteorite with the highest Al_2O_3 (Yamato 983885, with 22%), but that gap may be filled as more lunar meteorites are discovered.

An often cited characteristic of lunar meteorites is that FeO/MnO (or essentially equal Fe/Mn) is nearly constant and high compared to basaltic achondrites (Warren et al., 1983c; Treiman and Drake, 1983; Hill et al., 1991; Anand et al., 2003, 2004a). Whole rock FeO/MnO ratios are 70 ± 5 (mean $\pm$ standard deviation) for the feldspathic lunar meteorites ($Al_2O_3 > 20\%$), 72 ± 4 for the basaltic meteorites ($Al_2O_3 < 20\%$), and 73 for anomalous SaU 169. Whole rock FeO/MnO ratios are

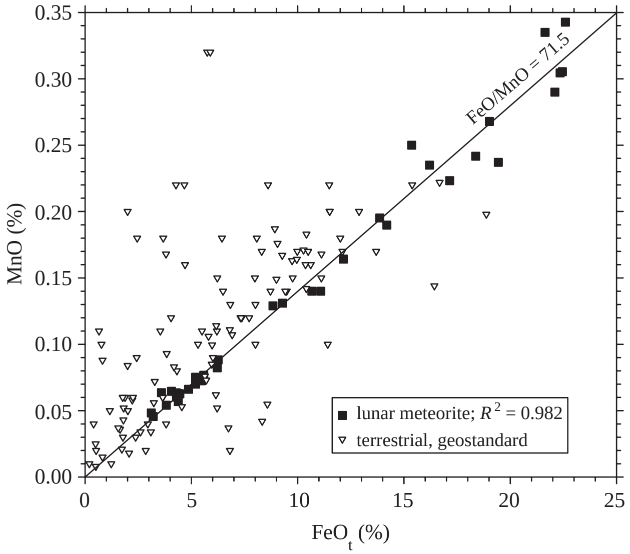

Fig. 9. Comparison of whole-rock MnO and FeO (total Fe as FeO) in lunar meteorites and terrestrial rocks. The line represents the mean FeO/MnO ratio of the lunar meteorites, 71.5 (standard deviation = 5.2). The terrestrial data are from Govindaraju (1994) for well-characterized international geostandards; data for ores, minerals, monomineralic rocks, and unconsolidated sediments are not plotted. Most points represent igneous rocks. Although the value is not particularly significant, the mean FeO/MnO of the terrestrial rocks plotted here is 64 (standard deviation = 47). The whole-rock FeO/MnO is useful for distinguishing lunar meteorites from asteroidal achondrites, but is not particularly useful for distinguishing lunar material from terrestrial material.

not particularly useful for distinguishing lunar from terrestrial material, however, because many terrestrial rocks fall in the range of the lunar meteorites (Fig. 9). The constancy of FeO/MnO is a result of the absence of ferric iron in lunar silicates and oxides and that there is no geochemical process on the Moon that can efficiently separate Mn^{2+} from Fe^{2+}.

A fascinating feature of lunar meteorites [and most lunar samples] is that concentrations of any pair of the highly incompatible elements, e.g., Sm and Th (Fig. 10a), are strongly correlated. Given the concentration of any one incompatible element, the concentrations of all others can be estimated with considerable accuracy (~10%), particularly in nonbasaltic polymict samples having moderately high to high concentrations of such elements (e.g., Taylor and Jakeš, 1974). This characteristic is useful in that the concentrations of Th and some REEs on the lunar surface were measured from orbit by Lunar Prospector. Thus, a map of the distribution of Th is essentially also a map of the distribution of Y, Zr, Nb, or Sm.

An important complication to the simplicity of lunar meteorite geochemistry is that although all of the lunar meteorites of intermediate composition (13–22%

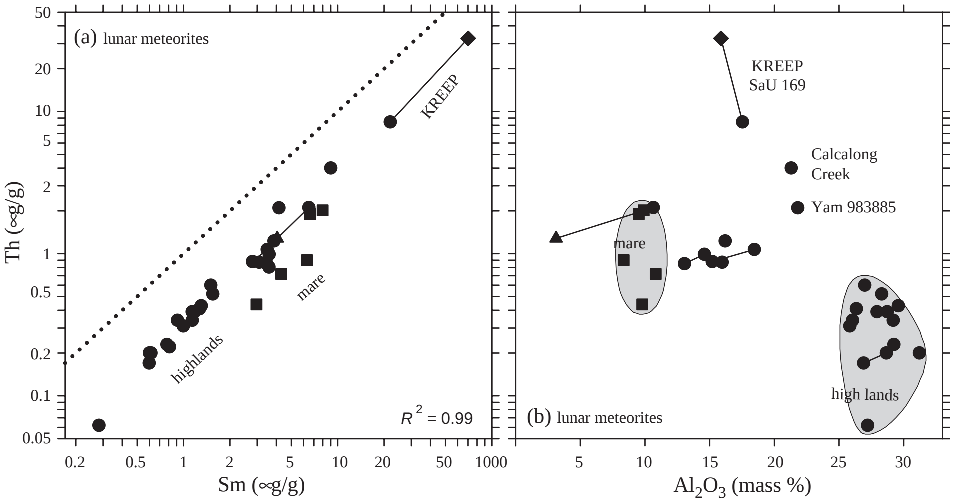

Fig. 10. (a) Concentrations of any pair of highly incompatible elements are strongly correlated among lunar meteorites. The dotted line represents the Th/Sm ratio in CI chondrites. (b) Some brecciated lunar meteorites with intermediate Al_2O_3 (SaU 169, Calcalong Creek, Yamato 983885) cannot be simple binary mixtures of mare basalt and material of the feldspathic highlands because they have greater concentrations of incompatible elements like Th than any mixture. The two gray fields encompass the unbrecciated basaltic (mare) and feldspathic (highlands) meteorites. Data are from many literature sources.

Al_2O_3) are breccias, not all are simple mixtures of the two extreme rock types, anorthosite and basalt. Some lunar meteorites [and many Apollo rocks] with Al_2O_3 intermediate to those of the basaltic and feldspathic meteorites have greater concentrations of incompatible elements than either extreme (Fig. 10b). Most anomalous is SaU 169 for which the impact-melt-breccia lithology has concentrations of incompatible elements that are ~30 times those of mixtures of feldspathic and basaltic meteorites (Fig. 10b) and several times greater than that of average terrestrial crust. Clearly, some brecciated meteorites contain a third lithologic component, one of intermediate (noritic) major-element composition that is highly enriched in incompatible elements, that dominates SaU 169, and that is not represented among the lunar meteorites as an igneous or plutonic rock.

[The Th-rich component of SaU 169 is designated KREEP in the Apollo lunar literature. The name is an acronym for K, REE, and P, all incompatible elements that have high concentrations in rocks and glass identified as KREEP (Hubbard et al., 1971). The non-standard term prevails because there is no terrestrial counterpart and the component is elusive as an igneous or plutonic lithology on the Moon. KREEP-bearing rocks are much more common in the Apollo collection than among the lunar meteorites. Most Apollo KREEP rocks, like the lunar meteorite SaU 169, are impact melt breccias, glasses, or regolith breccias; some apparently igneous rocks from Apollo 15 are identified as KREEP basalts. It is generally believed that correlations among incompatible elements such as that of Fig. 10a occur because KREEP is the only carrier of incompatible elements on the Moon and some form of KREEP occurs in all polymict breccias as a lithologic component and in some igneous rocks as an assimilant (e.g., Anand et al., 2003), but in relative abundances that differ from rock to rock over a range of 0–100%.]

One compositional characteristic of those lunar meteorites not dominated by basalt is that concentrations of Eu are nearly constant, e.g., 0.7–0.9 μg/g among the feldspathic lunar meteorites, but increase somewhat with increasing trivalent REEs (Figs. 8 and 11). This relationship occurs for a combination of reasons. Eu is carried entirely by plagioclase, the plagioclase composition and relative abundance in the nonbasaltic (mainly feldspathic) lunar meteorites is nearly constant, in nonmare plagioclase Eu concentrations increase with albite content of the plagioclase, and the plagioclase of Sm-rich nonmare rocks (e.g., SaU 169) is more albitic than that of low-Sm rocks (e.g., ALHA 81005). The behavior of Eu is useful for distinguishing lunar from terrestrial material because among terrestrial rocks, Eu concentrations and Sm/Eu ratios are much more variable (Fig. 11). [The range of Eu concentrations among all analyzed lunar basalt types is greater, however, 0.3–3.3 μg/g.]

All brecciated lunar meteorites have high concentrations of siderophile elements compared to igneous and plutonic rocks of the Moon (Fig. 12) and terrestrial sediments and igneous and plutonic rocks. In a typical brecciated lunar meteorite, 1–2% of the mass and 99+% of the highly siderophile elements derive from chondrites (Korotev et al., 2003b), with perhaps a minor fraction from iron meteorites.

As noted above, except for trace troilite, sulfide phases are virtually nonexistent in lunar meteorites. I am unaware of any data for S concentrations in lunar meteorites. [Sulfur in Apollo mare basalts ranges from 0.05% to 0.2%; in nonmare igneous and plutonic rocks, S concentrations are usually not reported because they are so low. The same is true of all volatile and labile elements.] Except for Zn, chalcophile elements have been measured in only a couple of lunar meteorites, both regolith breccias (ALHA 81005, MAC 88105). Zn concentrations may reach a few tens of μg/g in regolith breccias, but other chalcophile elements are much less than 1 μg/g; (Verkouteren et al., 1983; Lindstrom et al., 1991a, b). [Among Apollo samples, regolith fines have the greatest concentrations of labile and chalcophile elements and these elements largely derive from meteorites (Boynton et al., 1976). Thus, we can assume that lunar meteorites that are regolith breccias will have the greatest concentrations of chalcophile elements.] Because fragmental breccias were formed from unconsolidated material that was probably deeper in the regolith than that for regolith breccias (McKay et al., 1986), fragmental breccias contain lower abundances of elements derived from asteroidal meteorites.

1.5. Launch pairing

When the second lunar meteorite was studied and lunar meteorites were still regarded as extremely rare, a conservative approach led us to conclude that both, ALHA 81005 and Yamato 791197, were likely ejected from the same crater by a

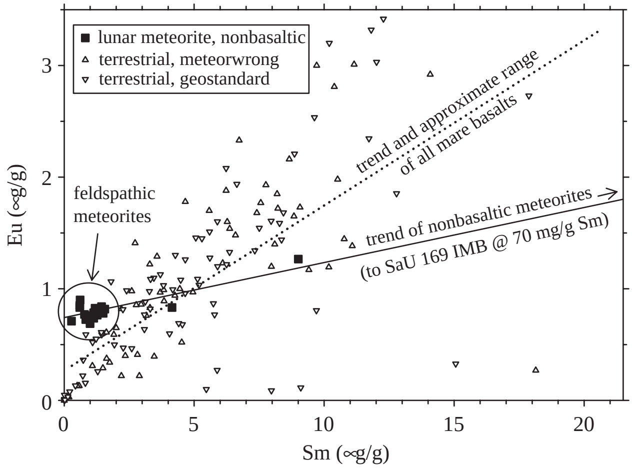

Fig. 11. There is little variation in Eu abundance among nonbasaltic lunar meteorites because Eu is carried almost exclusively by plagioclase and plagioclase abundances of nonbasaltic rocks are all similar. The solid line is defined by the mean composition of the feldspathic lunar meteorites (Sm < 2 μg/g) and the impact-melt breccia of SaU 169 (off scale at 70 μg/g Sm and 4.2 μg/g Eu; Gnos et al., 2004). [Apollo samples follow the same trend.] Although SaU 169 has a smaller proportion of plagioclase than the feldspathic meteorites, the line nevertheless has a positive slope because there is a strong correlation between abundances of Eu and Na in plagioclase from nonbasaltic lunar rocks and the plagioclase in SaU 169 is considerably more albitic ($Ab_{19–39}$ in the plagioclase of the melt matrix) than that of the feldspathic meteorites (typically, $Ab_{3–6}$). A graph of Sr vs. Sm would be similar for the same reasons. Most hot-desert lunar meteorites, however, are contaminated with Sr from terrestrial alteration (e.g., Korotev et al., 2003b). Among mare basalts (Apollo, Luna, lunar meteorite), the correlation between Eu and Sm is not as strong ($R^2 = 0.65$) but is largely defined by the dotted line. Terrestrial data from the sources of Fig. 3.

single impact event, i.e., they were launch paired (Lindstrom et al., 1986). There is still no strong evidence that these two particular meteorites are not launch paired (Warren, 1994; Eugster, 2003). The large number and variety of lunar meteorites now known along with distinct differences in cosmic-ray exposure histories argue, however, that the number of source craters represented by the meteorites must be a large fraction of the number of meteorites (Warren, 1994; Eugster, 1989; Nishiizumi, 2003; Korotev et al., 2003b).

Known or strongly suspected cases of launch pairing are the following. Basalts Yamato 793169 and Asuka 881757 are launch paired on the basis of compositional similarity to each other and dissimilarity to other basaltic lunar meteorites, similarity of their cosmic-ray exposure histories, and similarity in crystallization ages (Warren and Kallemeyn, 1993; Thalmann et al., 1996; Korotev et al., 2003a; Fernandes et al., 2005). Similarly, basalt NWA 032 originates from the same crater, and possibly even the same flow, as the LAP stones (Korotev et al., 2004). Dhofar 287 (Anand et al., 2003) is distinct. Thus, the five unbrecciated basalts represent three lunar craters.

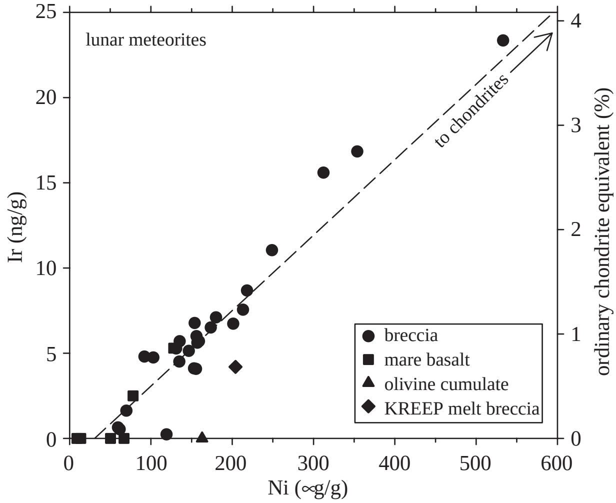

Fig. 12. Siderophile elements in brecciated lunar meteorites (circles) derive almost entirely from asteroidal meteoroids and interplanetary dust particles (micrometeoroids) that strike the lunar surface. The highest concentrations occur in regolith breccias because the lunar surface accumulates micrometeorites with time. Fragmental breccias have lower concentrations because the material from which they derive was deeper in the lunar regolith. The high end of the Ir scale, 25 ng/g, corresponds to ~4 mass percent meteoritic material as ordinary chondrites. The dashed line is defined by the mean concentrations in the brecciated lunar meteorites and ordinary chondrites (chondrite data of Wasson and Kallemeyn, 1988, weighted by relative abundance of chondrite types).

Among the mingled meteorites, there is strong petrographic and compositional evidence that the "YQ" meteorites (Arai and Warren, 1999), QUE 94281 and paired stones Yamato 793274/981031 (Lorenzetti and Eugster, 2002), derive from a common regolith (Arai and Warren, 1999; Jolliff et al., 1998). There is compositional, textural, lithologic, and launch-age evidence that EET 87/96 is also launched paired with the YQ meteorites (Korotev et al., 2003a; Nishiizumi, 2003). It has not yet been firmly established or rejected that any of the other basalt-rich breccias are related to each other or to the YQE meteorites, although there is compositional and petrographic evidence that breccia MET 01210 is also launch-paired with the Asuka-Yamato basalts (Arai et al., 2005). There is weak evidence that the other mingled meteorites all derive from separate craters. NWA 3136 and MET 01210 are somewhat similar to each other in composition (Korotev and Irving, 2005) and the basalt component of both appears to be low-Ti basalt (unlike the other basalt-rich breccias, all of which are composed of VLT basalt), but our unpublished compositional data indicate that NWA 3136 has a significantly greater Mg/Fe than MET 01201. The regolith breccia lithology of NWA 773 contains clasts of the olivine cumulate lithology, and no such clasts have been reported in any of the otherwise similar basaltic breccias. Thus, the six basalt-rich breccias may represent as many as four source craters. Calcalong Creek and Yamato 983885, which are more feldspathic, have similar major-element compositions, but cosmic-ray exposure data appear to preclude launch pairing (Lorenzetti et al., 2005). [On one hand, our Apollo experience argues that compositional data alone cannot be used to outright reject the hypothesis of launch pairing. Many kinds of rocks were collected at the Apollo 17 site, for example. On the other hand, the Apollo 17 site was deliberately chosen because of its geological complexity and most places on the Moon are not so diverse.]

It has not been demonstrated conclusively that any of the feldspathic lunar meteorites is launch paired with another, although pairings likely exist. A number of launch pairings are allowed by ejection ages derived from cosmic-ray exposure data, e.g., ALHA 81005, Yamato 791197, and Dhofar 081 (Warren, 1994; Nishiizumi, 2003; Eugster, 2003) or MAC 88104/5 and NWA 482 (Nishiizumi, 2003). Among the candidates, however, no two meteorites are so lithologically, petrographically, and compositionally similar that a relationship is self-evident. For example, Yamato 791197 contains a higher proportion of mare material than ALHA 81005, but it is not possible to add any type of mare basalt to ALHA 81005 and obtain a mixture with a composition like that of Yamato 791197 (Korotev et al., 2003b). Such mixing relationships would be expected [again, largely on the basis of our Apollo experience] for two different regolith samples taken within a few km of each other. Dhofar 081 is the most feldspathic lunar meteorite (30.4% Al_2O_3, Warren et al., 2001; ~32%, Greshake et al., 2001) and one of the most ferroan ($Mg' = 60$), whereas ALHA 81005 and Yamato 791197 are the least feldspathic (26%) and most magnesian (ALHA: $Mg' = 73$). It would be unlikely that feldspathic regoliths with such different petrologic precursors would occur within the target area of an impact making a crater a few km in diameter. There are some compositional similarities between MAC 88104/5 and NWA 482 in that NWA corresponds in composition to a mixture of MAC and anorthosite (Korotev et al., 2003b). MAC 88104/5 is a regolith breccia and NWA 032 is an impact-melt breccia, however. This difference does not exclude the possibility that the two meteorites are launch paired, but it does not provide evidence for a relationship. The feldspathic lunar meteorites likely represent numerous random locations in the feldspathic highlands (Korotev et al., 2003b).

2. Other observations relevant to lunar geochemistry

2.1. Astronomical observations

Since at least the time of Galileo (Whitaker, 1978) or even the ancient Greeks (Spudis, 1996), people have recognized that the surface of the Moon is dichotomous with respect to albedo and topography. The highlands or terra are light in color and have rugged topography. The seas or maria are dark, circular, and smooth. (Following the inconsistent convention of the lunar geological and geochemical literature, I use the terms mare [singular] or maria [plural] and highlands in this paper.) Gilbert (1893) argued in that impacts were the dominant geologic process on the Moon and Baldwin (1942, 1949) and Dietz (1946) advocated that most lunar craters were of impact origin, although others attributed craters to volcanic processes. Even as late as the 1960s there was disagreement about whether the Moon was cold, primitive (chondritic), and undifferentiated or had been geologically active and was chemically differentiated (Wilhelms, 1993; Spudis, 1996). By 1959, it was recognized that the surface material of the Moon was fine grained "dust" (e.g., Wilhelms, 1993). Telescopic observations revealed color differences between mare and highland regions as well as color differences between and within maria. These differences were attributed to differences in composition and mineralogy, particle size, and surface-exposure effects associated with absence of an atmosphere (Adams, 1967; KenKnight et al., 1967; Hapke, 1968; McCord, 1969).

2.2. Luna, Ranger, Lunar Orbiter, and Surveyor

The first images of the Moon obtained by spacecraft were those of the early Russian Luna missions, most notably Luna 3 (1959 flyby; first farside images), Luna 9 (1966, first soft landing), Luna 12 (1966, orbiter), and Luna 13 (1966, soft landing). The US Ranger 7, 8, and 9 missions (1964–1965, hard landings) obtained images of potential Apollo landing sites.

Five Lunar Orbiter missions acquired high-resolution photographic images of most of the Moon's surface from August 1966, through August 1967. For much of the lunar surface, these images (Bowker and Hughes, 1971; Gillis, 2004) still provide the best geomorphological data available (e.g., Schultz, 1976). Largely on the basis of Lunar Orbiter images, it was possible to make geologic maps and derive the relative chronological order in which the major impact basins were excavated (Wilhelms and McCauley, 1971; Wilhelms, 1987). The South Pole-Aitken basin on the farside is one of the oldest. The last large basin to form was Orientale on the western limb, and before that Imbrium on the nearside.

The first data for the chemical composition of lunar materials obtained from the lunar surface were acquired by the Surveyor 5 (September 1967), Surveyor 6 (November 1967), and Surveyor 7 (January 1968) spacecraft. Surveyor 5 landed in Mare Tranquillitatis, about 24 km away from the eventual landing site of the Apollo 11 lunar module. Surveyor 6 landed in another mare region, Sinus Medii, very near the center of the nearside of the Moon as viewed from Earth. Surveyor 7 touched down in the highlands less than one radius from the rim of the prominent rayed crater Tycho (85 km diameter) in the Moon's southern hemisphere on the nearside. Each robotic lander had an alpha-particle backscatter instrument that obtained concentration data for the major elements heavier than hydrogen (Turkevich, 1971).

The principal conclusions (Jaffe et al., 1970) drawn from the Surveyor chemical analyses were (1) the three most abundant elements in lunar surface materials are the same as those in the Earth's crust (O, Si, and "probably" Al), (2) the composition of lunar surface material was inconsistent with the Moon being the source of "most meteorites" and tektites, (3) the measured concentration of oxygen was "sufficient to form oxides of all the metals," and (4) overall, the compositions were most consistent with basalt. This last conclusion, along with observations of apparent volcanic morphologies in the Lunar Orbiter images, provided "strong circumstantial evidence that some melting and chemical fractionation of lunar material has occurred in the past" (Jaffe et al., 1970). In detail, the composition of the two mare sites were nearly identical and "may be best characterized as basaltic with a high iron content" (Phinney et al., 1970). The highlands (Surveyor 7) site was richer in Al and poorer in Fe and described as "basaltic with a low iron content" (Phinney et al., 1970; Fig. 4a). It was recognized that the low iron concentration of the highlands site could account for the lower albedo of the highlands. [In retrospect, the intermediate compositions of the two Surveyor mare sites (ellipses at 15% Al_2O_3 on Fig. 4) suggest that the corresponding regoliths each contain a substantial proportion of nonmare (high Al) material. This observation is entirely consistent with mare regolith samples collected on the Apollo and Luna missions. For example, the Apollo 11 regolith, from Mare Tranquillitatis, contains 28% nonmare material (Korotev and Gillis, 2001). All three Surveyor analyses plot off the trend of Fig. 4a, however. In detail, the derived Surveyor results appear to underestimate Al_2O_3 or overestimate FeO and MgO.]

2.3. Clementine and Lunar Prospector

The Clementine spacecraft orbited and mapped the Moon during 71 days (348 orbits) using five imaging systems in early 1994. Clementine was the first mission to obtain global spectral data of any type from the Moon. The most useful mineralogical and geochemical data has been obtained from the UV–VIS (nominally, ultraviolet–visible) camera, which had a 6-position spectral filter wheel with wavelengths of 415, 750, 900, 950, 1000 nm and a broad-band filter covering 400–950 nm. Pixel resolution for the UV–VIS camera varied from 80 to 320 m (Edwards et al., 1996). The 5-band reflectance spectra have been used to derive maps of the distribution of iron (Fe^{2+} as FeO; Fig. 13) and titanium on the lunar surface (Lucey et al., 1995, 2000; Gillis et al., 2004). The algorithms used to estimate FeO and TiO_2 concentrations are empirical and calibrated using Apollo regolith compositions. Nevertheless, even in the absence of Apollo samples, the method for FeO relies in large part on the depth of the pyroxene absorption band, which correlates with the relative abundance of pyroxene and FeO.

Some first-order information provided by Clementine includes the following. There is a strong correlation between albedo and derived-FeO concentration; the dark maria are rich and the light highlands are poor in FeO. Concentrations of TiO_2 vary widely among different maria and even within some maria. The highlands are very low in TiO_2. At shorelines, mixing of mare and highlands materials occurs over distances of 10–20 km. Impacts into the mare of meteoroids forming craters of ~10 km or more in diameter excavate nonmare material and emplace it as ejecta on basalt outside the crater, so basalt deposits in basins are not many km thick. Spectra of ejecta from small fresh craters are different (bluer) than nearby areas that appear not to have been disturbed (redder), indicating that some space weathering occurs at the surface. In some basins and large craters in the highlands, there are large regions of exposed slopes (minimal regolith) that show no spectral evidence for pyroxene or

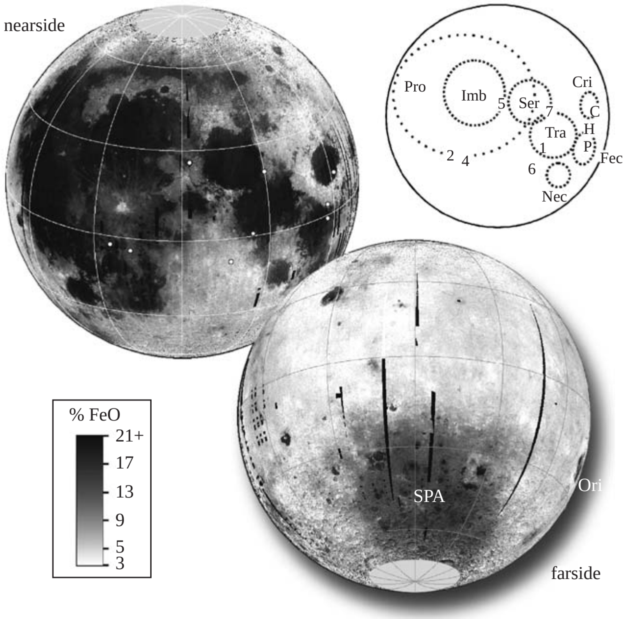

Fig. 13. Maps of FeO (wt%) distribution (Gillis et al., 2004) on the lunar surface based on Clementine UVVIS data. Locations of the Apollo and Luna landing sites are denoted by small white dots on the nearside hemisphere. The two hemispheres shown are in orthographic projection with a resolution of 5 km per pixel, and centered on 20° north latitude, 0° longitude and 20° south latitude, 180° longitude. Latitude and longitude lines have 30° spacing, originating at 0° latitude and 0° longitude. Black rectangular areas and gray ellipsoids around the poles are areas of missing data. The key is given in the circle on the upper right: Apollo 11 (1), …, Apollo 17 (7), Luna 16 (F), Luna 20 (H), Luna 24 (C). The approximate location of major basins discussed in the text are indicated by the dotted ellipses: Crisium, Fecunditatis, Imbrium, Nectaris, Serenitatis, South Pole-Aitken (farside), Orientale (limb), and Tranquillitatis. The approximate location of the alleged Procellarum basin is also shown (Whitaker, 1980). The maps were prepared by Jeff Gillis.

olivine. [In the Apollo context, these regions are interpreted as ''pure anorthosite'' (Hawke et al., 2003).] Stratigraphically higher material may contain mafic minerals. Spectral reflectance data for central peaks of craters in the highlands of 40–180 km diameter show that the lower crust is heterogeneous and that concentrations of mafic minerals increase somewhat with depth [''comparable to anorthositic norite'' (Tompkins and Pieters, 1999)]. The South Pole-Aitken basin on the farside is huge and deep. There is some mare fill, but nonmare locations appear to consist of more mafic [noritic] material than typical surface material of the highlands crust. (I have made these generalizations based largely on the works of Giguere et al., 2000; Gillis and Spudis, 2000; Hawke et al., 2003; Le Mouélic et al., 2002; Li and Mustard, 2000; Lucey et al., 1995, 2000; Pieters et al., 2001; Staid and Pieters, 2000; and Tompkins and Pieters, 1999).

Lunar Prospector began mapping the Moon in January 1998, and continued for 19 months. Two instruments provided chemical data, a gamma-ray and a neutron spectrometer. The instruments obtained data that have led to global maps of surface concentrations of K, Ti, Fe, Sm + Gd, and Th (Lawrence et al., 1998, 2000; Elphic et al., 2000). The most extraordinary finding was that the radioactive and geochemically incompatible elements, K and Th, are at high concentrations in the NW quadrant of the nearside and are low elsewhere, although there is some minor enrichment in the South Pole-Aitken basin (Fig. 14). The anomalous region coincides approximately with Oceanus Procellarum and the location of the proposed ancient and huge Procellarum basin (Cadogan, 1974; Whitaker, 1980; Lawrence et al., 1998; Haskin, 1998; Jolliff et al., 2000). Half-degree pixels in the region (230 km^2) have up to 12 μg/g Th, roughly twice that of terrestrial continental crust. Concentrations of K are strongly correlated with those of Th (Lawrence et al., 1998). Much high-Th material has been resurfaced with mare basalt of lower Th concentration, leading to a Th low in the center of the Imbrium basin (Haskin et al., 2000).

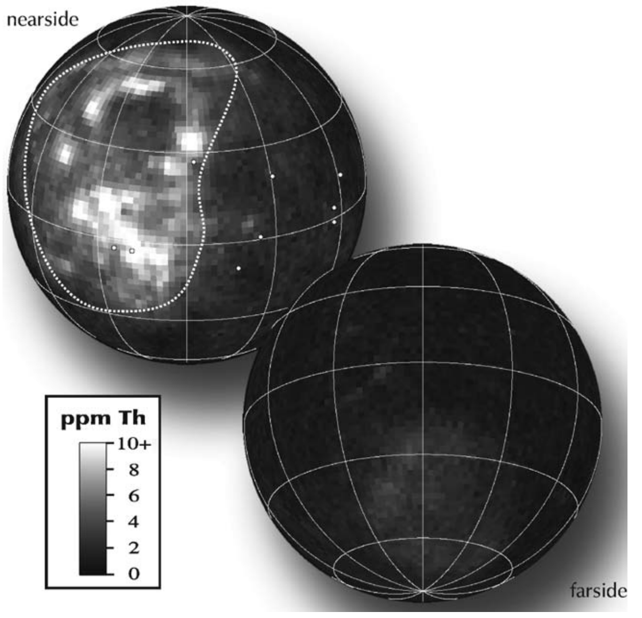

Fig. 14. Maps of Th distribution on the lunar surface as obtained from Lunar Prospector (Lawrence et al., 1998, 2000; Gillis et al., 2004). Locations of the Apollo and Luna landing sites are denoted by small white dots; the key is given in Fig. 13. The two hemispheres shown are in orthographic projection, as in Fig. 13, with a resolution of half degree per pixel (15 km) at the equator. The dotted field on the nearside indicates the approximate boundary of the Procellarum KREEP Terrane of Jolliff et al. (2000). On the farside map, the slight enrichment in Th in the southern hemisphere corresponds to the South Pole-Aitken basin. The maps were prepared by Jeff Gillis.

A key observation about the distribution of radioactive elements is that there is little correlation between Th concentration and the mare-highlands dichotomy (Haskin, 1998; Haskin et al., 2000). Some mare have high Th and others do not. Some nonmare regions have high Th but most do not. Nearly all areas with high surface concentrations of K and Th are topographically low (Korotev and Gillis, 2001) and have FeO intermediate to that of highlands areas and mare areas (Fig. 15). As with the lunar meteorites, at least three geochemical reservoirs are required to account for the variation in FeO and Th observed on the lunar surface from orbit, not just two as might be expected on the basis of the mare-highlands dichotomy.

3. A no-Apollo simple synthesis

In the absence of the Apollo program, we might have surmised the following scenario from the data and information derived from lunar meteorites, orbital and telescopic data, and robotic landers.

The early Moon was largely or totally molten. The first olivine and pyroxene to crystallize sank in what is known as the lunar magma ocean or magmasphere. When plagioclase began to crystallize, it floated, being of lower density than the Fe-rich magma. As a consequence, the Moon differentiated to form a crust of anorthosite over most of the surface. This crust has been designated the Feldspathic Highlands Terrane by Jolliff et al. (2000) to indicate that it is, in effect, an ancient craton. At least half of the lunar meteorites derive from the this terrane. [The magma-ocean hypothesis was, of course, developed on the basis of Apollo data. Apollo 11 data provided the first model (Wood et al., 1970). By the mid-1970s, details of the model had been established (Taylor and Jakeš, 1974, 1977). The mature model and alternative models are best described by Warren (1985, 1990, 2004), Shearer and Papike (1999), and Longhi (2003).]

By some mechanism (e.g., Hess and Parmentier, 2001; McCallum, 1998, pp. 54–55; Warren, 2004), differentiation of the Moon was asymmetric and the final liquid from magma ocean crystallization, rich in incompatible elements and much richer in iron than the anorthosite, was concentrated near the surface in the Procellarum region. Meteorite SaU 169 derives from this region, a unique geochemical province exposed over an area of 16% of the lunar surface, that Jolliff et al. (2000) designate the Procellarum KREEP Terrane. Because a high fraction of the Moon's heat-producing elements (e.g., 40% of the Th; Jolliff et al., 2000) are concentrated there, the Procellarum KREEP Terrane had a substantially different igneous and thermal history than the Feldspathic Highlands Terrane. Numerous basin-forming impactors collided with the Moon in its early history. The impactor that formed the Imbrium basin struck the Procellarum KREEP Terrane 3.9 Ga ago (Pb–Pb age of a zircon in the Th-rich impact-melt breccia of SaU 169; Gnos et al., 2004). Because the Imbrium impact was one of the largest on the Moon, it spread Th-rich ejecta over the Moon's surface, although most was deposited near the basin (Haskin, 1998; Haskin et al., 1998). Because Imbrium was the second-to-last big

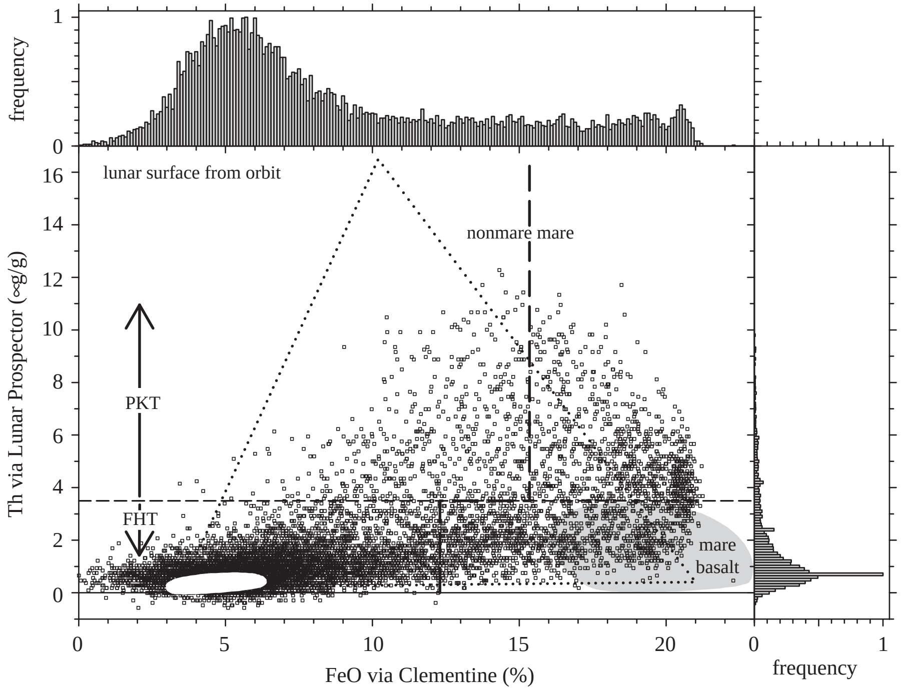

Fig. 15. Concentrations of FeO and Th on the lunar surface (60°S to 60°N) as determined from data obtained by Clementine (FeO, spectral reflectance, Lucey et al., 2000, calibration of Gillis et al., 2004) and Lunar Prospector (Th, gamma-ray spectrometer, Lawrence et al., 2000, calibration of Gillis et al., 2004). The figure is updated and modified from Plate 3a of Haskin et al. (2000). Each point represents an area of 2° of latitude and longitude. Regolith samples from the Apollo and Luna missions lie within and define the dotted triangle (Fig. 17). The distribution of orbital data is also approximately triangular. Both data sets, as well as the lunar meteorites, require at least three chemical reservoirs: material of the Feldspathic Highlands Terrane, the Procellarum KREEP Terrane, and mare volcanic material (mare volcanism occurs in both terranes). The white ellipse represents the range of the feldspathic lunar meteorites; the gray ellipse represents the range of all mare basalts (Apollo, Luna, meteorites). Of the 1406 points with >3.5 μg/g Th, 9 points represent locations within the South Pole-Aitken basin; the rest (99.4%) occur in (and define) the Procellarum KREEP Terrane (Jolliff et al., 2000). Regions represented by points to the right (high-FeO) side of the dashed lines consist mainly of mare material, those to the left mainly of nonmare material. The mean Th concentration of all points to the left of the dashed lines, excluding those within the South Pole-Aitken basin, is 1.2 μg/g. This value is a good estimate of the mean concentration of Th for the nonmare surface of the Moon. The mode for the feldspathic highlands is 0.7 μg/g Th.

basin to form, its ejecta deposits have not been significantly altered by subsequent impacts.

Although it formed in the Feldspathic Highlands Terrane, it is useful to regard the South Pole-Aitken basin as a terrane distinct from the other two terranes because it is old, huge, and geochemically distinct (Jolliff et al., 2000). The South Pole-Aitken Terrane is more mafic and richer in incompatible elements than the Feldspathic Highlands Terrane but not as rich in incompatible elements as the Procellarum KREEP Terrane (Fig. 14). Materials of the lower crust or upper mantle may be exposed (Lucey et al., 1995; Lawrence et al., 1998; Jolliff et al., 2000; Pieters et al., 2001). It is unknown whether the Th-rich materials in the South Pole-Aitken Terrane are the same as those of the Procellarum KREEP Terrane because no samples known to be from the South Pole-Aitken Terrane have yet been collected or identified among the lunar meteorites.

Differentiation of the Moon took place early, on the order of 4.5 Ga ago (Nyquist et al., 1996). The rate of impacts on the lunar surface was very much greater in the past than now (e.g., Ryder, 2002). Igneous rocks of the early feldspathic crust that have been minimally affected by subsequent impacts must be rare on the lunar surface because they do not occur as lunar meteorites and are rare in feldspathic lunar meteorites as clasts. Basaltic volcanism commenced and ended early in lunar history, but occurred largely after the period of high impact rate because there are unbrecciated basalts with crystallization ages of 2.8–3.9 Ga among the lunar meteorites but no unbrecciated anorthosites. The lunar maria consist of basalt for which the source regions must be similar to those of terrestrial basalts, indicating that the feldspathic crust overlies a mafic mantle. The low Al concentration and negative Eu anomaly of mare basalts reflect a source region with little plagioclase and one from which Eu has been removed during formation of the feldspathic crust (Taylor and Jakeš, 1974; Warren, 2004). Mare volcanism occurred in all three terranes. It is most prevalent in and around the Procellarum KREEP Terrane because the heat-producing radioactive elements are concentrated there (Wieczorek and Phillips, 2000).

Most of the Moon's incompatible elements are concentrated near the surface in the Procellarum KREEP Terrane (Korotev, 2000; Jolliff et al., 2000). Th is strongly correlated with Sm in nonmare lunar meteorites [and Apollo samples] (Fig. 10a); Eu is more nearly constant, but increase somewhat with Sm (Fig. 11). Thus, there is a strong correlation between Sm/Eu and Th (Fig. 16). Nonmare lunar rocks having approximately 1 μg/g Th have Sm/Eu that corresponds to no Eu anomaly. The mean concentration of Th on the nonmare surface is ~1 μg/g (Fig. 15). Thus, on average, the present nonmare surface has little or no Eu anomaly. If the bulk Moon has chondritic ratios of REEs, then there presently is no gross vertical separation of the plagioclase flotation cumulate and the liquid from which the plagioclase crystallized (Korotev and Haskin, 1988). The lateral separation is spectacular, but there can be no significant reservoir of solidified residual liquid sequestered beneath the crust because such a geometry would lead to an overall positive Eu anomaly for the surface.

There is some evidence that the present surface of the feldspathic highlands is richer in incompatible elements and, by inference, FeO (Fig. 15) than material at depth (Warren 2001b; Hawke et al., 2003). It has not been demonstrated whether or not this stratification is a result of deposition at the surface of ejecta from the Imbrium impact. Nevertheless, if the Imbrium impact had not occurred in the

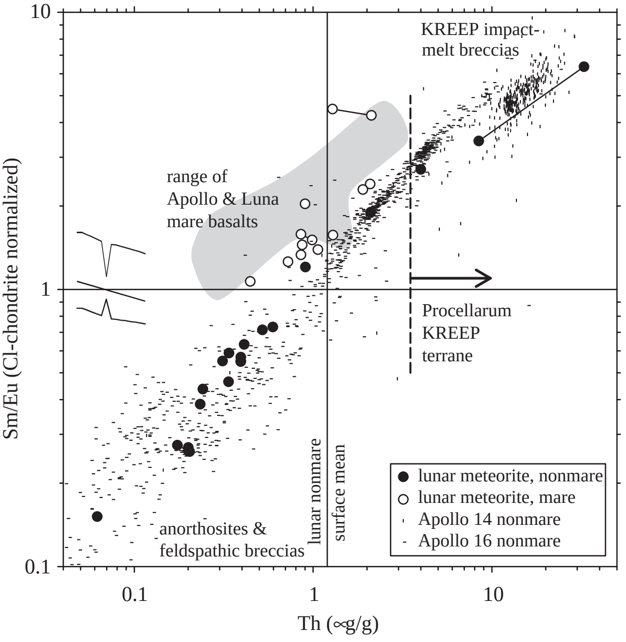

Fig. 16. The Eu anomaly, as expressed by the CI-normalized Sm/Eu ratio, as a function of Th concentration in lunar meteorites (circles), nonmare Apollo samples (small symbols), and Apollo and Luna mare basalts (gray field). Samples lying above the horizontal line have negative Eu anomalies; those below have positive Eu anomalies. For the meteorites, all those with <12% FeO are plotted as nonmare and those with >12% FeO are plotted as mare. Nonmare lunar samples with ~1 µg/g of Th have little or no Eu anomaly. Although Th concentrations across the surface of the Moon are highly variable, the nonmare surface has ~1.2 µg/g Th, on average (vertical line, from Fig. 15). Each small point represents a small (1–4 mm) nonmare, lithic fragment from the regoliths of the Apollo 14 or 16 sites (Jolliff et al., 1991a; Jolliff and Haskin, 1995; Korotev et al., 1997). High-Th Apollo 14 samples (all breccias) plot off the extrapolation of the trend of the Apollo 16 samples because they contain a component of alkali anorthosite with high a concentration of Eu (6±4 µg/g) compared to the clastic ferroan anorthosites (0.8 µg/g) of Apollo 16 impact-melt breccias, and a component of felsite, which has high Th/Sm compared to generic KREEP. Figure updated from Korotev and Haskin (1988).

Procellarum KREEP Terrane and spread Th-rich ejecta over the entire surface of the Moon, then the measured mean surface concentration of Th would be lower, likely leading to a mean surface with a positive Eu anomaly in Fig. 16. Much of the Procellarum KREEP Terrane has been resurfaced with basalt, however, disabling our ability to detect gamma-rays from the underlying material. If that basaltic veneer were absent, it is likely that the measured mean Th concentration of the nonmare surface might actually have a negative Eu anomaly. The argument of Korotev and Haskin (1988), i.e., that the surface of the lunar crust (nonmare) has no significant

Eu anomaly, has been misconstrued by O'Hara (2000, p. 1592) to refer, specifically, to the feldspathic crust. The lunar meteorites prove that the feldspathic crust is indeed enriched in Eu relative to trivalent REE (Fig. 8). When the Feldspathic Highlands and the Procellarum KREEP Terranes are considered together as "the crust" (as with terrestrial continental and oceanic crust), however, then there is no evidence of a Eu anomaly, on average.

4. Apollo and Luna samples

The Apollo landing sites were chosen on the basis of practical considerations such as orbital mechanics and mass and communications issues as well as scientific considerations derived from photogeologic data obtained by Ranger, Surveyor, and the Lunar Orbiters (e.g., Wilhelms, 1993). All six sites are clustered in a small area of the nearside near the equator (e.g., Warren, 1991; Fig. 13). The most distant sites, Apollo 12 and 17, are separated by 1760 km, only 16% of the circumference of the Moon. No orbital geochemical or mineralogical data were available at the time of site selections. Thus, it was not known that three of the six landing sites lay within the Procellarum KREEP Terrane and the other three were close enough to the huge Imbrium basin within the Procellarum KREEP Terrane (Fig. 14) that their regoliths contained a large proportion of Th-rich Imbrium ejecta (Haskin, 1998). Gamma-ray spectrometers on the orbiting command modules of the Apollo 15 and 16 missions (the 4th and 5th of the Apollo missions that landed) showed that the Procellarum region was rich in radioactive elements. Because of their limited coverage of the lunar surface (<20%; Metzger et al., 1977), however, they did not show that the Procellarum KREEP Terrane was, in fact, unique (Haskin, 1998).

The Apollo 14 lander set down (February 1971) on the ejecta deposit of the Imbrium basin in one of the highest-Th regions to be identified by Lunar Prospector 27 years later (Fig. 14). This geochemical anomaly was not known or even suspected at the time of site selection, however. In light of the orbital geochemical data, it is unremarkable, now, that the Apollo 14 rock suite consists mainly of moderately mafic, Th-rich (10–30 μg/g) impact breccias and regolith breccias derived therefrom (Jolliff et al., 1991a). In terms of the simple mare-highlands image of the Moon, however, the rocks were confusing when first studied. Because it is a nonmare site (no exposed basalt flows), Apollo 14 has usually been regarded as a highlands site (e.g., Spudis and Pieters, 1991, pp. 595–632) and the rocks as highland rocks. From the geochemical perspective, however, the site is neither mare nor feldspathic highlands (Fig. 17) and there is no particular advantage to regarding the site as in any way representing the highlands given that the site lies within the Procellarum KREEP Terrane at a point 1.7 km below the mean lunar datum (Smith et al., 1997). Apollo 12 landed 180 km to the west at a point where Th-rich Imbrium ejecta were covered by mare basalt. The nonmare rocks of the Apollo 12 site are essentially identical to those of Apollo 14, that is, they are dominated by mafic, Th-rich (12–33 μg/g) impact-melt breccias (Korotev, 2000; Korotev et al., 2002).

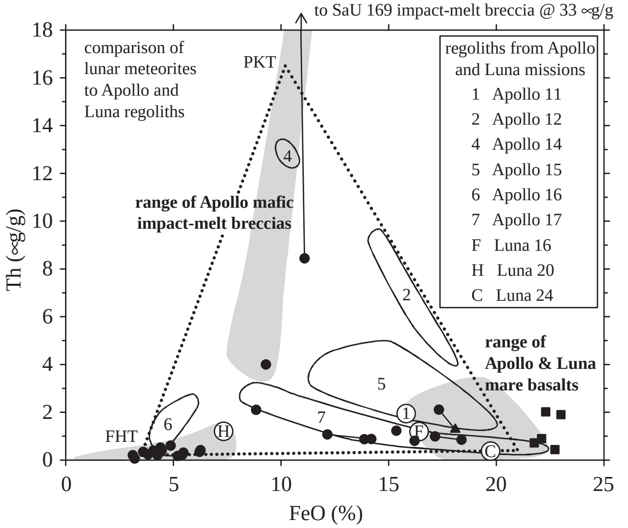

Fig. 17. Comparison of compositions of lunar meteorites (solid symbols; key in Fig. 4) to regoliths from the Apollo and Luna missions (after Korotev et al., 2003b). The Apollo and Luna regoliths inscribe a triangle (dotted) because they are mainly impact mixtures of mare volcanic material, material of the Feldspathic Highlands Terrane (FHT) and material (mainly impact-melt breccias) of the Procellarum KREEP Terrane. At any given landing site, the components do not plot exactly at the apices of the triangle but somewhere in the gray fields located at the apices because the lithologies representing the apices vary in composition from place to place. Lunar-meteorite regolith and fragmental breccias largely lie within the same triangle as the Apollo samples. The fields for Apollo regoliths are defined by samples of <1 mm fines collected at the surface and from trenches. The fields for the three Russian Luna missions are based on regolith (<0.25 mm fines) in a core taken at a single location. Th-rich, mafic impact-melt breccias of the Apollo missions span a wide range of Th concentrations. Those from Apollo 12 and 14 plot near the high-Th apex of the triangle; those from Apollo 16 and 17 tend to plot at the low-Th end of the range because the breccias contain a high proportion of feldspathic clasts.

At each of the other four Apollo landing sites Th-rich impact-melt breccias are also a significant component of the nonmare portion of the regolith. Many to most of the nonmare rocks of Apollo 15 and 17 are mafic, Th-rich impact-melt breccias (4–15 μg/g). The Apollo 16 mission is the only Apollo mission to have sampled the feldspathic highlands at point distant (200–300 km) from a basalt-filled basin. The majority of the rocks in the regolith are Th-poor anorthosites similar in composition to the feldspathic lunar meteorites, but many are mafic, Th-rich (4–10 μg/g) impact-melt breccias. At both Apollo 11 and 16, 25–30% of the nonmare material is the regolith (<1 mm fines) is or derives from such breccias (Korotev, 1997; Korotev and Gillis, 2001).

Three of the Russian Luna missions delivered robotic samplers and return vehicles to the surface of the Moon, collected small amounts of regolith (50–170 g), and brought the samples to Earth. All three missions landed near the eastern limb of the Moon and all three sites were more distant from the Procellarum KREEP Terrane than any of the Apollo missions (Fig. 13). Luna 16 and 24 landed in Maria; Luna 20 landed in the highlands on basin-ejecta deposits between Mare Fecunditatis and Mare Crisium. All of the "rocks" in the Luna 20 collection for which there are compositional data are <10 mg in mass. None is a mafic, Th-rich impact-melt breccia such as those of the Apollo collection (Korotev et al., 2003b).

5. An evolving new view

It is the author's belief that our view of the lunar geology has been strongly biased or skewed because the Apollo landing sites were all coincidentally located in an atypical region of the Moon, a region where rocks rich in Th and other incompatible elements were common to abundant. Also, only long after theories of big-scale lunar geology were proposed and accepted on the basis of the Apollo samples did we acquire the kind of global geochemical information, via meteorites from random locations and orbital data, that is required to put the Apollo sample data in proper perspective. In my opinion, some aspects of the old models are not consistent with the new global perspective and the magnitude of the misconceptions are still not well recognized. Thus, here I review two of the most important misconceptions that have resulted from the site-location coincidence, the non-ideal order of discovery, and the persistence of the notion that all lunar igneous or plutonic rocks must be either of "mare" or "highlands" affinity.

5.1. No global, subcrustal layer of magma-ocean residuum (KREEP)

The feldspathic lunar meteorites (3–6% FeO) provide our best estimate of the composition of, and compositional variation within, the Feldspathic Highlands Terrane (Korotev et al., 2003b). All of the numerous feldspathic the meteorites have low concentrations of incompatible elements (e.g., Th is <1 μg/g). In contrast, impact-melt breccias that are considerably more mafic (noritic, with 8–11% FeO) and that have concentrations of incompatible elements (4–33 μg/g Th) much greater than those of feldspathic lunar meteorites occur at all Apollo sites. Many such breccias, particularly those of Apollo 12 and 14, are essentially equated with the term KREEP. These mafic, KREEP-rich breccias dominate nonmare lithologies of the regoliths of the Apollo 12 and 14 sites, are common at the Apollo 15, 16, and 17 sites, and even occur among the minor nonmare component of the Apollo 11 regolith. Among 36 lunar meteorites, only SaU 169 is similar, and none of the numerous brecciated meteorites that clearly derive from the feldspathic highlands contain any significant component of Th-rich impact-melt breccias as clasts. With 2 and 4 μg/g Th, Yamato 983885 and Calcalong Creek may contain minor KREEP-like components in some unrecognized form (Figs. 8 and 10), but clasts of KREEP melt breccias have not been reported from either meteorite (Marvin and Holmberg, 1992; Arai et al., 2004; Cohen et al., 2005).

The Apollo mafic, Th-rich impact-melt breccias have long been regarded as the products of the ancient basin-forming impacts. The Apollo 12 and 14 sites were located on the continuous ejecta deposit of the Imbrium basin. The Apollo 15 and 17 sites are located on the edges of the Imbrium and Serenitatis basins and Apollo 16 site occurs near Nectaris. Virtually all the dated, mafic, Th-rich impact-melt breccias of the Apollo collection are old, ~3.9 Ga, and this age is taken as the time of basin formation (e.g., Ryder, 2002).

Ryder and Wood (1977) argued that if (1) the surface of the crust is feldspathic, (2) the crust is ~60 km thick, (3) basin-forming impactors are big enough to melt most of the column of crust in the target area, and (4) the impact-melt breccias of the basin-forming impacts are more mafic and richer in incompatible elements than the crust, then the crust must be layered, becoming more mafic and richer in incompatible elements with depth. Ryder and Wood (1977) preferred a 3-layer model. The middle layer, 18–36 km deep, was dominated by "KREEP norite," inferred to be "of substantial or even global extent" and the product of "large scale fractional crystallization." Later models put the KREEP layer at the base of the feldspathic crust (e.g., Spudis and Davis, 1986) and assume a "deep-seated" origin, even in the Procellarum KREEP Terrane (Wilhelms, 1993). Simple depictions of internal lunar structure of the early Moon often show KREEP (magma ocean residuum) concentrated at the bottom of the crust or between the feldspathic crust and the underlying mantle, sometimes in a global layer (e.g., Vaniman et al., 1991, pp. 6–26; Papike et al., 1998; Shearer and Papike, 1999).

The logic of Ryder and Wood (1977) was reasonable, but was based on the assumption that the Imbrium and Serenitatis basins formed in regions of typical feldspathic crust. We now have strong reasons to suspect that assumption to be invalid. The two basins are either in or on the edge of the Procellarum KREEP Terrane, an anomalous region where KREEP was concentrated near the surface at the time of the impacts. The mafic composition of the impact melt in the Th-rich melt breccias provides no evidence that anorthosite was an important lithology of the target area of the Imbrium or Serenitatis impacts (Spudis et al., 1991; Ryder et al., 1997). There is no KREEP, as we know it from Apollo, in the Luna 20 regolith on the edge of the Crisium basin, which is distant from the Procellarum KREEP Terrane. There is little or no evidence in the Lunar Prospector data that basin-forming bolides which impacted into the Feldspathic Highlands Terrane (e.g., Nectaris, Crisium) encountered KREEP, except that the South Pole-Aitken event may have encountered and exposed a small amount (Fig. 14; Pieters et al., 2001). The paucity of KREEP in lunar meteorites provides no support for the hypothesis that KREEP was globally distributed or that any form of KREEP was a lithology indigenous to the Feldspathic Highlands Terrane in prebasin times.

If lunar meteorites had been found and studied and orbital gamma-ray data had been acquired prior to sample collection missions, there would have been no reason to hypothesize that KREEP, as it is observed in the Apollo collection, was closely related to the feldspathic crust except in the broadest sense, that at least some anorthosite of the crust crystallized from a magma. If our suite of lunar meteorites had been found 30 years earlier or if the Apollo missions had landed 30 years later, even at the same sites as the actual missions, the various KREEP-rich lithologies obtained on the missions would have been recognized for what they are, differentiation products of a geochemically anomalous region of crust and the impact products derived therefrom.

5.2. No magnesian-suite ''highland'' rocks

Most rocks of the lunar highlands are breccias. In the late 1970s and 1980s, much effort was spent on finding and identifying, in the Apollo collection, relict igneous or plutonic rocks of the ancient lunar crust, rocks for which the mineral and compositional features had not been besmirched by the mixing and thermal effects of meteoroid impacts (e.g., Warren and Wasson, 1977; Warren, 1993; Norman and Ryder, 1979). Early works referred to such rocks as ''pristine nonmare rocks'' (Warren and Wasson, 1977; Warren et al., 1983a) as opposed to ''pristine highland rocks.'' Nevertheless, the pristine nonmare rocks of the Apollo collection are still generally taken to be products of the highlands (e.g., Papike et al., 1998; Warren, 2004; Cahill et al., 2004) and have a spatial relationship, specifically, with the feldspathic highlands because, in the simple, bimodal, mare-highlands model, there is no other option.

Two major suites of pristine nonmare rocks have been recognized, the ferroan (low Mg/Fe) anorthosites (e.g., Papike et al., 1998) or ferroan anorthositic suite (Warren, 2004) and the Mg-rich suite (e.g., Papike et al., 1998) or Mg-suite (Warren, 2004), which is more accurately designated the magnesian (high Mg/Fe) suite (e.g., Snyder et al., 1995a). The ferroan-anorthositic suite consists mainly of highly feldspathic ($>95\%$ plagioclase) anorthosites (most from the Apollo 16 site), but it also contains rocks as mafic as anorthositic norite (Warren, 1990; Jolliff and Haskin, 1995). Such rocks have the property, unusual on Earth, of consisting of highly anorthitic plagioclase (An_{96}) and relatively ferroan mafic minerals (Mg': 50–70). The magnesian suite comprises mafic plutonic rocks (norite, troctolite, gabbronorite, dunite, spinel troctolite), most with high Mg' (80–95), alkali anorthosites and norites, and KREEP basalts and related evolved rocks (e.g., quartz monzogabbro).

Ferroan-anorthositic suite rocks are clearly indigenous to the feldspathic highlands. Many studies, however, have shown that magnesian-suite rocks crystallized from magmas with high concentrations of incompatible elements, in essence, magmas that contain or are some kind of KREEP (Warren, 1988; Snyder et al., 1995a; Papike et al., 1996; Shearer and Papike, 1999). The norites, troctolites, dunite of the magnesian suite are thought to be plutonic rocks formed as cumulates from intrusions in the feldspathic crust. Diapirs that originated in the mantle assimilated KREEP at the base of the crust and perhaps anorthosite as they ascend into the feldspathic crust (Warren, 1988; Shearer and Papike, 1999). The alkali suite rocks also require a KREEP parent liquid (Snyder et al., 1995b; Shervais and McGee, 1999).

Rocks of the ‘‘highlands magnesian suite’’ (e.g., McCallum, 1998, pp. 54–55) such as the norites, troctolites, dunites, and alkali anorthosites of the Apollo collection are rare or absent as clasts in the feldspathic lunar meteorites (Korotev et al., 2003b). There is little evidence in Clementine data for any truly mafic plutons in the feldspathic crust (Tompkins and Pieters, 1999). Had we had lunar meteorites and orbital geochemical data prior to Apollo, it would have been self evident that the all or most of the magnesian-suite rocks of the Apollo collection are differentiation products of the Procellarum KREEP Terrane and have little connection with the Feldspathic Highlands Terrane (Korotev, 2000; Wieczorek and Phillips, 2000). Warren and Wasson (1980) did, in fact, recognize that there was longitudinal control over the distribution of pristine nonmare rock types that must ultimately result from global geochemical asymmetry.) With the possible exception of some of the gabbronorites of James and Flohr (1983), magnesian-suite rocks, as we know them from the Apollo collection, are nonmare rocks, but they are not ‘‘highland rocks,’’ if we restrict the term ‘‘highlands’’ to the feldspathic highlands. Only if it is demonstrated that rocks such as the norites and troctolites of Apollo 15 and 17 actually formed in a region of typical feldspathic crust would it be reasonable to classify them as ‘‘highland rocks.’’ Any other approach is only confusing and misleading because it oversimplifies the complexity of lunar geology.

6. Summary

Approximately 36 meteorites have been found on Earth and recognized to be of lunar origin since 1979. Some whole-rock compositional parameters are useful in identifying lunar rocks (square brackets designate concentrations or concentration ratios): $43<[\%\ SiO_2]<48$; $[\%\ MgO+FeO\ (\pm 3\%)$, total Fe as $FeO] = 40\%-1.06\cdot[\%\ Al_2O_3]$; 0.55 (anorthosites) $<[CaO/Al_2O_3]<1.2$ (basalts); $0.15<[\%\ Na_2O]<1.0$; $[\%\ K_2O]<1.6\%$ (and rarely $>0.5\%$); $400<[\mu g/g\ Cr]<4500$; $60<[FeO/MnO$, total Fe as $FeO]<85$; $15<[Cr/Sc]<130$; $0.6<[La/Yb]<4.0$; 1.6 (KREEP) $<[Yb/Th]<35$ (high-Ti basalt); and $0.3<[\mu g/g\ Eu]<4.3$. A particularly useful test is that for nonbasaltic ($<15\%$ FeO) lunar meteorites $[\mu g/g\ Eu\ (\pm 25\%)] = 0.75\,\mu g/g + 0.056\cdot[\mu g/g\ Sm]$. For basaltic ($>15\%$ FeO) lunar meteorites, $[\mu g/g\ Eu\ (\pm 60\%)] = 0.25\,\mu g/g + 0.149\cdot[\mu g/g\ Sm]$. Some Apollo samples and one lunar meteorite (the olivine cumulate lithology of NWA 773) do not meet all of the tests above, but most such samples are rare, have extreme compositions, or are very small.

Historically, the Moon’s surface has been viewed as dichotomous or bimodal, consisting of rugged highlands of high albedo with smooth circular maria of low albedo. The highlands rocks are mainly anorthositic (poor in Fe but rich in Al) and the mare rocks are basaltic (rich in Fe but poor in Al). The simple dichotomous model does not account for lunar geochemistry, however. The composition of the surface as observed from orbit, the compositional range of the lunar meteorites, and the compositional range of the Apollo samples each require a third kind of component, one of intermediate FeO but with much greater concentrations of incompatible elements than either the anorthosite or basalt. This third component is known as KREEP basalt of norite, when the term KREEP is applied to an igneous or plutonic rock. (Most KREEP-bearing rocks, like lunar meteorite Sayh al Uhaymir 169, are polymict breccias, however.)

In the dichotomous model, if an igneous rock is not a mare basalt, it must be from the highlands. The Apollo sample data were interpreted (largely before 1980) without benefit of global data provided by lunar meteorites (studied since 1982) and orbital geochemistry (since 1994). Thus KREEP, its unrecognized igneous precursor (urKREEP; Warren and Wasson, 1979), and related rocks of the magnesian suite of lunar nonmare rocks have long been taken to be highlands rocks. If the "highlands" are equated with "crust," that interpretation cannot be faulted. Operationally, however, "highlands" is usually equated with the typical feldspathic crust that covers most of the Moon. Thus, KREEP and other mafic magnesian-suite rocks are thought to originate from beneath the feldspathic crust and their existence at the surface is taken to be the result of plutonism and meteoroid impacts into the feldspathic highlands.

Two types of post-Apollo data argue that KREEP and related magnesian-suite rocks, as known from the Apollo collection, are not lithologies indigenous to the feldspathic crust. First, data obtained from the Clementine (1994) and Lunar Prospector (1998–1999) orbital missions show that there is an anomalous region of the crust in the Procellarum region in which KREEP is concentrated at the surface but which, geochemically and topographically, is neither mare nor highlands, although mare volcanism has occurred in the region. The boundary of this region, the Procellarum KREEP Terrane, is distinct in gamma-radiation emission because the region has high concentrations of K, Th, and U, but is largely invisible in visible radiation albedo. Second, feldspathic lunar meteorites, which derive from several locations in the feldspathic highlands, are largely devoid of KREEP and mafic, magnesian-suite rocks such as those in the Apollo collection. These observations and data argue that KREEP basalt and magnesian-suite rocks are differentiation products of the Procellarum KREEP Terrane, not of intrusions from the mantle into the crust of the Feldspathic Highlands Terrane. The misconception arises from preconception, historical accident, and non-ideal order of discovery: (1) the simple mare-highlands model obscures reasonable interpretation of the Procellarum KREEP Terrane, a region that is geochemically neither highlands nor mare, (2) the last basin-forming impactor to strike the nearside of the Moon targeted the Procellarum KREEP Terrane and distributed differentiation products onto the surface, (3) all the Apollo landing sites happened to be in or near the anomalous Procellarum KREEP Terrane, and (4) global geochemical data (lunar meteorites, Clementine, Lunar Prospector) needed to put the Apollo landing sites and samples in context were not acquired until long after Apollo samples were largely interpreted in a regional context.

There is some evidence that a true "highlands magnesian suite" does exist. Lithic clasts with mineralogies consistent with Apollo magnesian-suite plutonic rocks are observed in feldspathic lunar meteorites (e.g., Warren et al., 1983c; Treiman and Drake, 1983; Cahill et al., 2004). Nearly all such clasts are breccias, however, and all are considerably more feldspathic than the Apollo magnesian-suite rocks. It has not been demonstrated that such rocks are related in a petrogenetic sense (i.e., differentiates of a KREEP magma) to the magnesian-suite rocks of the Apollo collection and there is some evidence that they are not. The feldspathic lunar meteorites with high Mg/Fe (Figs. 6 and 7) and the magnesian, feldspathic granulitic breccias of the Apollo collection require a magnesian anorthosite precursor in the Feldspathic Highlands Terrane, one that is geochemically distinct from the mafic magnesian suite of the Procellarum KREEP Terrane (Korotev et al., 2003b). Bulk compositions of the feldspathic lunar meteorites attest that Mg/Fe ratios vary considerably across the surface of the feldspathic highlands and, on average are greater that those of ferroan anorthosites. On the basis of Eu and Al mass-balance constraints, a significant fraction, on the order of half, of the plagioclase in the feldspathic rocks of the surface of the Feldspathic Highlands Terrane cannot be associated with ferroan-anorthositic-suite rocks. The carrier of the ‘‘excess Eu’’ must be a magnesian anorthosite that has largely alluded us as a ‘‘pristine rock’’ (Korotev and Haskin, 1988). The conservative approach is to assume that there are two kinds of magnesian suites until proven otherwise. The identification and characterization of magnesian lithologies indigenous to the feldspathic highlands is an area ripe for research efforts, one particularly suited to a sample return from the South Pole-Aitken basin (e.g., Duke, 2003), which likely excavated material of the lower crust (e.g., Pieters et al., 2001).

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